The Anatomy of an Urban Modular Electric Vehicle: How the Architecture of the CityCar Enhances Personal Mobility and Supporting Industries

By

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SUBMITTED TO THE PROGRAM IN MEDIA ARTS & SCIENCES, SCHOOL OF ARCHITECTURE AND PLANNING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY IN MEDIA ARTS & SCIENCE
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2012

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Abstract

Growing populations, increasing middle-class, and rapid urbanization - for today's urban dweller, all of these escalating factors continue to contribute to problems of excessive energy use, road congestion, pollution due to carbon emissions, and inefficient personal transit. Considering that the average vehicle in a city weighs thousands of pounds, usually caries only one person per trip, and expends significant proportions of its gasoline simply searching for resources such as parking, new efficient and intelligent modes of transportation are in need of exploration.

This dissertation presents the design and development of an electric vehicle called the "CityCar" that confronts the aforementioned problems of urban mobility with a novel vehicle architecture. The assembly of the CityCar derives from a subset of "urban modular electric vehicle" (uMEV) components in which five core units are combined to create a variety of solutions for urban personal mobility. Drastically decreasing the granularity of the vehicle's subcomponents into larger interchangeable modules, the uMEV platform expands options for fleet customization while simultaneously addressing the complex rapport between automotive manufacturers and their suppliers through a responsibility shift among their respective subcomponents.

Transforming its anatomy from complex mechanically-dominant entities to electrically-dominant modular components enables unique design features within the uMEV fleet. The CityCar for example exploits technologies such as a folding chassis to reduce its footprint by 40% and Robot Wheels that each are allotted between 72 to 120-degrees of rotation to together enable a seven-foot turning circle. Just over 1,000 pounds, its lightweight zero-emitting electric platform, comprised of significantly fewer parts, curbs negative externalities that today's automobiles create in city environments. Additionally, the vehicle platform developed from the assembly of several core units empowers a consortium of suppliers to self-coordinate through a unique modular business model. Lastly, the CityCar specific uMEV confronts problems within urban transit by providing a nimble folding mobility solution tailored specifically to crowded cities. Benefits, such as a 5:1 parking density and its reduced maintenance demands, are especially reinforced in the context of shared personal transportation services like *Mobility-on-Demand*.

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Acknowledgements

It's been a long time coming...

There are so many people to which I would like to express my sincere gratitude. Inspiring imagination, nurturing ideas, forming a vision, tackling challenges, and persistently "preaching the gospel" - reaching this milestone is a true testament of the collective efforts of the former Smart Cities SOB's, **s**ons (and daughters) **of** **B**ill, led by a great mentor. William J. Mitchell was a true visionary whose broad intellect and warm personality endlessly motivated his students to dream big, and do big. Although he is dearly missed, his spirit carries on in so many he has affected, directly and indirectly.

To the core team members who indeed defined my experiences at the Media Lab, taught me much, shared a laugh, pulled an "all-nighter" or two in the workshops, and supported me through this adventure, I'd like to offer a heartfelt thank you. To dare and name everyone might require an additional chapter. However, I would like to express my appreciation to Nicholas Pennycooke who tirelessly worked alongside me to bring the CityCar vision a significant step closer to reality, and to Ryan Chin who coordinated so many of the daily efforts necessary to keep opportunities available. Additionally, I'd like to offer many thanks to the UROPs who contributed their time to help make my ideas come to life.

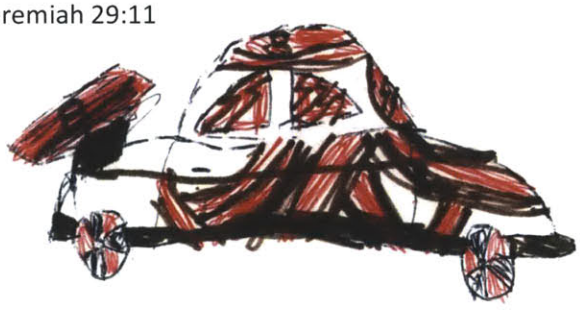
Of course, many of these undertakings would not possible without the Media Lab staff. Facilities, Necsys, administration and others have always given me support and shown patience, even during the times where I may have deviated from protocol, or needed immediate assistance. And Cynthia, thank you so much for looking after the group and me. It's amazing how you're able to manage the overwhelming volume of activities. I'll miss our little impromptu chats.

To my newest Basque and Spanish friends overseas - eskerrik asko, gracias, thank you. Embracing the vision, you've been able to tackle many of the challenges and turn the CityCar concept into a reality. The Hiriko project and everyone involved will always be cherished to me. You literally made my dreams come true. I wish you the best of luck and much success on your future endeavors.

Kent, thank you so much for being there when needed. I am very grateful for taking me under your wing. You inherited a significant responsibility and embraced me and others without hesitation. What I appreciate the most is that, like Bill, you have always made time for me. From Larry Sass, to Bill Mitchell, to you – each has not only been a great advisor but has also kept thought to my future opportunities, enabling smooth transitions from undergraduate studies all the way through to my doctorate.

Finally, I want to recognize the consistent love and support from all my family and friends. My mom and dad have provided unwavering faith and care along every endeavor and my younger brother Josh has been a genuine companion who I always attempt and hope to make proud. To my wife, Vanessa, I love you. Your patience and support were just what I needed to accomplish some of these feats over the past decade. I look forward to our next challenges together.

Jeremiah 29:11



...you're next Julian

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INTRODUCTION

Continual climate shifts, increasing petroleum costs, rapidly growing populations, and the considerable increase of the world's middle class causes many of us to reanalyze how we use today's global resources. One factor that has influenced these changes has been the automobile. Providing unprecedented mobility, the automobile has increased access to resources and productivity. Yet this century old marvel also bears significant responsibility for increasing pollution, traffic jams and excessive resource consumption of both materials and energy. In addition to the continual shifts in interrelated parameters of climate, petroleum and population, projections by the United Nations show that the 50% of the world's population, currently residing in urban areas, is projected to increase to 60% over the next twenty years. Understanding all of these factors, it soon becomes easy to forecast that a growing global middle class will increasingly demand more sources of mobility. So do we simply provide more automobiles to the masses? Such vehicle solutions like the Tata Nano address the demand for inexpensive mobility, but do so by reinforcing existing technologies that only exacerbate the aforementioned problems.

In order to create significant environmental changes while providing sustainable solutions for the growing demand, we must consider a radical paradigm shift. MIT professor William J. Mitchell illustrated the paradigm of today's typical automobile; "The typical automobile weighs 20 times as much as its driver, requires more than 100 square feet for parking, travels over 300 miles without refueling, and attains speeds well over 100 miles per hour. Each of these characteristics is considerably more than what is needed in major cities worldwide, where most of the world's people now live. In fact, while today's vehicles are designed to meet almost all conceivable needs for transporting people and cargo over long distances, these requirements drive considerable cost, energy, mass, and space inefficiency into the vehicle."[1] Although impressively engineered, today's typical sedan or sport utility vehicle seems to be over-equipped for the urban commuter. Considering the moderate commuting speeds, shorter distances, and the growing congestion & pollution within cities, compact and clean vehicles with reserved performance and range become highly suitable in these dense urban areas. The paradigm of the do-all mega vehicle may no longer be sustainable for the planet's growing cities.

What if tomorrow's paradigm instead offered a relatively lightweight, affordable, compact, clean and sustainable option? Imagine vehicles designed around core electric platforms that conserve energy in idling traffic; vehicles that can take an exceptionally sub-compact footprint to ease parking and preserve precious real estate. Visualize tomorrow's vehicles drastically simplified and tailored to operate in urban environments – vehicles specifically built to operate and adapt to the city.

[1] (Mitchell, Borroni-Bird, & Burns, 2010)

1 BACKGROUND

The automobile has provided for unprecedented mobility over the past century allowing us to access resources, expand our interactions, and broaden our ranges of commute. Its impact on modern society has been profound. Vehicles today continue to advance as engineering marvels by improving their performance, increasing their intelligence of surroundings, and integrating more sophisticated technologies than ever before. However, today's automobiles do create negative externalities that provide for challenges especially in major cities around the world. Inefficient energy use, air and noise pollution, and carbon emissions damage our environment while consuming a significant proportion of energy sources. Additionally, the dependence on fossil fuel resources continues to stimulate geo-political conflict.

On a local level, the abundance of vehicles within cities results in urban congestion and large proportions of paved land dedicated to roadways, access points, and parking areas. For example, a relatively less metropolitan city such as Cambridge, Massachusetts dedicates roughly a third of its landscape solely to paved vehicle surfaces (roads, parking, and access ways). In many metropolitan areas around the world, one-third of the land is dedicated to parking structures alone.[2] The need for vehicle parking also creates a burden on residential and commercial building developers, requiring new construction to provide corresponding spots for each of their residents and employees.

As the world's population continues to grow, more people are living in cities today than in rural areas. Billions flock towards cities in order to access resources, carry out careers, and socialize within their communities. Additionally the global middle-class continues to expand, especially in Eastern countries like India and China. Such upward class shifts result in an up swelling of citizens who seek to improve their status, especially in means of transportation. Areas of Taiwan for example have over 14 million registered scooters which make up for two-thirds of its ridership.[3] These Taiwanese streets and lots are already overwhelmed by scooters; however as growing families seek safer means of transportation, problems of congestion and parking will only be made worse by larger vehicles.

The combination of growing populations, increasing middle-classes, and rapid urbanization collectively exacerbate problems of excessive energy use, road congestion, pollution from carbon emissions, and ineffective personal transit in major cities around the world. As cities adopt more inhabitants and more vehicles, space is at an all-time premium – resulting in escalating parking prices, congestion zoning, micro-sized living spaces, and mega-sized parking lots.

[2] (Ben-Joseph, 2012)
[3] (The China Post, 2011)

Cities around the world continue to address the challenges with smaller apartments, deeper garages, increasing energy costs, and zone pricing (as implemented in cities like London, Hong Kong, and Mexico City). Radical fundamental changes can be explored instead on our actual means of personal mobility. The automobile, which has not fundamentally varied much in its make-up since its actual inception in the 1800's, can instead be rethought. Urban vehicles can be redefined specifically for the needs of urban transit. Tomorrow's personal mobility solution should strive to increase its accessibility, maneuverability and connectivity, while becoming lean on energy and space consumption in order to curb the rapid consumption of our planet's resources.

Aside from the urban challenges that come from the overwhelming number of vehicles, the automobile sector itself has seen its share of recent industry woes. The United States car industry especially has stumbled in the face of daunting labor and pension burdens, vertically integrated inflexible supply chains, and delayed embracement of innovative technologies. Detroit has begun to turn around, but even foreign companies like Toyota that have recently dominated the market also face real trials of decreasing profit margins. Even the utmost efforts of value engineering do little to maintain revenue margins in the saturated market.

1.1 Large Scale Problems in Transportation

Urban mobility faces three major challenges. Environmental – How do curb the negative externalities that the automobile has on our planet from its resource consumption and polluting exhaust? Transit – As populations rise and economies expand globally, how do we provide sustainable and efficient mobility options for the masses? Industrial – With shrinking profit margins in a saturated automobile sector, what novel strategies can be taken to enable new vehicle markets either for existing or emerging companies?

1.1.1 *Environmental Side Effects*

Crowded, congested, polluted, and expanding – these are unfortunately common traits of many major metropolitan cities. As ecological concerns continue to rise, we must ask ourselves what condition our environment will be in over the next decades. Making worse these problems is the fact that cities are only exploding in population. Within the last years our global population has witnessed a shift as we now have more people living in cities than in rural areas. This urban population shift is projected to rise to 70% by 2050[4] as even more of the world's population will dwell in cities. Currently there are no signs of these numbers turning around anytime soon as roughly 80% of the world's wealth will also be concentrated in cities by the same year.

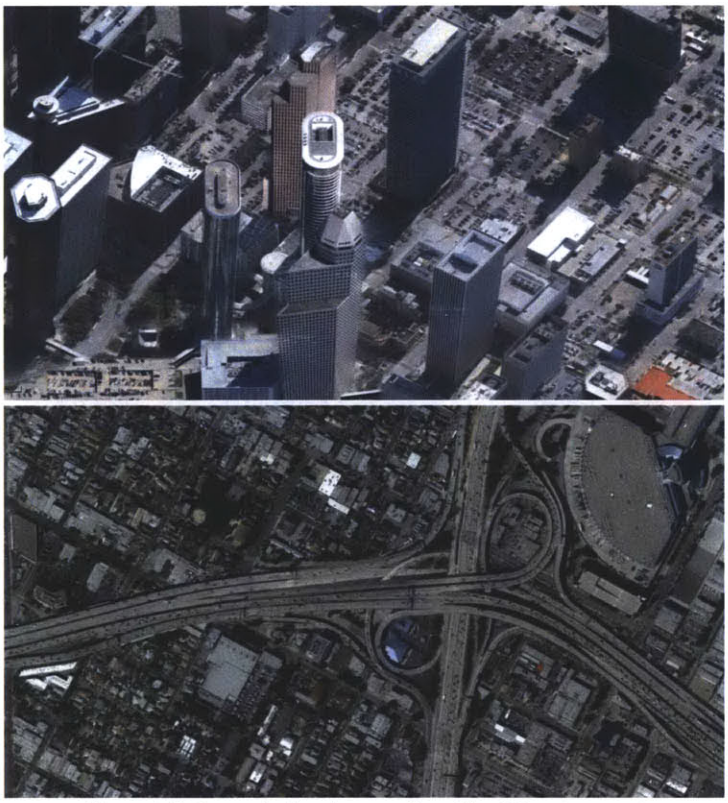

Figure 1-1: Congested and expanding cities (Google maps)

Understanding these trends and how they affect our environment, we can begin to focus in on a number of opportunities to make substantial changes to the urban landscape and how many of its own features impact its surroundings.

Considering that cities are major consuming and producing environments, there are two obvious contributors which we can initially focus on in these areas - buildings and transportation. While urban pollution does not account for all greenhouse gas effects (other significant contributions come from agriculture, forestry, and industrial plants), it is a major contributor considering that transportation, buildings, and power consumption account for half of global emissions. In 2005 transportation alone tied for the fourth largest contributor to carbon emissions.[5] Unfortunately, by 2030 it is projected to move up to the second most polluting factor, producing 11.4 gigatonnes of carbon dioxide (CO_2) equivalents.

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[4] (United Nations, 2008)

[5] (McKinsey & Company, 2009)

The increase of carbon dioxide and other gasses, such as methane, lead to greenhouse effects in which these gasses trap infrared radiation. This containment of the sun's radiation refers to the phenomenon of "global warming." Secondly, the combustion of hydrocarbons in internal combustion engines result in not only CO_2 but also, poisonous carbon monoxides (CO), and unburned hydrocarbons (HC) which are responsible for carcinogens and nitrogen oxides (NO_x) which also lead to smog. Finally, besides all the potential environmental health benefits that would come from reducing the volume of internal combustion engine exhaust byproducts, minimizing noise levels in crowded cities is also very desirable for the comfort of its inhabitants.

Steps are being made to incorporate more environmentally conscious components (hybrid platforms, increased range through the combination of improved engine performance and aerodynamics, biodegradable materials, more energy efficient LED lights); still they are few and incremental. An aggressive approach should instead be taken to address the escalating challenges in transportation. Not only must we exploit new technologies that that allow vehicles to behave more efficiently but we must consider how personal mobility solutions can exploit local intelligence and networking to behave even more cohesively as a proficient system. We cannot only design "green" vehicles, but also green vehicles that are networked to each other and effectively communicate to their surroundings to enable efficient flow of transit. It is only then that we can start to make significant impacts through a multi-faceted approach – a comprehensive green approach.

1.1.2 *Problems in Urban Transit*

Whether it is cities in the United States like Boston, New York, and San Francisco or across the seas in London, Berlin, or Hong Kong, many of the world's major metropolitan areas are facing serious challenges from current means of transportation. Problems in parking, safety, and congestion plague these areas and commuters are left with few alternative solutions.

As cities become denser with people and vehicles, finding parking continues to grow as a problem. Given that space is in high demand in crowded cities, parking prices can easily exceed $500 a month in New York City and over $400 a month in Boston.[6] The top ten cities in the United States average a monthly parking price of $312, and the national average is $155 a month. This expense plays a large factor in the actual total cost of car ownership. Even more, in large European and Asian cities monthly parking cost can skyrocket over $1000 (London: $1083, Zurich: $822, Hong Kong: $745, Tokyo: $744). In many cases, especially in US cities, up to 50% of public parking prices are subsidizes by local governments. The value of this urban landscape is at a premium and large percentages of it are occupied by dormant automobiles. Such high parking prices create complexities for car owners, building developers and managers, and managers of larger vehicle fleets.

For individual automobile owners, the cost of parking in major cities increases their annual transit costs by 21% on average. The average person spends roughly $9,000 a year to own an automobile.[7] This cost does not include parking. Given that the average annual parking cost in US cities is around $1860 ($155 per month), having the means to store their vehicle when it is not in use is significantly prohibitive to some owners in larger cities like New York, Boston, San Francisco, and Philadelphia (each with monthly rates of $541.^{00}, $438.^{00}, $375.^{00},303.^{63} respectively).

[6] (Moore, 2011)
[7] (AAA, 2009)

For building developers, the challenge to provide sufficient parking accommodations can be just as daunting. Parking lots creates significant burdens on new construction. Residential buildings must incorporate large structures underground or adjacent to the main structure. Parking structures demand a significant amount of space and become very costly when built underground. As construction costs in major US cities exceed $30,000[8] per car with each of these cars requiring just under 300 square-feet (parking space, access pathways, and surrounding structures), costs and land requirements can easily exceed five million USD for 100 parking spaces. One of the underground parking levels in MIT's Stata Center, for example, that can accommodate 340 vehicles, requires over 120,000 square feet and can easily exceed $7M USD for each of its levels.

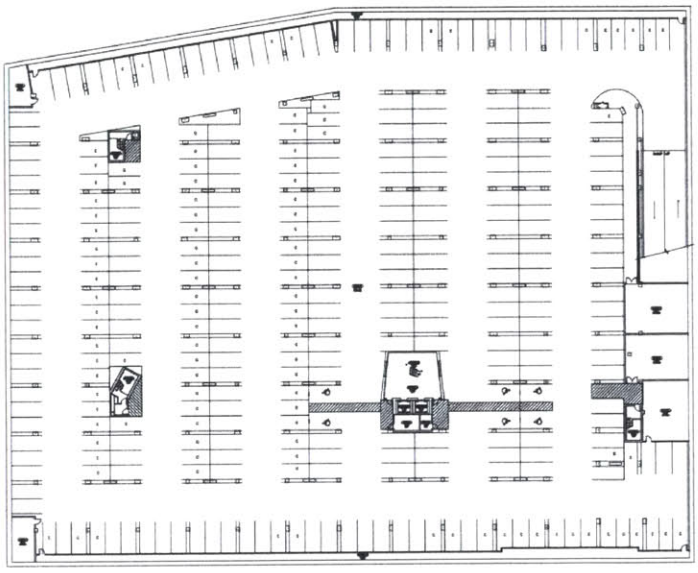


Figure 1-2: MIT Stata Center parking lot

Adding to the problems of urban transit is congestion. Roadways space is being occupied more and more by vehicles. Overwhelming traffic causes many to spend a large percentage of time stuck in the commute. Commuters in some of the worst US cities (Washington D.C., Chicago, Los Angeles, and Houston) spend around 70 hours every year stuck in traffic.[9] That's practically three days strait sitting still in a vehicle. Cities worldwide that can no longer manage the vehicle congestion, such as London, Florence, Hong Kong, and Mexico City, resort to congestion pricing, which financially discourages the high influx of automobiles within the city centers. Unfortunately, such policies lead to inequitable resolutions in which the have-nots are more inconvenienced from commuting into the city core – the areas where the majority of business and wealth is developed.

Congestion continues to grow as a significant problem worldwide. Although there have been slight reductions in the rate of growing traffic in the US, this side effect of economic recession is only temporary. Urban mobility reports illustrate that congestion continues to worsen in both cities and rural areas. Vehicle congestion causes Americans to purchase an extra 1.9 billion gallons of fuel, costing $731 per commuter and $101 billion nationally.[10] Also, this squandered time adds up to 4.8 billion hours a year nationally – 34 hours per commuter each year. Future projections estimate that time wasted will grow 28% to 41 hours per commuter (7.7 billion hours) by 2020. By this time, the amounts of wasted fuel will grow to 3.2 billion gallons, costing the average commuter $1,232 a year ($175 billion nationally). Swelling traffic jams not only cause driver inconvenience and frustration but significant financial repercussions and inefficient use of fuel resources.

[8] (Shoup, 2011)
[9] (Halsey III, 2011)
[10] (Schrank, Lomax, & Eisele, 2011)

1.1.3 *AUTOMOTIVE INDUSTRY WOES*

The struggles of the automobile industry in 2008 validated close examination of the business strategies for many of the major manufacturers. Although there's no consensus on a single tactical error that led to the significant shortcomings, drops in sales of larger vehicles like SUVs and trucks as result of the combined energy and financial crises proved too overwhelming for most original equipment manufacturers. Many manufacturers had focused much of their resources on these larger vehicles give that they provide the most substantial profit margins. Besides the energy and financial hurdles of the twenty-first century, automotive manufacturers face other swelling challenges that complicate business:

- *CAFE Standards:* New corporate average fuel economy, or "CAFE," standards place demanding requirements on all United States manufacturers and foreign manufacturers that sell vehicles within the US. CAFE standards that were first started in the mid 70's were developed to improve the fuel economy for light trucks, cars, vans and sports utility vehicles. The legislation requires that a company's fleet of automobiles meet an estimated combined average fuel economy – currently 34.1 miles per gallon (MPG) for vehicles produced from 2012 to 2016.[11] Even with redirected marketing efforts to encourage the purchasing of small and hybrid vehicles, automobile companies will not be able to control the purchasing habits of the general public. It is therefore tempting to remain reactionary to sales trends, market research and stakeholders. Nevertheless, the development of smaller more fuel efficient options will grow as long as CAFE standards require such. Balancing fleets with a variety of vehicle profiles will be necessary even if the end goal remains to sell greater quantities of larger vehicles. Overall, more fuel efficient smaller vehicles will be increasingly needed to even permit the sales of larger less fuel efficient SUVs and trucks. Optimists may be hopeful that the general public will utilize this emerging opportunity to assess the greater selection and variety of vehicle types in order to reevaluate their true personal mobility needs.

- *Low Profit Margins*: Multiple factors play into the low profit margins that OEMs are seeing. The market is relatively saturated with multiple companies, each competing to out-engineer and price undercut their competitors to gain customers. Also, options previously perceived as new technologies eventually become expected entry-level features; therefore manufacturers are challenged to find even more clever ways to cut costs. This 100 year old industry is fairly mature and as natural resources become more sparse, specifications more stringent, and technologies more common between competitors, margins will continue to diminish unless a radial game-changer is introduced.

- *OEM-Supplier Relationships*: Through decades of squeezing out profit margins through maximizing manufacturing and engineering efficiencies of vehicle components, relationships between original equipment manufacturers (OEM) and suppliers have been described as "hostile" and "downright war" at times. Additionally with the recent economic woes that have hit Detroit and manufacturers abroad, these relations have become stressed even worse. With less than a nickel of profit in a dollar part (appendix 7.L), many suppliers that were at times scarcely hanging on have gone out of business. Manufacturers and suppliers are continually in a tug-of-war over razor-thin margins. However, with many suppliers fighting for the opportunity to develop parts for few manufacturers, the manufacturers typically are typically in an advantaged position to let go of the rope and find a new player with to negotiate.

  In an era when innovations are needed more than ever for efficient personal mobility in our growing cities, we need all players collaborating effectively to develop solutions for tomorrow. A

[11] (U.S. DOT, NHTSA, 2010)

myriad of technical breakthroughs will not likely come from one manufacturer, but will be a concerted effort between the multiple developers. Interactions must be inclusive novel ideas encouraged between both parties. A platform must be developed that enables suppliers to be motivated stakeholders by which their relationships are improved with manufacturers through the joint interactions focused to invent solutions for tomorrow's challenges in mobility.

1.1.4 *Incremental Changes*

The automobile's fundamental architecture has not changed much over the past several decades – still it has continued to advance in a couple manners despite the hurdles that this longstanding industry has seen. Government policies will continue to force incremental improvements to the automobile's subsystems. Recent aggressive proposals project 54.5 miles per gallon by 2025.[12] Whether this target fuel economy is met or not, such pressures will result in multiple improvements engineered into various subsystems of the car (hybrid platforms, lowered weight, reduced drag from improved aerodynamics, and lower roll resistance from tires).

Automobiles are already electronically sophisticated, computationally complex machines, and the level of electronic technologies continue to increase. However most of the sensing and computation is internalized for its own drive, safety and passenger comfort functions. Improvements are still needed in external awareness and connectivity to other vehicles, people and surrounding environments in order to optimize the commute. Such technologies can assist congestion avoidance, finding parking, quicker access to resources, and overall reduction of wasted time and energy.

There may not be a silver bullet for the vehicle's energy platform. Internal combustion engines provide long range, but are only about one-third efficient, burning fossil fuels and emitting local pollution. Electric vehicles eliminate local emissions and have better local efficiency (80% efficiency battery-to-wheel[13]) but do not provide comparable range. Fuel cell platforms eliminate emissions and provide comparable range but currently do not have supporting infrastructure. Hybrid options do well at balancing some of the best qualities of each but are inherently more complex. As we move forward to tomorrow's automobile, we are likely to see a growth in diversity of the energy platform. Hopefully through innovative designs of modular vehicle platforms and cleaver management of supply chains, vehicles will be provided more custom to their environment – tailored to necessary range, size, and climate demands.

Advances in Mobility

Hybrid and Electric Vehicles: One of the incremental changes we may see more of over the next five to ten years is the increasing availability of hybrid and electric vehicles. While internal combustion based vehicles will likely still dominate the percentage of cars on the road in the near future, automotive manufacturers do recognize the growing demand for alternative energy vehicles. Many vehicle platforms today are designed to accommodate hybrid electric options to customers. During these transitions, manufacturers continually improve their existing platforms through incremental technologies. Revised stop-start systems allow engines in city vehicles to quickly shut down at stop lights and rapidly turn back over when the driver reengages. These small frequent idle periods improve fuel economy up to 10% in urban settings.[14]

[12] (U.S. DOT, NHTSA, 2011)
[13] (Miller, Holmes, Conlon, & Savagian, 2011)
[14] (Colwell, 2011)

Shared Mobility Systems: An emerging trend, prevalent in many European cities and growing in the United States, addresses mobility efficiencies in a different manner – through vehicle sharing. In the US, the most predominant of these, Zip Car, is a two-way system that expedites the rental process but restricts the flexibility of use. Car2Go in Austin Texas on the other hand is an example of 1-way shared personal mobility service. Still, with only a couple hundred vehicles in the fleet, a small fraction of the potential demand and insignificant to generate large scale environmental benefits, larger personal mobility systems are still in need. For example, bicycle sharing programs with greater numbers of vehicles within their fleets such as HubWay in Boston and Bixi in Barcelona begin to tap into the urban demand. The more established bicycle sharing program in Paris, Velib, began its initial deployment with tens of thousands of bicycles distributed throughout the major metropolitan areas. These 1-way bicycle sharing services do witness heavy utilization and are continuing to grow; however, major challenges exist in the redistribution models which usually prevent the services from being profitable. Additionally, not all fundamental strategies from these bicycle sharing programs can be transferred to larger vehicles. For one, the method for redistribution - collecting dozens of bicycles onto the back of truck beds - cannot be scaled up to automobiles. Vehicle refueling and/or recharging also presents challenges in fleet management about which bicycle sharing programs need not worry.

Ubiquitous Network Support: One of the methods to be further explored for clever redistribution relies on real time networked monitoring of the vehicles. If system operators are able to track the location and state of each of their vehicles in the shared fleet, they can be better equipped to deploy distribution incentives and provide timely maintenance in order to maximize the uptime of their fleet and minimize customer inconvenience. Intelligent utilization of vehicle sensing and network communications may not only enable efficient travel for the drivers but also streamline interactions between the system operators and their vehicle fleets. In all existing shared mobility programs, labor dedicated to redistribution and maintenance tends to be the largest cost factor, inevitably prevent many of these systems from becoming or remaining profitable. Offering information at relatively convenient times for the user or contextually sensitive incentives can encourage the driver to play a part in the management of the vehicle distribution, potentially providing mutually beneficial outcomes for both parties.

1.2 Mobility on Demand

Concerted efforts from the Media Lab's former Smart Cities research group and the Changing Places group focused in on trends in mobility and comprehensive ways in which they could be positively influenced. Although efforts were focused in on improving the means of mobility, by redefining the automobile itself, a systemic approach was proposed to more effectively utilize thousands of vehicles present within the urban fabric. The system of "Mobility on Demand" proposes a network of ubiquitous vehicles within a city that can be conveniently borrowed and reused several times throughout the day.

1.2.1 *Summary MoD System*

Mobility-on-Demand (MoD) is a shared system of personal transit in which members can quickly use one of many fleet vehicles that may be lent and returned at various hubs throughout the city. This vehicle micro-rental service not only provides 1-way options for mobility but also utilizes existing transit infrastructures. While both public transit and personal vehicles each have their conveniences, inconveniences, efficiencies and inefficiencies, MoD attempts to seamlessly bridge the two together in order to take advantage of each mode's benefits. As MoD utilizes fleets of personal vehicles at clustered stations for users to rent and return, these systems rely on significantly less infrastructure than subways, trains, or other similar public transit systems. Striving to provide effective personal mobility in the most convenient locations, MoD looks to bookend public transit by providing seamless first-mile and last-mile mobility solutions.

Instead of trying to replace traditional automobiles or relying on larger infrastructures of public transportation, MoD strives to supplement each by providing a solution that can expand multi-modal personal transit. The system operates through coordinated stacks throughout major points of interest in a city, such as airports, shopping centers, business districts, residential areas, and of course subways, trains and other public transit stations. Additionally, by utilizing fleets of electric and hybrid vehicles, the proposed Mobility on Demand system addresses vehicle recharging and peak energy demands from buildings through a coordinated energy grid.

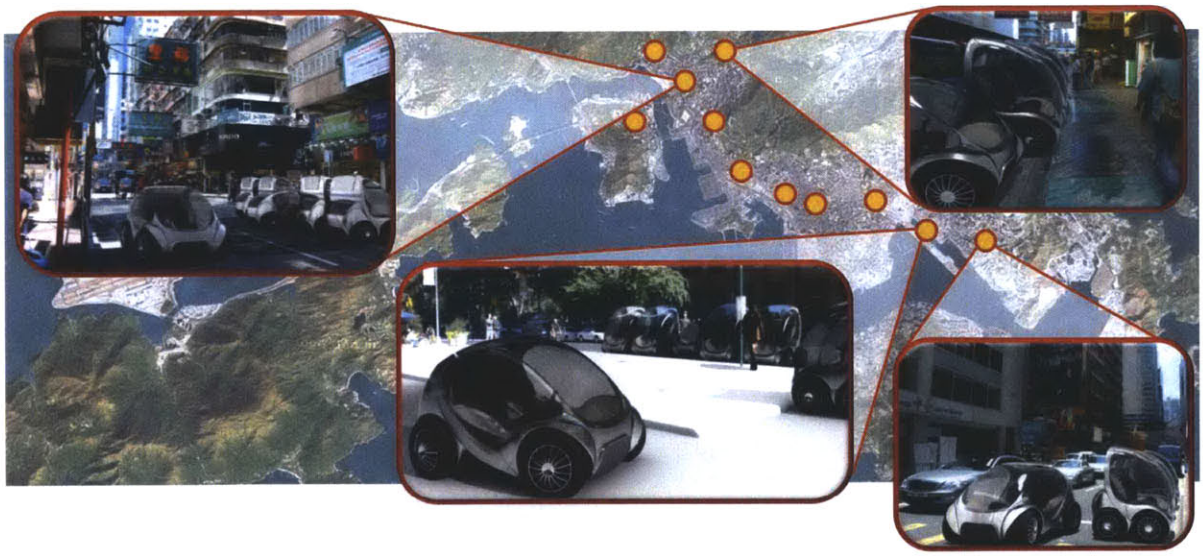


Figure 1-3: Mobility on Demand

1.2.2 *Dynamic Incentives*

One of the largest challenges to a Mobility-on-Demand service will be the proper management of the 1-way sharing option. Throughout the day, vehicles are rented with fluctuations in demand from unique travel patterns, larger events and occasional errands. These variations in travel can cause a significant imbalance in vehicle stocks at each parking station. 2-way micro-rental services like Zip Car manage the variety of demand through strictly controlled reservations. However, 1-way services can provide more convenient flexibility if vehicles are available to be rented and dropped off at member's discretion. To meet user expectations such systems will have to employ clever management of their large vehicle fleets to ensure reliable availability.

One attractive method to address the challenge of one-way mobility lies in what is called, "dynamic incentives." Discounts for the rental or local businesses may influence a driver's transit pattern to deposit the vehicle nearby an area preferred by the system operator. Incentives can be customized to each member, giving consideration to each person's preferences (comfortable walking distances, product preferences, and disposable time). *The Market Economy of Trips*[15] and *Dynamic Incentive Scheme for Rental Vehicle Fleet Management*[16] investigates how the inventory of vehicles can be better balanced through game theory when basic levels of information are ascertained from the users. Real-time price or incentive fluctuations can be used to encourage or discourage particular flow patterns.

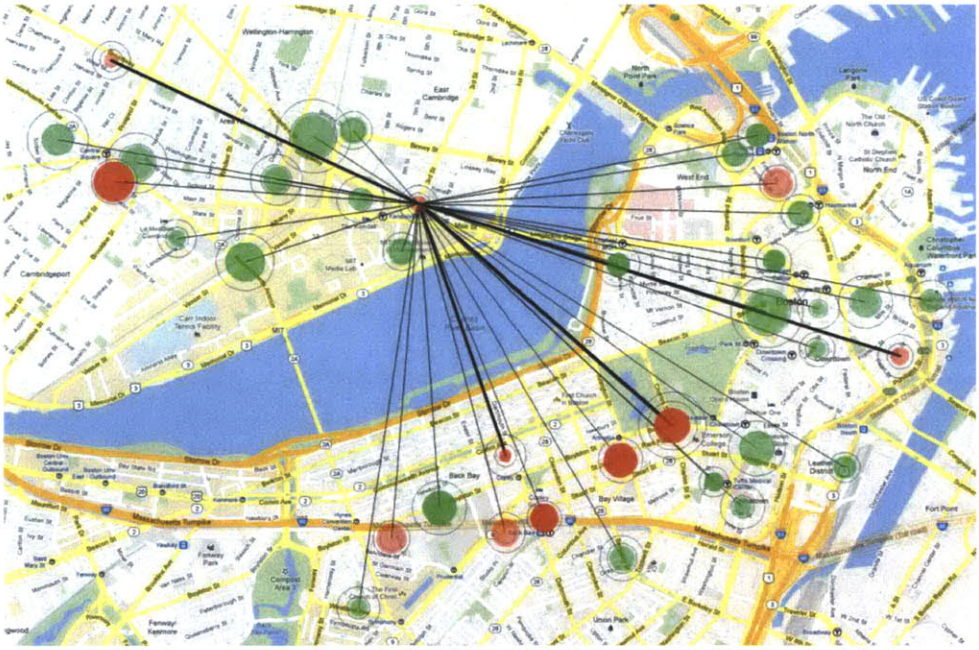


Figure 1-4: Operator interface displaying cost at a variety of stations, by Jet Sizhi Zhou

Most of these critical features of MoD depend on a reliable network to feed information in real-time to the system operator. The system operator(s) may then be able to use for its employees and inform their staff of maintenance needs to juggle incoming factors as they coordinate their fleet in similar fashion to an air traffic control room.

Along with redistribution challenges, another hurdle that presents itself when transitioning from bicycle sharing to vehicle sharing is energy (or fuel) management. Ensuring that all vehicles available for

[15] (Papanikolaou, 2011)
[16] (Zhou, 2012)

rent have a sufficient state of charge to at least permit the user to get to their desired location with a determined buffer will be just as crucial to vehicle availability. In most cases with electric vehicles, the station hubs where these vehicles are parked and monitored may also serve as charging stations. Ideally, each time the vehicle is returned to one of its stations, the recharging process is immediately initiated.

1.2.3 *Metrics Valued by System Operators*

Customers of a Mobility on Demand system are likely to expect common traits as in other products and services: convenience of rental, reliability of vehicles, reasonable prices, and perhaps in today's digital era some level of intelligent personalization. From the perspective of MoD system operators however, additional characteristics are valuable in order to manage a viable service. Listed below are some of the metrics System Operator will need to continually monitor mobility systems:

- Vehicle location
- Vehicle maintenance (parts in need of repair)
- On-site staff (current task & location)
- State of charge (or fuel) of each vehicle
- Vehicle demand & availability
- Station occupancy

Some of the other MoD engineering challenges will be:

- Vehicle robustness – managing vehicles that are robust enough to withstand high utilization by many different users (who additionally may not be as attentive to taking care of the vehicle when in use)
- Personalization – exploiting the vehicle's capabilities to dynamically alter the vehicle and experience to best fit each user. Although the end user will rarely ever use the same vehicle, each time they use MoD, it should feel and/or appear like it's their vehicle each time.
- Energy management – Not only will MoD system operators need to monitor and manage the state of charge (or fuel) of each vehicle throughout the day, but in the case where electric vehicles are used, they also have the opportunity to cleverly manage and redistribute power at the charging stations (uninterrupted power sources, battery buffers, peak shaving, renewable energy sinks).

1.3 Changing the Methodology

As mentioned, one of the first efforts to address the polluted and congested cities is to continue to push for alternative energy vehicles – mainly electric. Hybrid electric vehicles have begun to see greater commercial success as they are able to achieve impressive fuel efficiencies and can minimize carbon emissions in slow and idle city driving. However their redundant energy systems (internal combustion engine and electric drive motor with battery – including an intricate transmission negotiating between the two) result in greater complexity, weight and maintenance. Fuel cell vehicles exhibit a promising alternative for future vehicles; yet not only do they possess complex energy systems but they also require large infrastructural investments to provide hydrogen fueling stations. Pure electric vehicles however can provide clean simple short to medium driving platforms for tomorrow that can be recharged both at home and in the city.

Of course electric vehicles alone are not a novel idea. They have a long history and are even older than internal combustion engine vehicles. Their inception at the dawn of the 20thcentury demonstrated potential; yet with insufficient battery technologies and various competitive factors, including the mass production of Ford's Model T, the electric car market faced too many hurdles for immediate commercial success. Today, with the improved performance of lithium-based batteries and environmental pressures to implement alternatives to petroleum-based vehicles, we are seeing a resurgence of electric vehicle programs – electric hybrids, fuel cells with core electric platforms, and fully electric vehicles. In addition, electric vehicles of shorter range are highly suitable for dense urban settings where the typical commute is well under 20 miles. With proper city infrastructure (sourcing from the cities electrical grid) to support more frequent charging schemes, a light short-range electric vehicle may be ideal for the growing urban populations. Nevertheless, let us first examine both the fundamental opportunities and constraints of electric energy platforms to successfully propose a new effective design.

One major constraint, that demonstrates no evidence of significantly changing in the near future, is the considerably smaller power density of batteries compared to that of gasoline. Even the most advanced battery technologies exhibit power densities an order of magnitude smaller than gasoline. Therefore when attempting to match the driving range of gasoline vehicles with battery power, some designers load the vehicle with a large mass of batteries, resulting in excessively greater weight. Instead, considering an electric vehicle that contains a fraction of the battery capacity and range can decrease the excessive weight while promoting eased frequent charging solutions.

1.4 Theoretical Construct

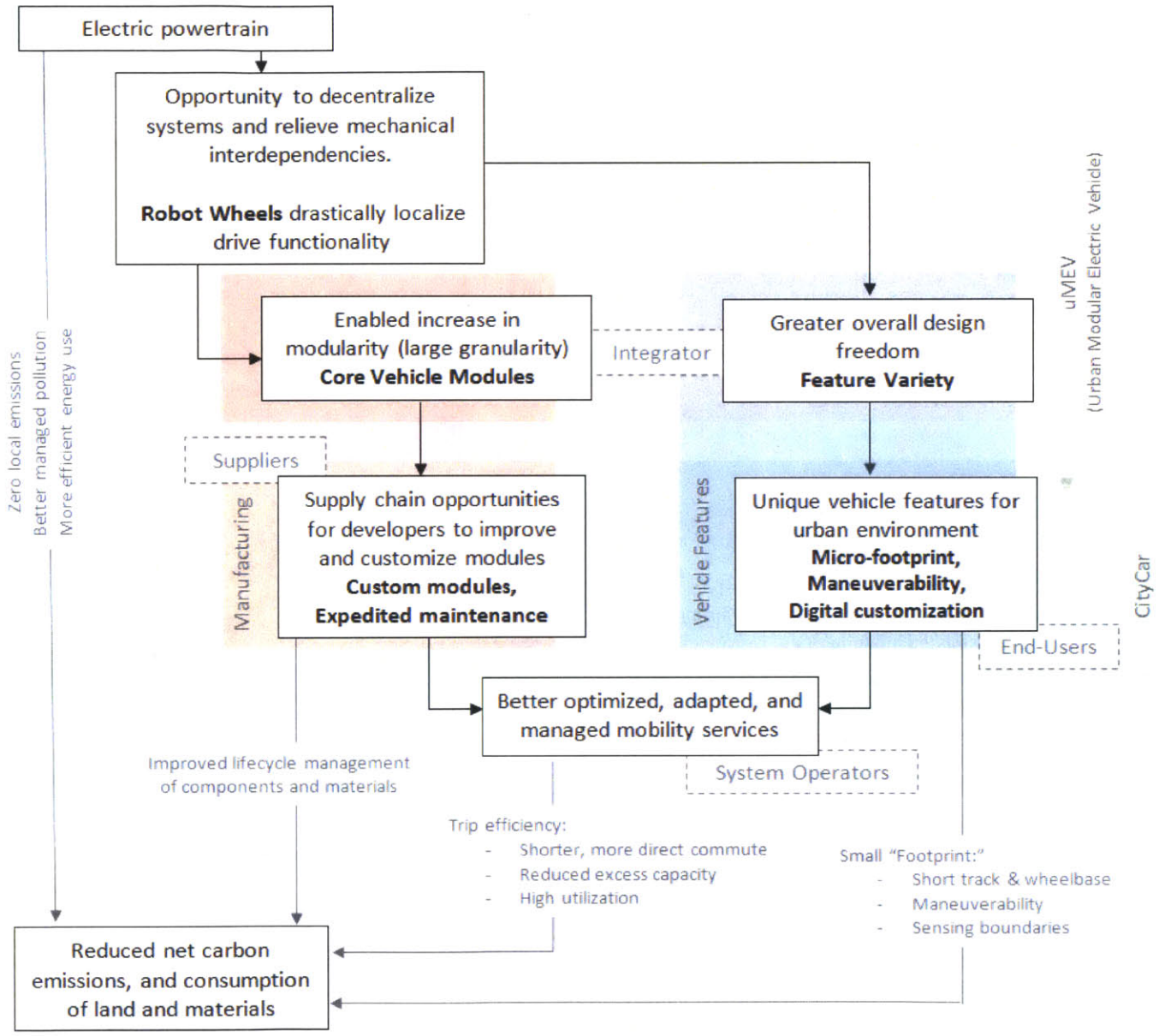
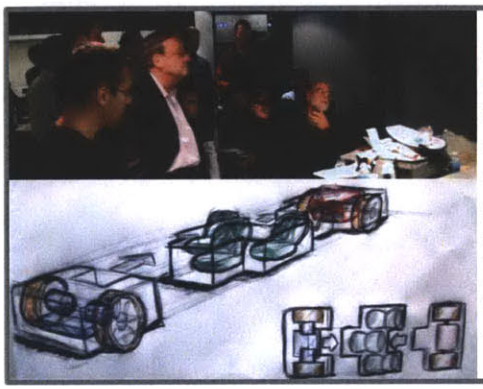


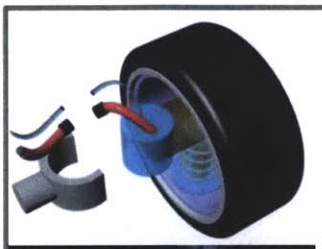
Figure 1-5: Diagram of research theoretical construct

1.5 Prior Works

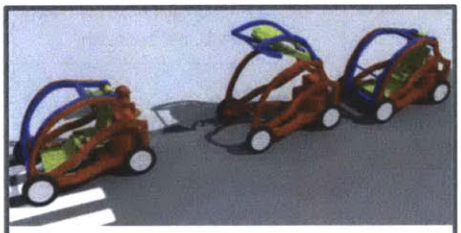
As in the collaborative nature of the Smart Cities group, many of the developments that led towards the CityCar and Mobility on Demand breakthroughs we enabled by the collective efforts of many students that contributed various pieces to the puzzle. The following images and captions chronologically highlight most of these major design milestones.



Early design workshops with Ghery associates allowed for exploration and sketch designs of vehicles that could be "better citizens to the city." -William J. Mitchell

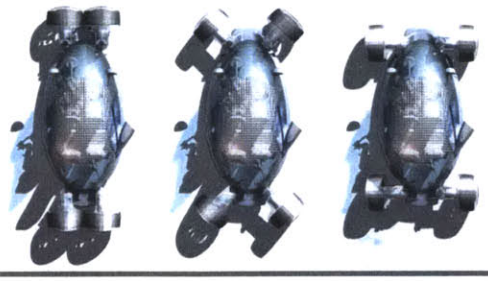


Patrick Künzler designed and promoted what he called "Hubless Wheels" which packaged the major drive parts in the space of the wheel hub.

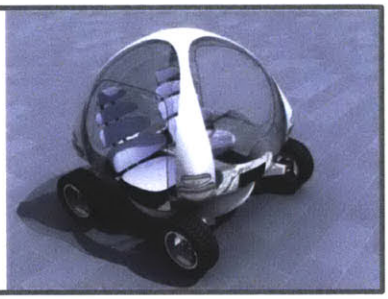


Will Lark developed a very rudimentary shopping-cart style stacking car which Franco Vairani assisted in animating.

Mitch Joachim created concept designs incorporating soft bodies surrounded by exo-skeletal structures. Designs also utilized the Hubless Wheel (later known as "Robot Wheels").[17]

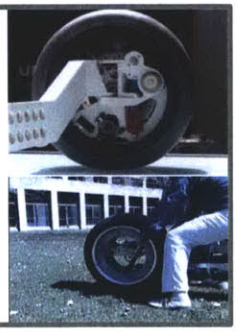


Franco Vairani creates animation following brainstorming session between Patrick, Will, and himself. Concept promotes mini-sized omni-directional car.



Will Lark shares idea of upward tilting vehicle in order to reduce wheel base and place driver in standing position.

Peter Schmidt promotes more in-depth prototyping of Robot Wheels. He builds functional components at multiple scales.[18]

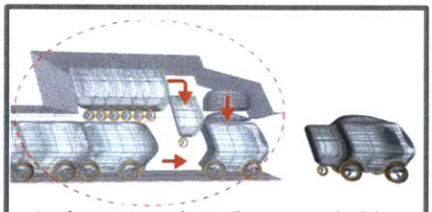


[17] (Joachim, 2006)
[18] (Schmitt, 2007)

Figure 1-6: Smart Cities collaborative contributions (1 of 2)

Marcel Botha, Phil Liang and Will Lark work together on "Backpacker" concept that promotes front entry and customizable add-on modules.

[19]



[20]

Andres Sevtsuk explores stackable vehicle services in which expandable units can be added and subtracted as needed at stations.

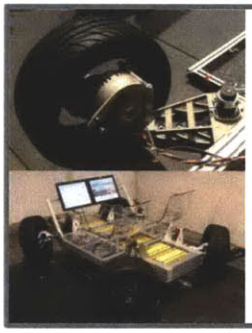
[21]

Mitch Joachim & Will Lark design exo-skeletal front entry CityCar with "Split Active Caster" Robot Wheel by Raul-David Poblano.

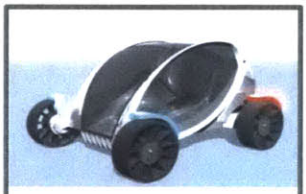
[22]

Franco Vairani designs tandem stacked CityCar, later to be called "bitCar." Vairani's renderings begin to show potential space savings in cities.

Will Lark designs and animates 3-point entry CityCar with decoupled rear compartment. First design to separate rear storage compartment from folding body.



Raul-David Poblano and Will Lark, with much help from undergraduate assistants, build demonstration Robot Wheel and 4-wheeler.



Will Lark creates design exploration for mechanical solutions of folding chassis and front door.

Will Lark enters near-final designs into Peugeot contest.

Will Lark develops final CityCar design to showcase combination of explored features.

Will Lark leads development of half-scale prototype with major contributions from Nicholas Pennycooke, Raul-David Poblano, Charles Guan and numerous undergraduates.

[19] (Lark, 2005)
[20] (Sevtsuk, 2006)
[21] (Poblano, 2008)
[22] (Vairani, 2009)

Figure 1-7: Smart Cities collaborative contributions (2 of 2)

2 DESIGN SOLUTION

One of the first efforts to address the polluted and congested cities includes the push for alternative energy vehicles – mainly electric. Pure electric vehicles can provide clean simple driving platforms for tomorrow that can be recharged both at home and in the city. Lightweight electric vehicles have demonstrated the potential following benefits:

- Zero tailpipe emissions
- Significant reduction of the vehicle's weight
- Greater flexibility in the design
- Potential reduction in part count
- Reduced maintenance of dry systems
- Less demanding maintenance due to the reduction of subsystems

Increased design freedoms result from the electrical energy platform. Too often, many commercial and concept electric vehicles do not take full advantage of this flexibility. They instead design around the same model of traditional automobiles – more or less exchanging the internal combustion engine based power-trains for electric ones while attempting to match parameters of range and size. Nevertheless, what may further promote the proliferation of electric vehicles will instead be a radical redefinition of the vehicle architecture. Battery platforms offer the possibility for a drastic reduction in necessary mechanical drive components by localizing functions (for example placing independent drive motors within the wheels) and optimizing components for multiple uses (such as using the same drive motors for braking and recharging, or even capturing dispersed battery heat for cabin climate control). Vehicle power can be transferred, distributed and governed by voltages and bits, instead of steel. The design is no longer limited by hardware but liberated by software. Component locations and spatial relationships can be reexamined. Electric vehicles can be design more like computers – modular.

2.1 Exploiting the Opportunities of an Electric Vehicle Platform

As we continue to see incremental advancements to the automobile, improved MPG, increased intelligence, driver assistance, and a variety of propulsion platforms, the overall architecture of the vehicle tends to remain the same. For traditional manufacturers, this is a logical progression which supports their long invested infrastructures and established supply chains. Even in most new hybrid vehicles that use an internal combustion engine (ICE) and an electric motor in parallel, maintaining the same platform makes sense given that the vehicle still uses most of the same subsystems and components that support the gasoline engine. Nevertheless, when developing a vehicle platform whose core componentry is powered by electricity, many traditional design assumptions can be challenged.

Unlike a gasoline engine powertrain whose complete transference of movement depends on mechanical couplings outputting from the crankshaft through the transmission, driveshaft, universal joints, differential, axle shafts, wheels and tires, the inherent nature of the electronic platform allows for many of these mechanical couplings to be substituted by the transfer of electrons. Of course simple substitution of the ICE with an electric motor provides an electric alternative on an identical vehicle platform – in this case the electric motor could output to an optional transmission (depending on the motor characteristics), transfer the rotational movement mechanically to the rear differential and out to the wheels just as before.

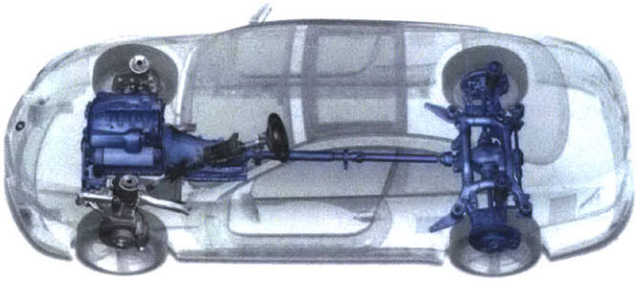


Figure 2-1: Automobile Powertrain (BMW)

Yet this substitution does not take full advantage of opportunities that are given from electronic products (especially in consumer electronics). Subsystems and components of electronic products communicate through the transfer of data and energy, all through wire conduit significantly smaller and lighter than mechanical couplings. Such flexible interfaces allow for tighter packaging, of lightweight modular products. Therefore the challenge is to mimic these relationships between components in order to share the design and feature advantages that benefit consumer electronics.

When the traditional mechanical couplings are reduced and in some cases eliminated, a variety of electric vehicle (EV) configurations can be used.[23] The drive train consists of three major subsystems; the propulsion, power, and auxiliary systems which can are compartmentalized in various configurations. The auxiliary system typically consists of elements such as the HVAC (heating, ventilation and air conditioning) and other systems that assist the driver, like power steering. The power unit is made up of the energy source (the battery module in most electric vehicles), the energy management system (battery management system, BMS), and the componentry for refueling. Finally the electric propulsion subsystem is made

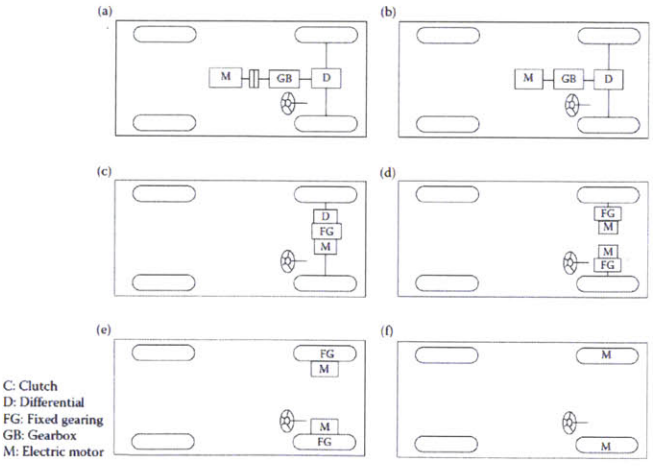


Figure 2-2: Electric vehicle configurations (Ehsani 2010)

[23] (Ehsani, Gao, & Emadi, 2010)

from the arrangement of the power converter, the electric motor, the vehicle controller to govern the behavior of the motor, any necessary transmission elements to obtain specified torque and speed requirements, and finally the driving wheels to propel the vehicle forward. The propulsion system may be organized in multiple configurations. *Modern Electric, Hybrid Electric & Fuel Cell Vehicles* highlights six basic configurations of a modern electric vehicle drive train, from the most basic substitution of engines (figure 2.2a) to the most radical mechanically minimized platform with in-hub motored wheels (figure 2.2f). In-hub motored wheels discard all transmission components and attach the wheel directly to the outer motor rotor. This type of assembly requires the motor to be built in a manner capable of running at relatively slower speeds and produce relatively higher torque values (on the order of 600 RPMs and 150 Nm, derived in section 3.2.2). However in some cases, the electric motor's consequential cost and weight instead justify the incorporation of a fixed gearing coupled with a smaller, less expensive drive motor. Such more common commercial motors runs nominally at higher speeds around 5000 RPM with lower torque values of 15 Nm (as seen in figure 2.2e).

2.2 The Robot Wheel

When comparing the various EV configurations in Figure 2-2, from "a" to "f" the solutions become less mechanically complex and more electronically dependent. When the configurations become less mechanically dependent and more decoupled, the entirety of the drive train can be compartmentalized in the local region of the wheel. Similar hub-motors have been implemented on past vehicles – from Porsche cars at the dawn of the 20th century to recent conversions of Mini-Coopers by PML Flightlink.[24] Although the drive trains are further modularized in these examples, the other supporting drive systems, steering, suspension, and brakes, still remain tightly coupled to the rest of the vehicle. Actual benefits of modularity however can fully be utilized when all subsystems of the vehicles movement are grouped into one unit.

The "Robot Wheel" addresses this challenge by packaging all major drive systems into one interchangeable module. Drive, steering, suspension, and braking – all mechanisms responsible to moving and stopping the vehicle in a determined direction - are packaged into a single unit that may be repeated at all four corners. Each of the vehicle's four wheel assemblies is a self-contained mobile unit, supplying its own motor, suspension, brake, and steering. There are no mechanical drive linkages necessary between the Robot Wheels since all drive components are local to the wheel module. Subsequently, the car is fully drive-by-wire – each wheel needing only an electric cable, data cable, and a snap-on mechanical connection to the chassis. The local drive mechanics also allow each wheel robot module to be highly maneuverable (in some cases up to 120 degrees of steering).

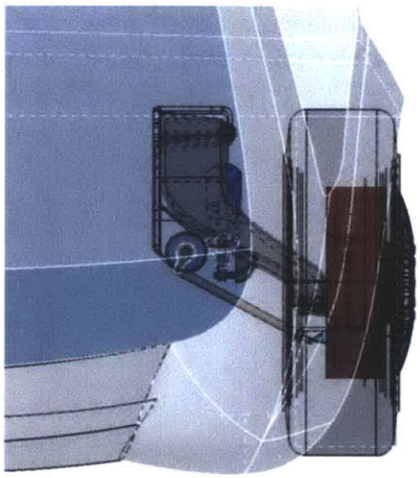


Figure 2-3: Front left Robot Wheel

Multiple manufacturers have developed a variety of motored-wheel components such as the Michelin Active Wheel. If we take a modern comparison of the modular electric vehicle platform to the consumer electronics industry, the Robot Wheel can be thought of as a similar component to the hard-drive in a computer. It is an independent module, mechanically secured to the computer chassis, supplied power and data to perform some of the most crucial tasks of the product (in the case of the EV – propulsion, in the case of the computer – save and replicate data).

Each robot wheel corner units requires three core elements – (1) mechanical connection to the chassis, (2) power to the drive and steering motors, and (3) data signals to facilitate information exchanges between a variety of sensors. Since many automotive applications utilize brushless direct-current motors, pulse-width modulated (PWM) power signals will be used to control each motor.

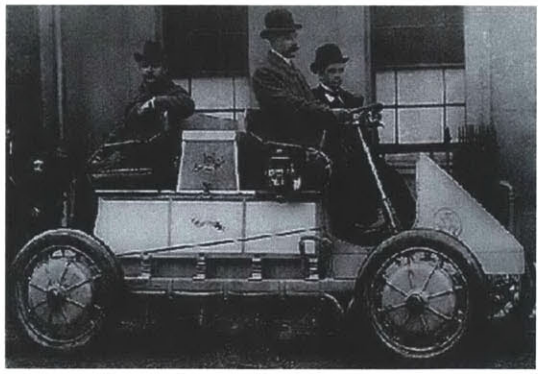


Figure 2-4: Lohner-Porsche hybrid vehicle with independent motor wheels

[24] (Hutton, 2007)

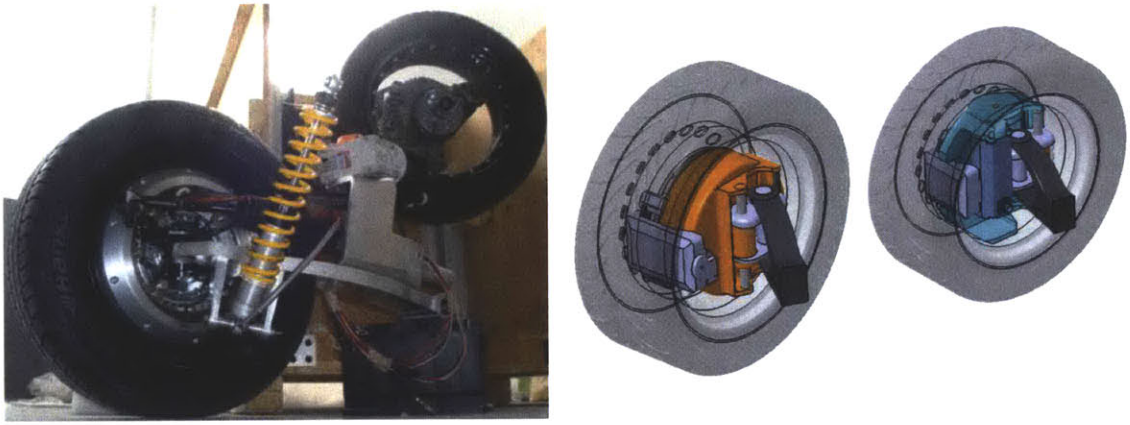


Figure 2-5: Robot Wheel prototypes

Another benefit of localizing the functionality into the Robot Wheel is the containment of the vehicle's complexity. This has multiple benefits to the manufacturer, the supplier, and the owner of the vehicle. For the manufacturer, packaging these core functions into one module reduces complexities in system integration. If original equipment manufacturers (OEMs) can instead delegate specifications and interfaces to their supplier(s), their efforts can be more streamlined and focus on other systems and overall vehicle integration. As for the Robot Wheel supplier, assuming responsibility of a larger portion of the vehicle can potentially increase their profit margins, allow them to become more integrated into the design process, more valuable to the OEM, and maintain a channel for innovation. For the vehicle owner, whether it be an individual or fleet operator, modular systems can present expedited servicing of the units and options for advantageous customization. Made-to-order and assembled-to-order modules can allow customers to develop highly tailored propulsion systems that best fit their needs. For example, at least six different drive configurations can be derived from various combinations of Robot Wheels – with and without drive and with and without steering, as seen in Figure 2-6: Various propulsion and steering configurations.

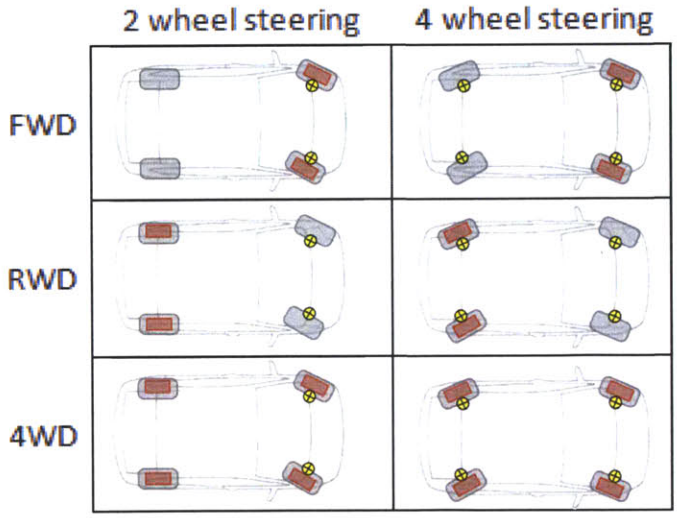


Figure 2-6: Various propulsion and steering configurations

Lastly one of the most attractive benefits of the Robot Wheels, from a vehicle designer's perspective, is the spatially liberated platform from the localized drive train. The platform is no longer encumbered by the large front central engine, which is surrounded by its auxiliary systems and continued through to the four corners by mechanical drive shafts. Typically after the drive train is completely laid out on a traditional automobile platform, there is not much flexibility to alter the vehicle's architecture. However, when utilizing Robot Wheels on an EV the rest of the vehicle practically becomes a clean slate for design.

2.3 Expanding Modularity

The modularity that is exploited upon the drive train into the Robot Wheel can be expanded to other systems and components of the electric vehicle. Properly managed modular products have greater potential to provide benefits of streamlined supply chains, supplier engagement, and component customization within the platform.

Since the majority of the power-train connections no longer need to be mechanical but instead electrical, spatial relationships of the components may be re-imagined. In a modular electric archetype vehicles of tomorrow can be designed around an architecture that is extremely accommodating, relatively lightweight and simple. Exploiting highly modular platforms gives us the opportunity to rethink clean transportation and promote flexible markets for mobility. Already, generally modular products have demonstrated the following benefits to both manufacturers and customers:[25]

- Modular platforms and products accommodate uncertainty through higher flexibility by adjusting to continually evolving markets and emerging technologies.
- Parallel development allows different modules to be worked on concurrently.
- Customers look favorably on loosely-coupled designs if they know they can be later upgraded or mix and match components in the future.
- Modular platforms encourage flexible manufacturing, minimizing the need to heavily "tool up" and result in less required production capital.
- Standardized interfaces provide easier servicing, replacement and upgrading.

Modular electric vehicles have the opportunity to capitalize on these benefits while promoting even more advantages – such as (1) adaptive platforms that may advance their performance and utility, (2) responsible component lifecycle management schemes, and (3) flexible interfaces that may further engage suppliers in the development and innovation of various components.

- Adaptive Platforms: Offering diverse and adaptive mobility alternatives can provide efficient best-fit solutions for unique city characteristics. Instead of pushing a one-size-fits-all model to varied regions of the world (each having unique demands), a modular electric vehicle platform can promote minimal tailored transportation solutions. Compartmentalized vehicle components can be selected, assembled, and tuned for optimal performance and utility depending on the environment.
  Performance, range, utility and capacity characteristics can be customized, adjusted or exchanged as needed if platform interfaces accommodate for a variety of motor-wheel, battery, and storage accordingly. Robot Wheels can be packaged with a variety of drive motors, suspension and steering packages. Therefore, a vehicle's performance specifications, which also affect its energy efficiencies, can be altered by exchanging Robot Wheels. An energy conservative commuter vehicle (city Robot Wheels: small efficient drive motors, narrow tires, and simple suspension) may potentially be transformed into a sporty weekend leisure car (sport Robot Wheels: larger high-torque drive motors, wide high-traction tires, and tightly tuned performance suspension components). Other components that are decoupled via modularization can greatly impact the vehicle's utility capabilities, like the storage compartment. Imagine the convenient compactness of a Smart ForTwo car but also having the optimal storage capacity of a small sport utility vehicle or truck. With a platform that can accommodate for an assortment of utility these traditionally incompatible features may become more attainable. Even more, when interfaces are governed electronically, the potential for

[25] (Ulrich K. , 1991)

vehicle components and accessories that may be offered as exchangeable modules becomes less and less bounded. Such modules can begin to achieve meaningful customization to users, as opposed to typical superficial choices of paint color and body kits. Modular electric vehicles can provide the following options to individual and fleet customers:

- Customized drive-by-wire interfaces
- Mobile office amenities
- Dynamic Storage
- Performance-varied Robot Wheels
- Custom and/or Varied Snap-In Body Paneling
- Easily upgraded/downgraded luxury features
- Flexible power-train supplements/options
- Interior design variety

In order to best manage the potentially high variety of modules, careful thought should be given to their economic value. Understanding the utility and relative cost of all included units can help system integrators better access the viability of each of these modules. Assessments can be mapped upon a "cost-utility plot"[26] to guide strategic positioning within a product.

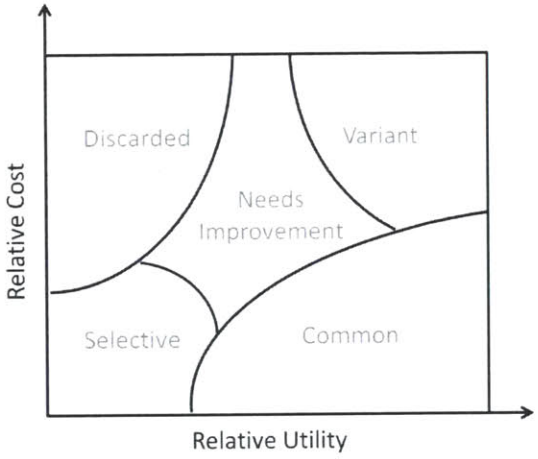


Figure 2-7: Cost-utility plot

This plot assists in determining which of the modules best serve as stable, cost effective staples and which should be positioned as less valuable options. Research in product family modeling by Jiao and Tseng define five categories for product modules: *(1) Common modules* are those that contain the most utility while minimizing cost. *(2) Variant modules* however have significantly larger relative cost but are essential to the product. *(3) Selective modules* are generally cheaper and less effective and therefore lower priority. Other potential low value modules that are unjustifiably expensive need to be (4) improved or (5) discarded.

Although more in-depth analysis may better guide industry strategies, this simple economic evaluation serves as a useful initial tool to manage the modules to determine which ones should be positioned as core entry-level components and which ones serve best as supportive accessories.

- Component Lifecycle Management: Reanalyzing the spatial relationships and connection points of all components of the vehicle is not only beneficial for eased variety, production and maintenance but also for serious consideration in how components may be later broken down, reused and/or recycled.

  Currently vehicles are so complexly integrated that disassembly is anything but easy. Components of highly utilized urban vehicles are subject to breakdown and have varied replacement rates – hence their different lifecycles. After a decade or two, once typical vehicles are completely useless and defunct, many of them end up compacted in decrepit junkyard piles. Thorough disassembly and recycling is an arduous task because of the complex fashion in which unlike materials and massive wire harnesses are integrated. However, if careful consideration is

[26] (Jiao, Tseng, Duffy, & Lin, 1998)

given to how the modules are built, assembled, and eventually disassembled, properties that aid lifecycle management can be embedded into each component. Materials can be easily decoupled and subassemblies may be simply broken down for reuse or recycling.

Even in the life of the vehicle the manner and ease in which modules are assembled and disassembled can be influenced by module variety and anticipated rate of change.[27] Commoditized components can be typically fastened with robust stable connections as they may be seldom exchanged. *Variety-intensive* modules (such as performance varying Robot Wheels) must too maintain a stable connection but provide an interface that can support range of options. *Change-intensive* modules, in which newer generations render their previous technologies obsolete (such as evolving battery technologies), may behave more like USB interfaces where they are embedded with enough flexibility to accommodate continual advancements. Other components considered *dynamic* (customized accessories for modular EVs) require the most interface flexibility to support a high variety of modules that may be frequently exchanged. Overall, considering variety and exchange rates into the modules design will assist seamless adaptation and responsible management of the components.

- Engaging Suppliers: How do we best begin to manufacture and deploy such a radical system? Opening the field to many players in such a budding architecture can accelerate innovation and adoption of new product archetypes. Accordingly, properly establishing engaging interfaces and maintaining flexible low-entry platforms may prove the best approach to involve many potential suppliers into a new market.

  Typically mechanically dominant vehicles are optimized by fully integrating functional components into their form. While this architecture serves well for efficient commodity, it often results in an overly constrained artifact and many times discourages necessary flexibility for variety, customization or modification. By instead redistributing functional components in modular platforms it becomes possible to provide products with enhanced adaptability.

  For developers, modular product grammars may enhance a product's value chain in multiple stages – standardized interfaces can enable more open input from multiple suppliers, while at the same time, manufacturers and distributors may offer more product variety and gain greater abilities to mass customize their products. A potentially more open platform can promote opportunities within the supply chain for traditionally passive developers.

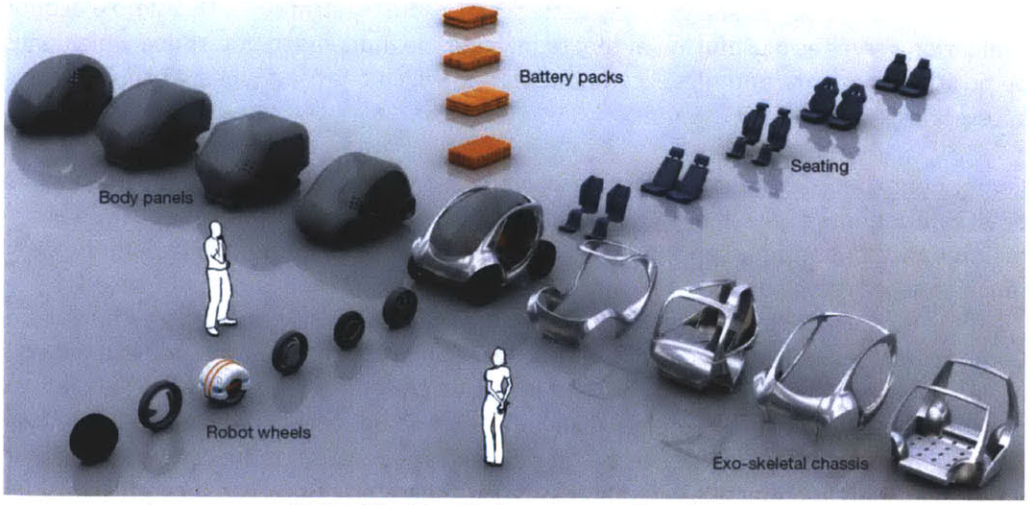


Figure 2-8: Assemble-to-order modular vehicle

[27] (Sanderson & Uzumeri, 1997)

2.4 uMEV, the Urban Modular Electric Vehicle

Offering diverse and adaptive mobility alternatives can provide efficient best-fit solutions for unique city characteristics. Instead of promoting an over-equipped model to crowded cities across the world, the new urban modular electric vehicle platform seeks to suggest minimal tailored transportation solutions that are assembled from a variety of modules. Components can be selected, assembled, and tuned for optimal performance and utility depending on the locational demands.

An urban modular electric vehicle, or "uMEV," embodies a number of core principles that allow it to effectively offer an adaptive personal mobility solution for crowded cities.

- regionalize function (local spatial relationships ensures maximum modularity)
- minimize the amount of "stuff" that needs to be transported around (reducing weight and energy consumption)
- provide accommodating interfaces
- simplify systems by substituting hardware with software wherever possible (minimize mechanical components)
- embed local intelligence (enable each module to self-monitor & sense surrounding)

The uMEVs promote the development of vehicles whose components with strongly related design parameters are spatially contained into units from which derivative products can be efficiently created. Such technologies can offer great benefits of product variety, mass customization, adaptability, and efficient component reuse for both customers and manufacturers. Although implementation of modular systems typically require up to twenty-five percent greater overhead, investments are soon recuperated by better satisfying customers, promoting both parallel development and testing, reducing order lead time, and accommodating for market uncertainties.

The uMEVs utilize the fully integrated in-wheel drive systems, Robot Wheels. Because of these electronically controlled localized mechanical systems, the overall construction and layout of the vehicle may be completely re-imagined. Similar to General Motor's HyWire[28] concept vehicle, designers are now afforded a clean slate to create the vehicle's carriage. Figure 2-10 illustrates minimum uMEV requirements of (1) Robotic Wheels connected to a (2) unibody that houses (3) interior interfaces and an (4) energy & control unit. The form factor for the robotic wheels is fairly defined and more or less vary in scale depending on it performance demands. The energy and control units can take on multiple forms since lithium based cells can be organized in a variety of geometries. It is advisable to keep these units low and central to the vehicle since their relative heavier weight will influence drive dynamics of the vehicle. The outer body of the uMEV can take on a high variety of shapes depending on the vehicle's utility, passenger capacity, performance requirements, safety needs, or simply customer preferences.

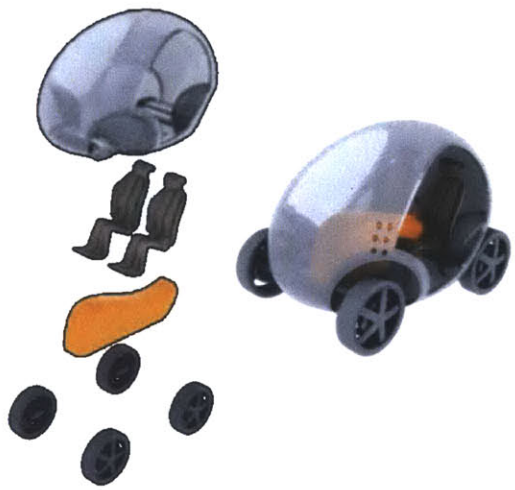


Figure 2-9: uMEV rudimentary architecture

[28] (Markus, 2003)

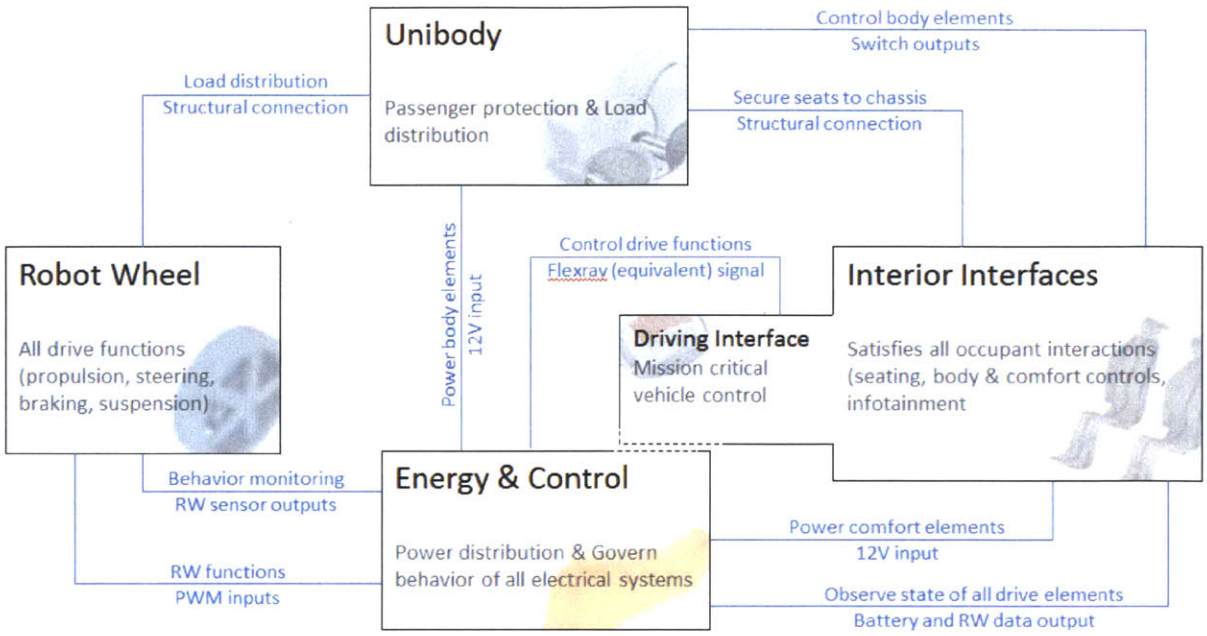


Figure 2-10: Minimal uMEV modular architecture

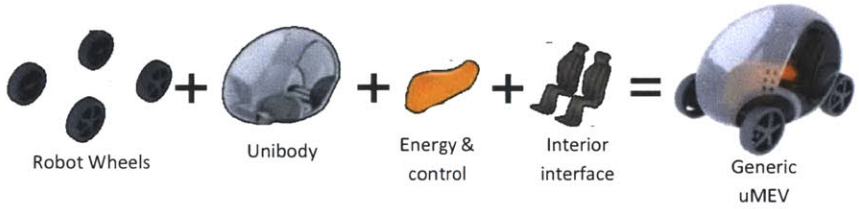


Figure 2-11: Basic solutions for urban modular electric vehicles

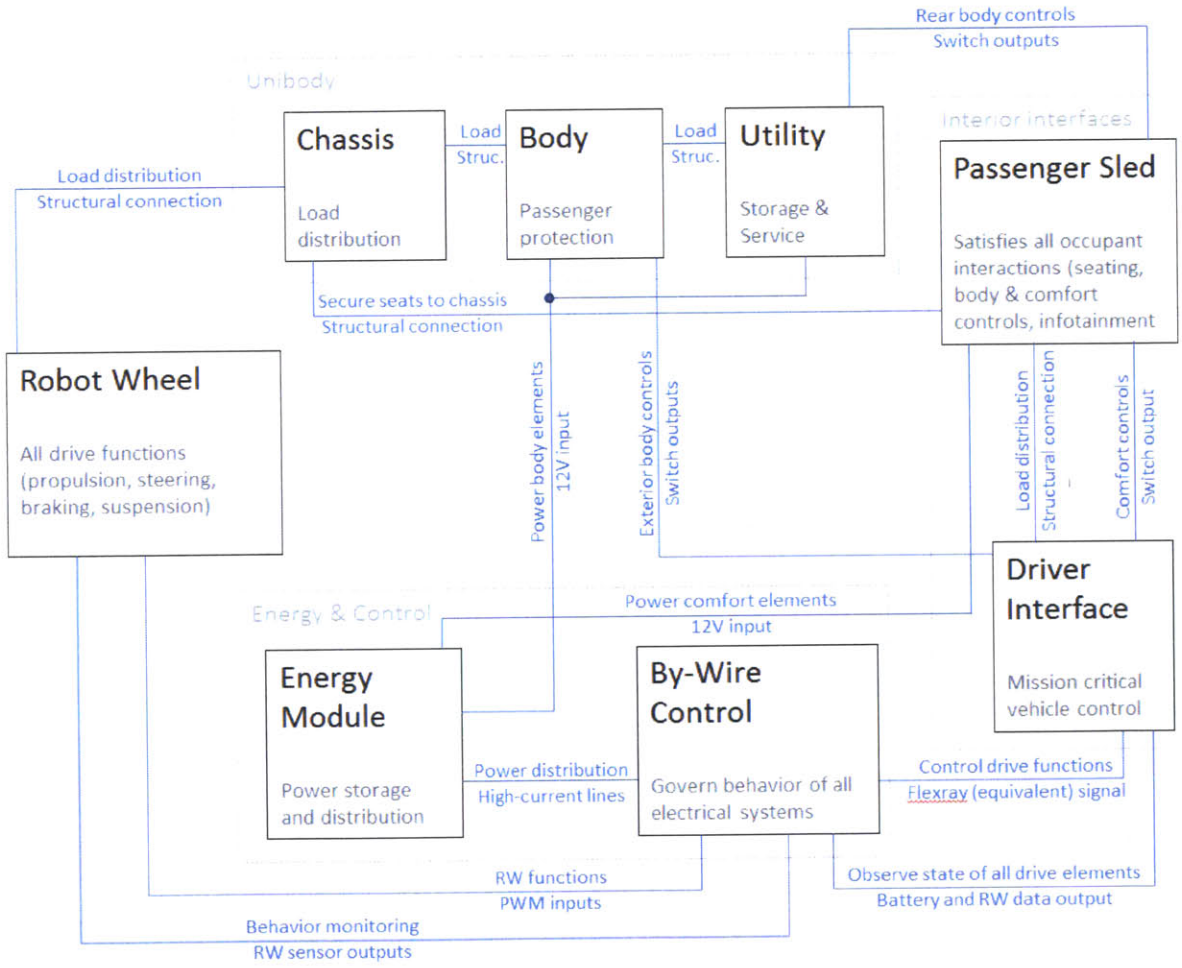
The number of modules, or "granularity," of the uMEV architecture can vary. Some complex modules such as the energy & control unit can even be further parsed. Utilizing fewer modules of coarse granularity tends to insure improved reliability since more subcomponents will be directly designed to function together.[29] Assemblies of uMEVs that are derived from a greater number of modules (fine granularity) however promote more vehicle variety. A variety of mobility options can be formed from the fundamental grammar of the urban modular electric vehicle shown in figure 2-10

Given that the final output results in electrical power, the energy module can vary in source. Prior PowerPod research (appendix 7.B) briefly investigated how battery, fuel-cells, and even small internal combustion engines could be combined in manners to offer different energy platforms. The driver interface, or human machine interface (HMI), module is slightly more challenging to group. From the vehicle designer's perspective, the HMI is a component very central and fundamental to the interior interfaces.

The highly modular architecture of the uMEV makes it unique from most electric vehicle designs. Elimination of the traditional engine and drive train enables modularization of the mechanical systems and offers great flexibility in design of the body and interior.

[29] (Ericsson & Erixon, 1999)

Figure 2-12 shoes a diagram of uMEV modules further parsed resulting in more mechanical and electrical connections between each. While the complexity of each module is reduced, increased dependencies between all developers must be carefully managed.



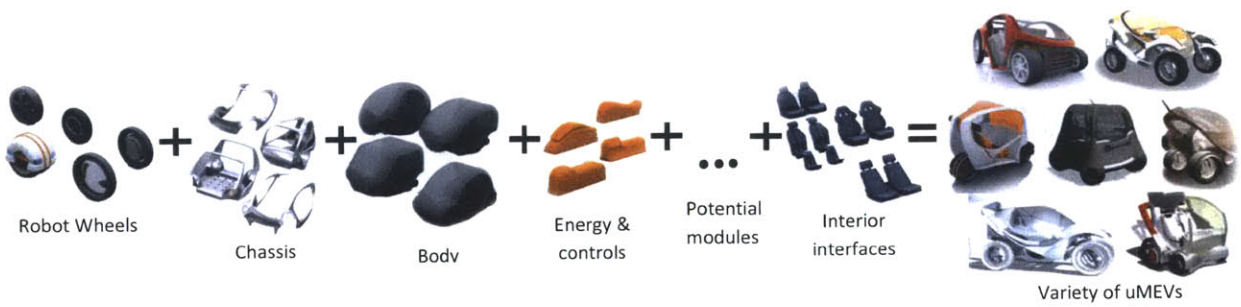


Figure 2-12: Parsed uMEV modules result in finer granularity

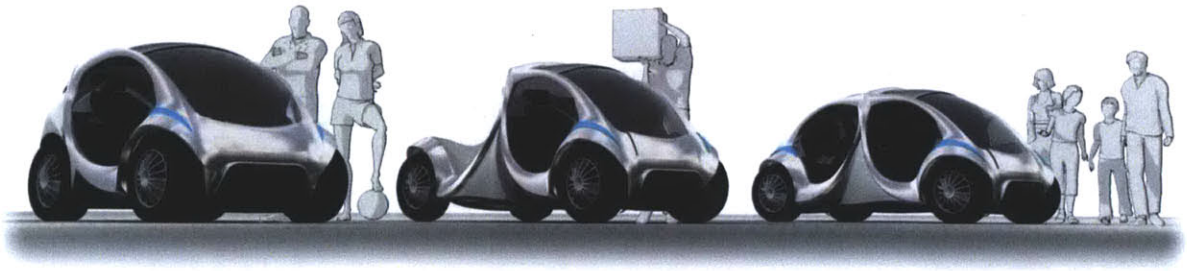


Figure 2-13: uMEV variations

Variations in the assembly of the uMEV unibody and payload capabilities of the Robot Wheels can create a variety of vehicles for commute, delivery, services, or recreation. An example of a relatively highly developed uMEV is the CityCar. The CityCar exploits the decoupled uMEV modules to push the functional boundaries of the chassis and Robot Wheels. Because of reduced mechanical impedances, the chassis is permitted to transform in footprint and Robot Wheels are granted the freedom to rotate more than usual.

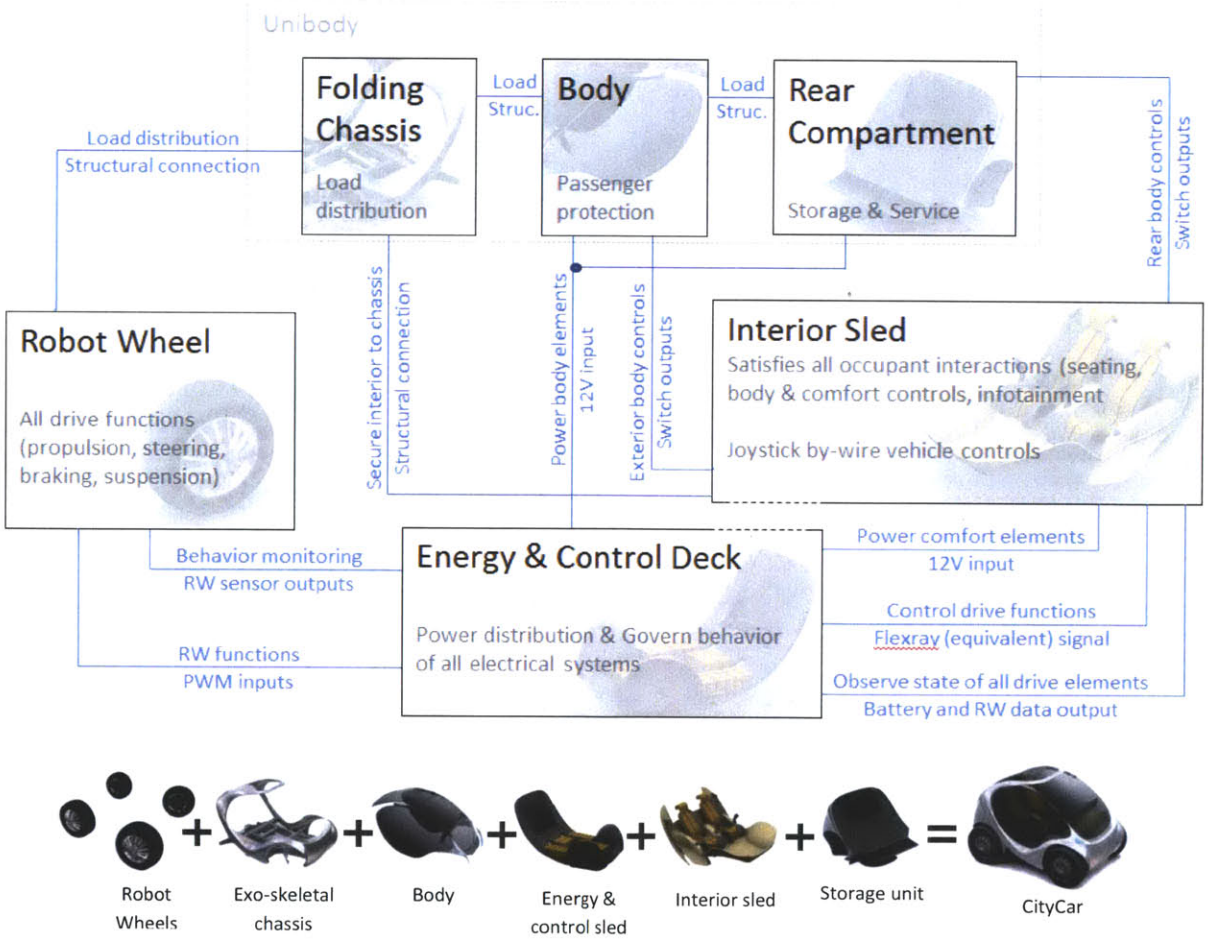


Figure 2-14: CityCar, the folding highly-maneuverable uMEV

2.5 THE CITYCAR

The CityCar is an intelligent, clean, lightweight, electric concept vehicle that folds up to provide space-saving personal mobility. The Shifted propulsion corner elements allow the CityCar to fold to minimize parking footprint, and to provide front ingress and egress. This dramatically changes its relationship to streets and cities. It can park nose-in to the curb in far less than the width of a traditional parking bay, and do so at very high densities. It is possible to park three CityCars in the length of one traditional parking bay.

Figure 2-15: Folding CityCar

2.5.1 *VEHICLE ARCHITECTURE*

This vehicle is comprised of six main modules: robot wheels, a folding exo-skeletal chassis, body panels, an interior sled, energy and control deck, and the rear compartment.

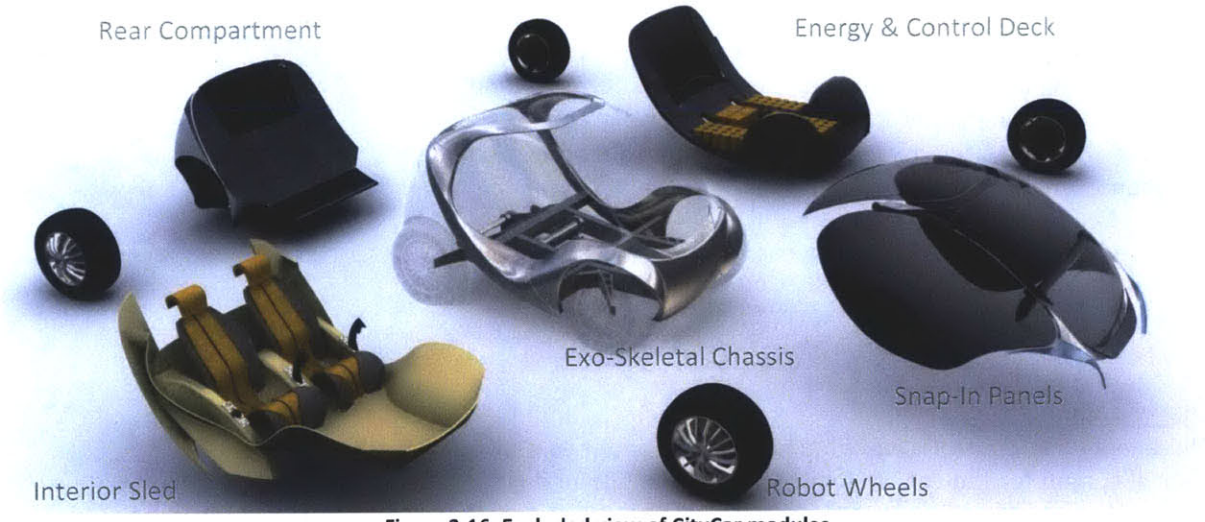


Figure 2-16: Exploded view of CityCar modules

Robot Wheels

The CityCar utilizes Robot Wheels with particularly high-degree of turning capability to provide the vehicle greatly improved maneuverability. Each wheel can turn up to 120 degrees (95-degrees in one direction and another 25 in the opposite).

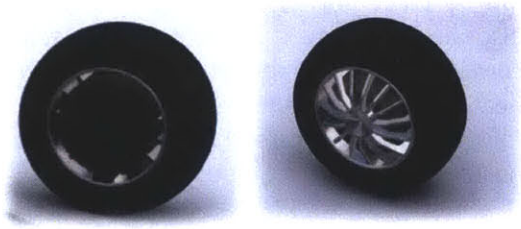


Figure 2-17: Robot Wheel module

Estimated Weight: 50+lbs each (200 lbs. total)
Proposed Materials/Components: Alloy rims, drive & steering motors, suspension mechanism
Key interface/standard: mechanical, power and data connections required
Estimated Lifecycle: 10+ years (tire likely to require multiple replacements)

Body Paneling

The vehicle is primarily covered by polycarbonate lens modules, which snap into the chassis. Substituting polycarbonate for the glazing offers a number of benefits. First, polycarbonate is typically half as dense as glass – this helps to keep the vehicle light. Second, polycarbonates are characterized by their high-impact strength and flexibility which allow us to use the glazing to bear some structural loads, provide a safe cabin, and maximize surface area viewing. The side lenses must also maintain their modularity for safety measures. The side modules will be designed to release from the chassis for an emergency exit scenario where front egress is not possible. In addition, the side lens modules have high potential for personalization and/or custom design since these units are fairly independent from the rest of the vehicle's subsystems.

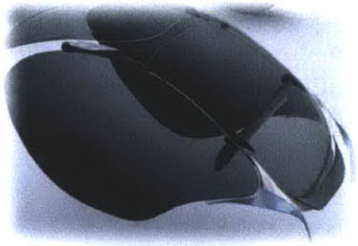


Figure 2-18: Body module

Estimated Weight: 130 lbs. total
Proposed Materials: polycarbonate
Key interface/standard: mechanical connection only
Estimated Lifecycle: 7 years (potential to haze over time)

Interior Sled

Another module, which has great potential for high customization, is the interior passenger sled of the vehicle. Since the vehicle is full drive-by-wire, the design of the interior cabin and drive controls are almost unbounded. This provides an open platform to find the optimal city-driving interface and also explore potential driving controls that may be personally customized to address unique preferences, requirements or disabilities.

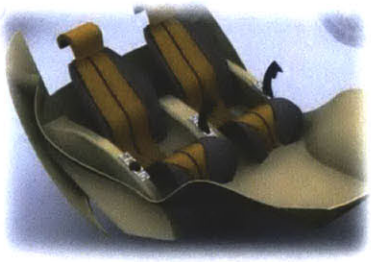


Figure 2-19: Interior module

Estimated Weight: 80 lbs. total
Proposed Materials/Components: high strength plastics (potential composites), durable cloths (
Key interface/standard: mechanical and data
Estimated Lifecycle: 10+ years

Energy & Control Deck

The energy and control sled contain the main batteries and central control system for the vehicle. All power distribution and processing is hosted here. The densest of these components, the batteries, will be housed low and towards to front of the vehicle to best maintain a low center of gravity at all stages. The energy and control sled may also accommodate a suitable cooling system for the batteries and computational components since they tend to produce significant heat. The layout of this vehicle no longer justifies a hood to pop open for maintenance; instead access panels on the underbelly and front nose may be the best solution.

Figure 2-20: Energy & control module

Estimated Weight: 230 lbs. total
Proposed Materials/Components: high strength plastics (potential composites), lithium-based batteries, CAN-bus control system, high voltage wires & connections
Key interface/standard: power and data
Estimated Lifecycle: 8 years – individual ownership, 3 years – shared use

Rear Compartment

Last, the rear compartment module provides the vehicle vast opportunity for storage and utility flexibility. The initial primary purpose for decoupling the rear compartment from the vehicle body was to ease the vehicle folding by reducing the necessary components that gets lifted while maintaining a low center of mass. This decoupling fortuitously results in a highly modular rear component that can either be swapped out or custom built to best serve storage or utility needs. In addition to the expandable storage the rear modules also presents an opportunity to provide the vehicle with additional power units to supplement the vehicle's core electric platform. While the CityCar will not require such a power unit, uMEV alternatives based on the same platform can satisfy unique characteristics such as extended range through hybrid power generators or simply additional battery units to best complement required drive profiles. Supplemental energy modules such as PowerPods (appendix 0) can be incorporated as needed.

Figure 2-21: Rear module

Estimated Weight: 40 lbs. total
Proposed Materials/Components: high strength plastics (potential composites)
Key interface/standard: primarily mechanical (potential power and data connection for supplemental energy sources)
Estimated Lifecycle: 15+ years

Folding Exo-Skeletal Chassis

The folding exo-skeletal chassis is designed to maximize passenger safety while drastically reducing exterior components of the vehicle. The chassis contains three main safety features: (1) the exterior (or exo-skeletal) ring that protects the passengers from any external impediments, (2)the internal beams that help to distribute impact, and (3) the folding four-bar linkage structure, which not only reduces the vehicle's footprint while parked but also assists to decelerate the passengers in a front or rear impact collision. In addition to safety features, the exo-skeleton chassis is also designed with a minimal approach to keep the CityCar relatively simple and lightweight. While traditional automobile bodies are constructed with a unibody chassis covered by relatively delicate sheet metal panels and paint, the CityCar looks to treat the chassis more like the construction of eyeglasses in which an external frame houses a polycarbonate lens. Such an approach not only offers an opportunity to significantly reduce part count but also presents a platform for highly customizable side panels, or "lens modules."

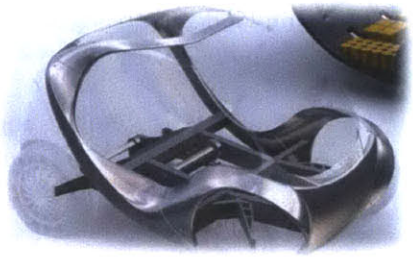


Figure 2-22: Folding chassis module

Estimated Weight: 300 lbs. total
Proposed Materials: aluminum alloy exterior and internal steel beams
Key interface/standard: primarily mechanical connections
Estimated Lifecycle: 15+ years

2.5.2 *CORE FEATURES*

Four core features enable the CityCar concept to address challenges in the city unlike today's automobiles:

1. Wheel Robots - In-Wheel electric motor module with embedded suspension, electronic braking, and independent electronic steering system. The CityCar utilizes four of these independent Robot Wheels that each turn up to 120-degrees. The large sweep in each wheel coordinate to provide the following maneuvers:
   - O-turn: allowing the vehicle to spin on a dime continuously
   - Translation: allows the vehicle to side-step perpendicularly
   - 4-wheel steering: provides tight turning radius and enables slight translation while driving

2. Front Egress - Frontal entry system that integrates front windshield, driver controls, and accommodates easy ingress/egress for passengers. The CityCar utilizes a door in the front of the vehicle to ease entry and exit of its passengers onto the sidewalk once the vehicle is folded. In addition to the eased ingress/egress, the lack of side doors allows the vehicles to park tightly next to one another, maximizing parking surface area.

3. Folding Chassis - An actuated folding mechanism connects the front passenger cabin with rear storage module. The CityCar utilizes a dual 4-bar linkage folding system to reduce its footprint by up to 40% when parking and maneuvering in tight low-speed situations. Passengers can remain in the vehicle during all states (unfolded, folded, and in-between), and most complex and weighted systems remain low to the ground to maintain a low center of gravity. When unfolded and driving normally, the CityCar is slightly larger than the Smart ForTwo car. However when folded, it reduces its foot print to about 5' x 5' (five feet by five feet).

4. Drive-by-Wire - Vehicle control system built upon a FlexRay bus (or reliably equivalent) and CAN bus technologies. The control backbone of the vehicle uses redundant systems to ensure all mission-critical components receive reliable time-triggers information.

Secondary Features provide additional benefits to the end-user:

- The CityCar can utilize either an electronic wheel, yoke controller (similar to airplane controls) or dual joysticks to control the vehicle. Each interface communicates to the vehicle's drive systems through a by-wire backbone.
- A noticeable feature of the CityCar is its large amount of transparent surface area. This is done not only to improve the visibility of the driver, but additionally to better engage the passengers with their city surroundings.
- One feature to be further explored on the CityCar is the proposed energy absorption through its folding chassis. Most traditional vehicles today absorb front and rear collisions through crumple zones; however, the small CityCar does not have such an option. Instead this vehicle may utilize shock absorbers integrated with the folding mechanism to better decelerate its passengers.
- The CityCar runs completely on electric power provided by Lithium-ion battery packs.

Combining the previously listed features provides CityCar occupants the following amplified benefits:

- Reduced footprint and vehicle sweep - folding chassis, front entry/exit, omni-directionality
- Improved maneuverability – tight steering radius from RWs, reducible wheelbase, proximity sensing, increased visibility
- Eased entry/exit – front door (sidewalk exit), elevated seat from folding, drive-by-wire interface reduces obstruction
- Safety – open cabin eliminates impeding dashboard, dynamic deceleration from folding, external vehicle sensing can prepare vehicle for impact, 4-wheel steering, power and brake allow for vector control at all four corners

CityCars accommodate two passengers, which suits them to meeting the requirements of the vast majority of urban trips without excess capacity. This CityCar weighs less than a thousand pounds, parks in much less space than a Smart Car, and is expected to get the equivalent of over 100 miles per gallon of gasoline. Since it is battery-electric, it produces no tailpipe emissions. They are designed for intra-urban trips, which are fairly short between recharge opportunities. This fits them gracefully to the capabilities of battery technologies that are presently available or likely to be available in the near future. They are not designed for inter-city travel, for which different modes of transportation (such as mass transit or personal automobiles) are more appropriate.

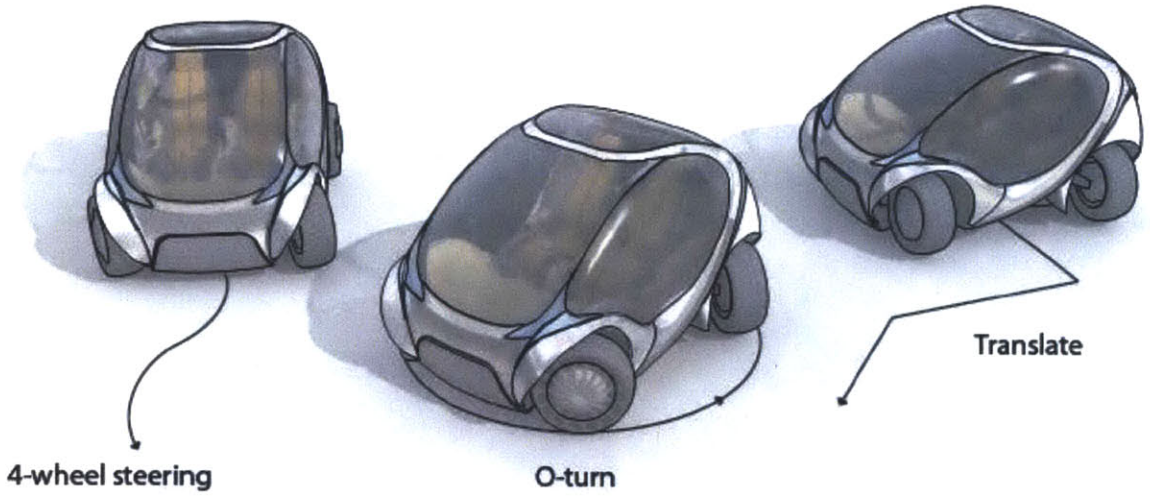


Figure 2-23: CityCar maneuverability - 4-wheel steering, O-turn, and translation

The CityCar exploits the most maneuverable types of Robot Wheels, each able to turn up to 120 degrees. This gives the vehicles omni-directional capabilities to translate sideways, spin on a dime, and engage in precise 4-wheel directional movements. Such nimble capabilities can prove useful in congested urban environments. Additionally as roads are populated with more and more of these omni-directional CityCars (and other uMEV types), navigation can become more fluid allowing them to effectively negotiate for compact spaces.

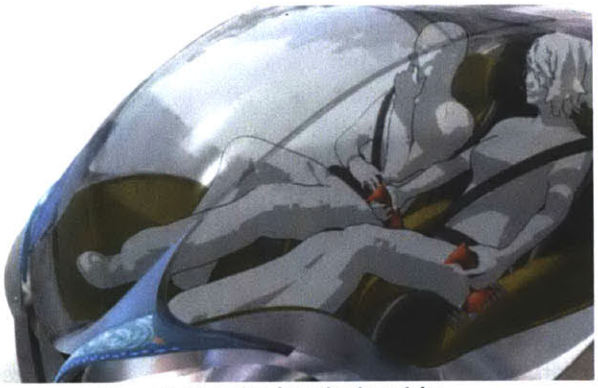


Figure 2-24: Drive-by-wire joysticks

The CityCar's HMI utilizes a by-wire dual joystick interface, which in conjunction with localized motor wheels allows for drastic design freedoms. Without the impeding steering wheel, dashboard or drivetrain mechanics located at the nose of the vehicle, the CityCar is open to front entry and exit capabilities.

To confront the problem of scarce and expensive urban real estate, the CityCar is able to fold up to reduce its footprint by 40 percent (final folded footprint is only 60" by 60"). This folding maneuver not only lets the vehicle occupy an ultra-compact space but permits dynamic front impact dampening and easily allows the passengers to step right out onto the sidewalk as the vehicle conveniently places you into a semi-standing position. When folded the CityCar is very compact and has an on-street parking ratio of at least 3:1 compared to traditional automobiles. Initial designs estimate the CityCar to be very lightweight, at around 1,000 lbs.

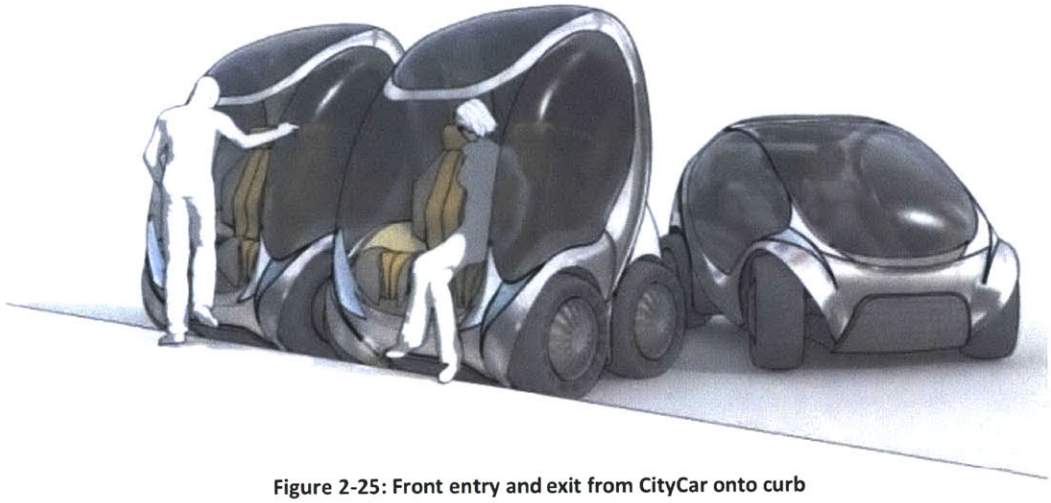


Figure 2-25: Front entry and exit from CityCar onto curb

Figure 2-26: Core features of the CityCar

2.6 CityCar Developments

Over the past five years, the CityCar has received its share of exposure; from multiple museum installations in Cambridge, New York, Sidney and other locations worldwide, to media specials like Dean of Invention (featuring the inventor of Segway and many other ventures Dean Kamen), the National Science Foundation's Green Revolution, and spots on CBS and CNN. Combined with companionable mobility solutions (GreenWheel bicycle, and RoboScooter), the CityCar was a prominent featured technology that helped capture a first place award in the 2009 Buckminster Fuller Challenge.[30]

Figure 2-27: Buckminster Fuller Challenge 2009 winner

Soon after, the same vehicle design shared the cover with GM's PUMA concept (eventually named enV) on *Reinventing the Automobile*, a book that addressed future trends and technologies for personal mobility in the future. Following the publicity successes of the digital designs, renderings and animations of the vehicle concept, efforts were dedicated to proving that such a radical type of vehicle could actually be developed. Therefore, a half-scale prototype was developed to demonstrate all of the CityCar's potential features. After an abundance of developed material and the complementary support of Mobility on Demand, soon it was only a matter of time until the CityCar concept caught the attention of the correct audience. In 2010, the intrigue of the proper spectators led to an essential collaboration. Through collective efforts with Basque manufacturers, a full-scale fully-functional CityCar, named "Hiriko," was unveiled towards the end of 2011 in Brussels.

Figure 2-28: Reinventing the Automobile & prototype

Figure 2-29: MIT team in Brussels during Hiriko CityCar debut

[30] (Buckminster Fuller Institute, 2012)

3 EVALUATION

Following the design, engineering, and publication of the main uMEV concept, CityCar, a variety measures were used to validate the proposed personal mobility solution. First to examine some of the more complex assemblies and functionality of the digital design, a drivable and foldable functional half-scale prototype was developed. This construction revealed a number of alterations that would need to be implemented in order to consider future real-world applications. Soon after, a collaborative venture was formed with an overseas supporter to industrialize the CityCar concept and develop production version vehicles. The project "Hiriko" developed the concept vehicle with local supply manufacturers in a modular vehicle and business architecture. The team, led by core MIT engineers, created a fully operational vehicle maintaining all core CityCar features in a manner near mass-production objectives. Specifications of the validated CityCar design were then analyzed within the context of a shared mobility system (Mobility on Demand) to illustrate the compounding benefits of a city tailored vehicle in such a personal mobility service. Last, feedback was gathered and assessed from essential stakeholders in the production and consumption of CityCar (also known as Hiriko) vehicles.

3.1 The Half-scale Prototype

Throughout 2009 a half-scale prototype of the CityCar was developed. The prototype was not only an exercise in design, but also a comprehensive study of functioning components. Whereas most smaller-scale models focus on single aspects of a concept (usually its overall form), this half-scale CityCar addressed all major components in their fullest possible detail – applying the closest fit proposed materials, technology, subassemblies, and fasteners whenever possible.

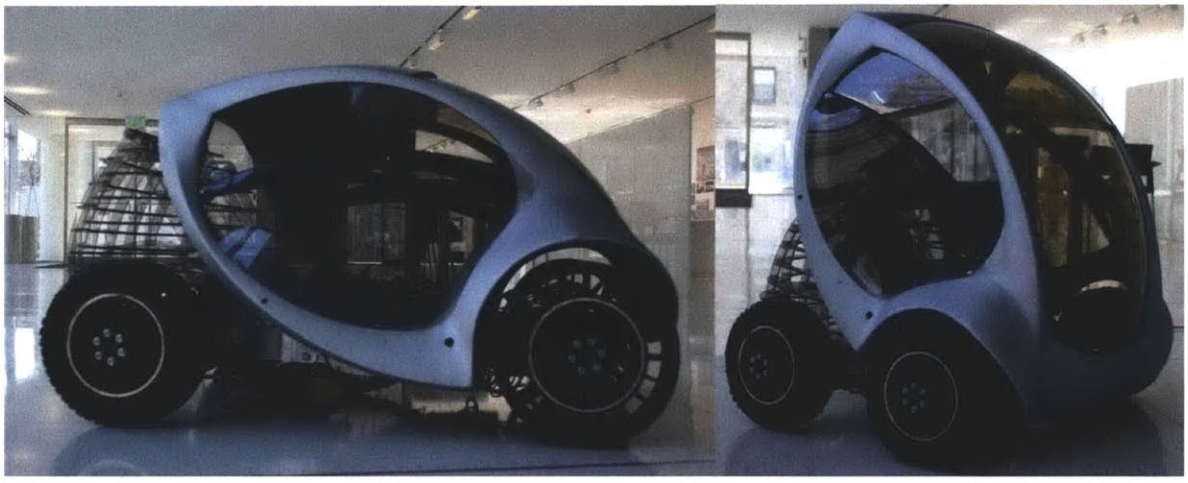
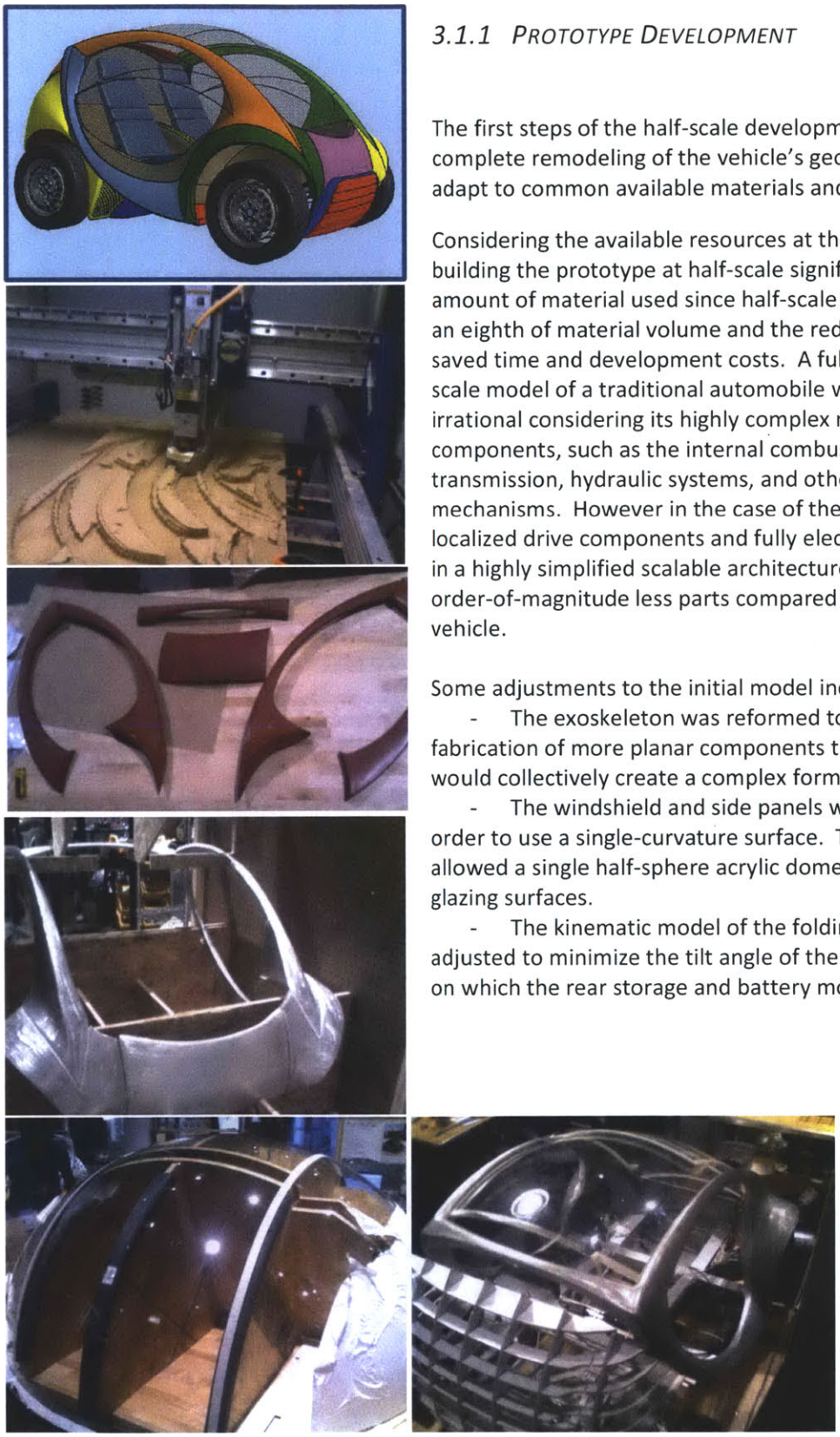


Figure 3-1: Half-scale functional prototype of CityCar

The investigation of design details, the half-scale CityCar served as a platform to further examine the interfaces between the modules, and as a guide to establish thorough module architecture for following vehicle iterations.

The construction of the prototype also served as a case study for flexible and open development processes by dividing module responsibilities between research assistants... Although at this stage it was not be possible to fully emulate mass production scenarios, the process of outsourcing components and engaging local suppliers provided insight on techniques in fabrication and the coordination necessary to develop complex products.



3.1.1 *Prototype Development*

The first steps of the half-scale development involved complete remodeling of the vehicle's geometry in order to adapt to common available materials and accessible tools.

Considering the available resources at the Media Lab, building the prototype at half-scale significantly saved the amount of material used since half-scale models only require an eighth of material volume and the reduced scale also saved time and development costs. A fully functioning half-scale model of a traditional automobile would prove irrational considering its highly complex mechanical components, such as the internal combustion engine, transmission, hydraulic systems, and other intricate mechanisms. However in the case of the CityCar, the localized drive components and fully electric platform result in a highly simplified scalable architecture, which has an order-of-magnitude less parts compared to a conventional vehicle.

Some adjustments to the initial model included:

- The exoskeleton was reformed to accommodate the fabrication of more planar components that once assembled would collectively create a complex form
- The windshield and side panels were also reshaped in order to use a single-curvature surface. This redesign allowed a single half-sphere acrylic dome to be used for all glazing surfaces.
- The kinematic model of the folding chassis was adjusted to minimize the tilt angle of the rear powertrain axle on which the rear storage and battery modules rest.

Figure 3-2: Development process of half-scale prototype (1 of 2)

3.1.2 *Lessons Learned from Prototype*

The half-scale prototype served as a base-line test to confirm that such a radical vehicle architecture could function harmoniously. It also served as the first pass to further consider constraints in design for manufacturing (DFM) processes. The following vehicle elements revealed some real world constraints when transferring from the digital to physical realm.

Folding chassis implications

- Introduction of dual 4-bar linkage to maintain full drive operation when folded
- Clash elimination between rear compartment, main cabin, and chassis linkages
- Handling of load distribution throughout chassis

Vehicle Packaging

- Wheel sweep ("butterfly") accommodations
- Battery and electronics compartmentalization
- In-hub motor and steering packaging

Sliding front door

- Continuous cross-section necessary for opening
- Parallel guide rail integrated into complex form of exoskeleton
- Position of division for front glazing to provide overlapping coverage of the front door once open and to avoid line-of-sight obstructions.

Side Window operation

- Planar upper window for eased operability
- Side impact reinforcement (also adapts transition from curved side panel to planar window)
- Eased operation through pivot about single axis in front of vehicle
- Fully operational window along curve of exoskeleton jawbone

Table 3-1: Development process of half-scale prototype (2 of 2)

3.2 Industrialization of the CityCar

In 2010, a company named DenokInn became a Media Lab sponsor in order to industrialize the CityCar concept. DenokInn is a business incubator for emerging projects and technologies in the Basque region of Spain. The project became known as "Hiriko," which is Basque for "city." In order to best facilitate the collaboration and knowledge transfer, the project was led by core MIT designers and engineers who moved to Spain for over a year to work directly with local automotive supply manufacturers. The design for manufacture process through Hiriko became a true litmus test for the feasibility and viability of the CityCar concept.

3.2.1 The Hiriko Project

The modular strategy of the CityCar was well embraced as automotive suppliers local to Vitoria-Gasteiz each engaged their resources to develop particular modules of the vehicle. One of the largest initial challenges was not only establishing the specifications and features that would be maintained in this product version of the CityCar but also to manage the roles and responsibilities of each of the suppliers within Hiriko. Especially since the vehicle architecture is completely novel to the automobile industry, there was no initial reference to begin.


EL CORREO ECONOMÍA 41

El Hiriko eléctrico arranca en junio

El consorcio de empresas vascas que fabricará este vehículo urbano prevé tener listas 700 unidades para 2013

Figure 3-3: Basque newspaper, El Correo, announces new joint venture

Hiriko was slated to be developed under a particular classification of vehicle in Europe, the micro-vehicle or "heavy quadricycle."[31] This particular vehicle classification opened up major automotive design hurdles as its main restrictions were weight (450 kg without batteries) and power (15kW nominal max).

In addition to the core CityCar design and features, the complementary principles of Mobility on Demand were also embraced. Maintaining this larger perspective on developing a vehicle not only for efficient personal transit but also for a comprehensive system helped to preserve a focused vision. The final Hiriko vehicle that premiered in Brussels in the fall of 2011 maintained all core features championed by the CityCar. The Hiriko group continues to progress and expects to release a small run of production vehicles in 2013.

Figure 3-4: CityCar Design to Industrialized Hiriko

[31] (European Commission, 2009)

3.2.2 *Modular Architecture of Hiriko*

The Hiriko project embraced a modular platform fairly equal to the uMEV proposal. As stated by the new ventures website, www.hirio.com, the consortium of suppliers has taken on the following roles:
GUARDIAN, an enterprise dedicated to the production and transformation of glass, will be in charge of developing the glass components for the vehicle.
MASER – MIC, an enterprise devoted to the development and manufacture of electronic and mechatronic equipment for the automotive industry, will develop the vehicle's electronics.
FORGING PRODUCTS, an enterprise dedicated to developing forged pieces, will be in charge of developing and manufacturing the vehicle's aluminum chassis.
TMA, an enterprise that offers comprehensive solutions for metallic construction, will be in charge of developing the vehicle's structure and the front door.
SAPA PLACENCIA, an enterprise devoted to the design and manufacture of electric machinery and mechanical transmission. SAPA will be in charge of the drive-by-wire system and the haptic steering wheel.
BASQUE ROBOT WHEELS is a new enterprise that designs and manufactures modular and independent driven and guided wheels for electric vehicles. B.R.W. is developing the vehicle's robotic wheels.

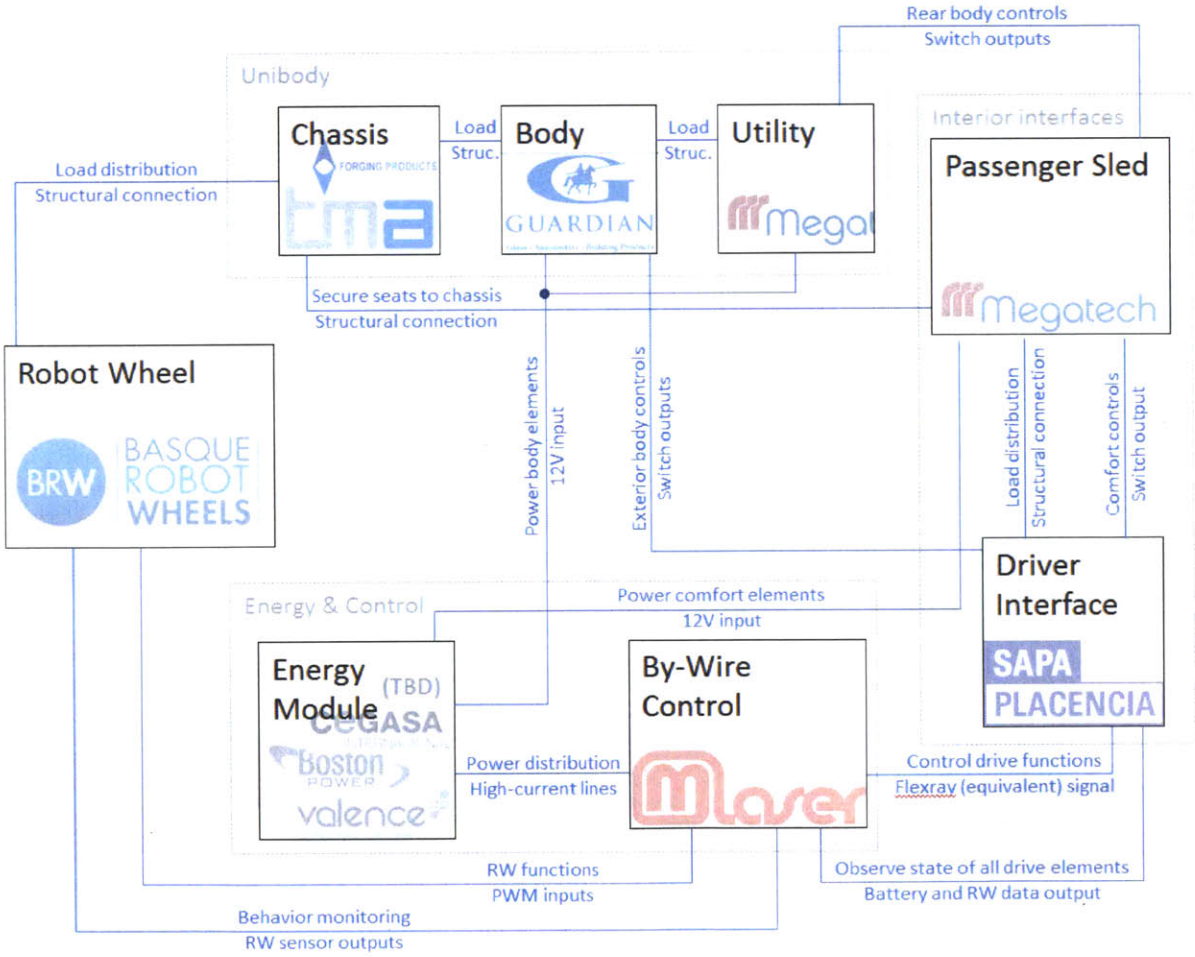


Figure 3-5: Hiriko modular business model

While the division of responsibility amongst the core module manufacturers is not completely isolated, each supplier was able to handle the majority of development independent from one another. Suppliers such as *Forging Products* and *TMA* collaborate on the manufacturing of the folding chassis. Figure 1-3 illustrates most of the major divisions between modules.

Figure 3-6: Hiriko exploded view of modules, by Marie Le Monnier - ETUD

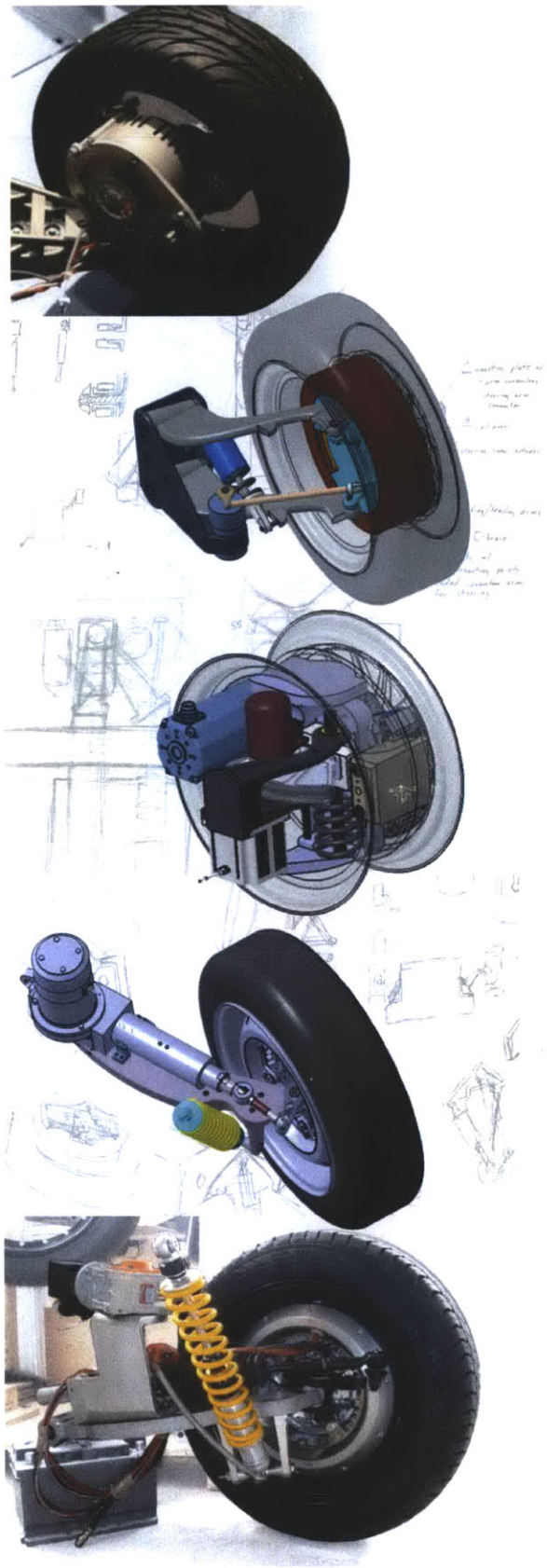


Figure 3-7: Evolution of Robot Wheels

3.2.3 *Evolution of the Robot Wheel*

Throughout Hiriko project the development of the Robot Wheel sparked much debate on the best methods to achieve the core functional requirements. Although the fundamental concept of the Robot Wheel strives to package all major drive components within the corner space of the vehicle, the methods to do so can vastly vary. Since there are multiple ways of achieving the main functions with numerous actuators, gearing and packaging options, the solution space can rapidly multiply.

First the vehicle and Robot Wheel geometry had to be further investigated to better understand the resultant effects of each option on the overall specifications. Meeting functional requirements for both the drive and steering motors became just as paramount as the modular vehicle packaging. Also the Robot Wheel's effect on energy consumption, reliability, safety, manufacturability, and business strategies weighed heavily on arriving at the best design solution.

3.2.2.1 Challenges in Design Parameters

Although the fundamental characteristics and packaging explorations of the Robot Wheel have been well established throughout the research of the Smart Cities and Changing Places groups at the MIT Media Lab, further studies was needed to engineer their design and specifications for manufacture. Calculations for each Robot Wheel motor performance characteristics (torque, speed, power, and duty-cycle) for a particular vehicle weight and capacity, in this case a 450 kg micro-vehicle, needed to be understood.

Drive Motor Specifications

The derivation of the Hiriko robot wheel specifications (Appendix 7.C) established a minimum output torque of 136 Nm at the wheels. How that torque is achieved however can vary.

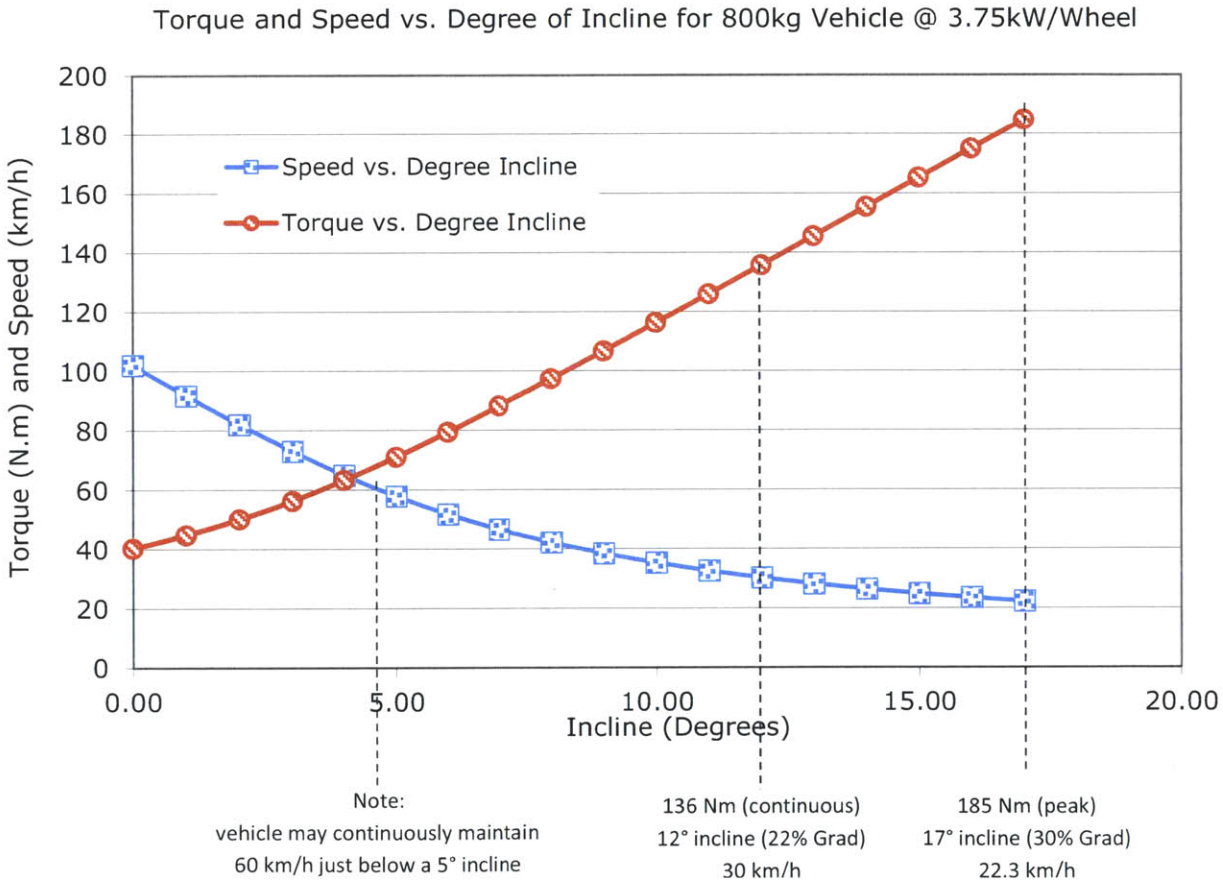
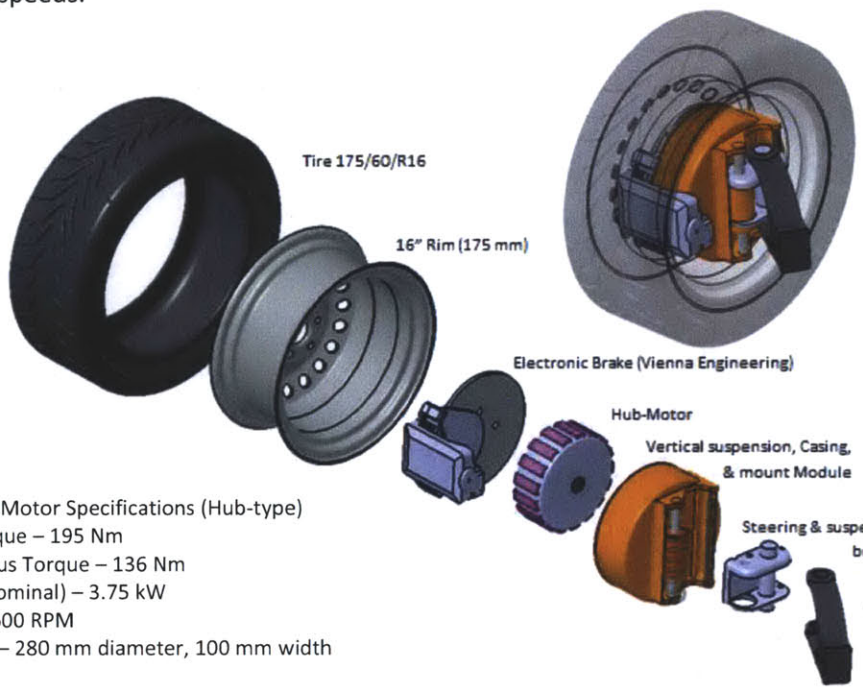


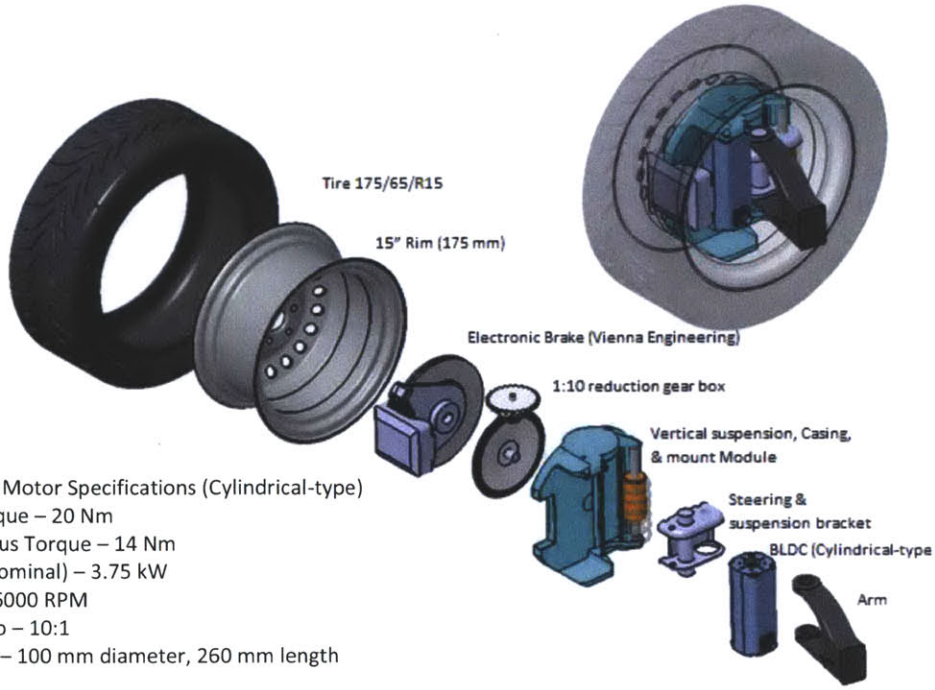
Figure 3-8: Torque and speed vs. incline for 800kg vehicle @3.75kW per wheel

Throughout the design investigations, two different approaches were explored when specifying the drive motor and its subcomponents that would be necessary to reach the established functional requirements. Choosing which type of motor to use, (1) a large "hub-type" motor with higher torque capabilities at lower rotational speeds versus (2) a slimmer high-speed "cylindrical-type" motor with lower torque accompanied by a gear reduction, resulted in a chief debate.

Each option has its unique benefits and challenges. The hub-motor version keeps the assembly relatively simple and fits well with the form factor of the wheel. However the weight requied to support the larger magnets, coils, and rotor (which the rim directly connects) results in significant drawbacks in heavier mass. Conversely when using a cylindrical commercial BLDC motor, savings in weight are traded for an increase in parts and maintenance from the gear reduction, necessary for achieving the proper torque and speeds.



Required Motor Specifications (Hub-type)
Peak Torque – 195 Nm
Continuous Torque – 136 Nm
Power (nominal) – 3.75 kW
Speed – 600 RPM
Max Size – 280 mm diameter, 100 mm width



Required Motor Specifications (Cylindrical-type)
Peak Torque – 20 Nm
Continuous Torque – 14 Nm
Power (nominal) – 3.75 kW
Speed – 6000 RPM
Gear ratio – 10:1
Max Size – 100 mm diameter, 260 mm length

Figure 3-9: Assembly comparison between Robot Wheel architectures

Steering Motor Specifications

Although the Robot Wheel can provides significant reductions in vehicle complexity and a liberated platform upon which to design, the reduction of mechanical element does present new complications unique to independent corner units. For example now that every drive function, such as steering, is independently operated within the Robot Wheels, the vehicle can no longer benefit from the shared reactionary forces that are distributed through the mechanically coupled tie rod and steering rack assembly.

The turning front wheels of a vehicle undergo complex and significant forces throughout the duration of a trip. The contact between the tire and road present substantial a scrub friction that the wheels must overcome to change direction. The scrub radius, which is dependent upon the position of the steering assembly's king pin axis relative to the center of the contact patch, creates a force vector in the opposite direction of propulsion. This force results in a moment about the king pin which each Robot Wheel must independently manage.

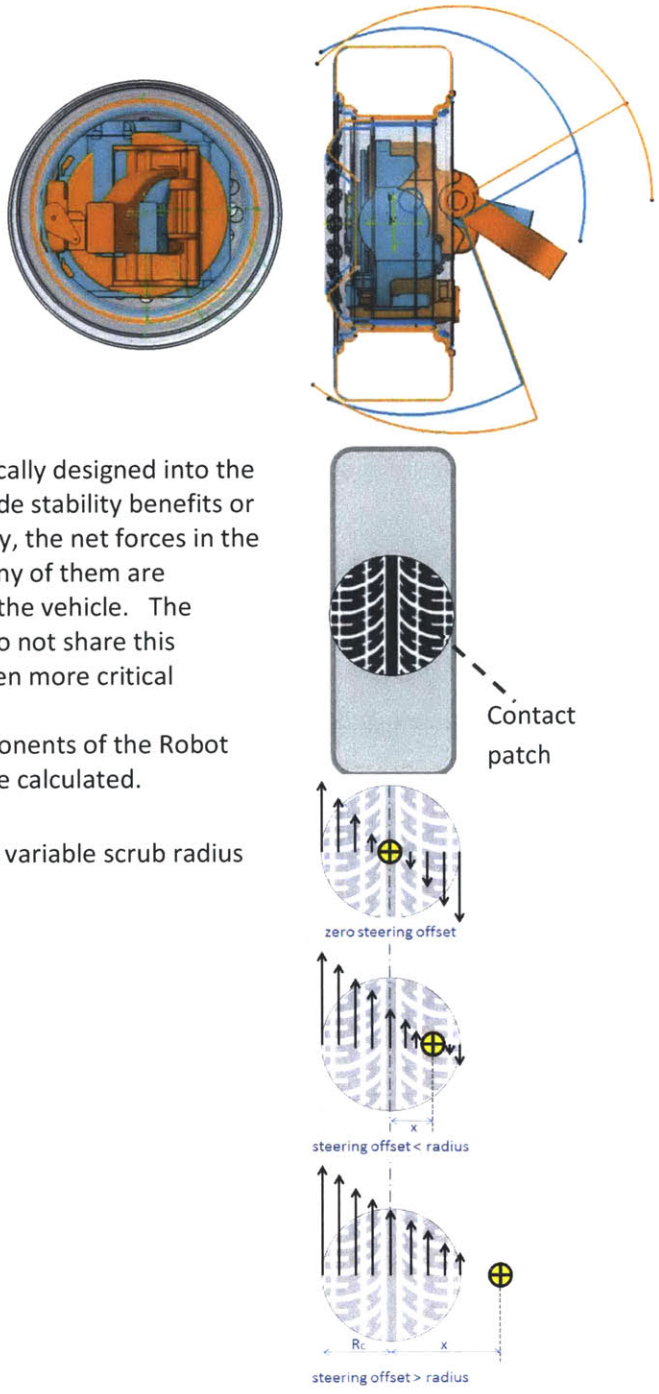


Figure 3-10: Steering friction across contact patch

These forces from the scrub radius are typically designed into the behavior of traditional steering assemblies to provide stability benefits or advantages to the driver when parking. Additionally, the net forces in the traditional steering assembly are reduced since many of them are counteracted between the left and right wheels of the vehicle. The independent Robot Wheels as designed however do not share this benefit; therefore, the scrub radius becomes an even more critical parameter to tune in the overall design.

To properly specify steering actuator components of the Robot Wheel, the minimum necessary torque must first be calculated.

Calculating Minimum Steering Torque for a variable scrub radius

$\tau_s = steering\ torque$
$x = steering\ offset$ *(Scrub radius)*
$F_N = Normal\ Force$
$P = pressure\ at\ contact\ patch$
$\mu_s = Coefficient\ of\ friction$
$A = area\ of\ contact\ patch$
$R_c = radius\ of\ contact\ patch$ *(1/2 tire width)*

First, the steering torque (τ_s) at a given location of the contact patch can be calculated from the frictional force ($\mu_s F_N$) applied at distance from the center of rotation. Assuming the tire creates a relatively round contact patch, the torque is leveraged over its radius, r. Therefore steering torque will be calculated from the following equation:

$$\tau_s = r\mu_s F_N \quad \textbf{Equation 3-1}$$

The normal force at the contact patch can then be defined as a uniform pressure over the area of the contact patch:[32]

$$F_N = PA \quad \textbf{Equation 3-2}$$

Therefore the steering torque equation changes to include the pressure across the contact patch and the full radius about which the wheel turns ($x + r$). When the point of rotation resides in the center of the contact patch, $x = 0$.

$$\tau_s = (x + r)\mu_s PA \quad \textbf{Equation 3-3}$$

At this point we can confirm that the necessary steering torque is a factor of scrub offset (x), the tire width ($2r$), friction between the tire and road, and the vehicle weight that adds to the pressure (P) across the contact patch. Therefore the Robot Wheel module will be at an advantage to minimize its scrub offset and tire width. As torque varies across the area of the contact patch:

$$d\tau_s = (x + r)\mu_s P \cdot dA \quad \textbf{Equation 3-4}$$

In polar coordinates the derivative of the area equals:

$$dA = r \cdot dr \cdot d\theta \quad \textbf{Equation 3-5}$$

Therefore, when plugging in equation 3.5 into the previous equation 3.4:

$$d\tau_s = (x + r)\mu_s P \cdot r \cdot dr \cdot d\theta \quad \textbf{Equation 3-6}$$

The integral of both the radius and angle must be taken resulting in the following double integral:

$$\tau_s = \mu_s P \int_0^{2\pi} \int_{-R_c+x_0}^{R_c+x_0} (x + r)\, r \cdot dr \cdot d\theta \quad \textbf{Equation 3-7}$$

Finally this results the following equation for the steering torque as result of the scrub friction:

$$\tau_s = 2\pi\mu_s P \left(\frac{r^3}{3} + \frac{r^2 x}{2}\right)\Big|_{-R_c+x_0}^{R_c+x_0} \quad \textbf{Equation 3-8}$$

Given a chosen tire width of 175mm ($2R_C$) and a gross vehicle weight of 700 kg ((F_N/g)*4), the minimum steering torque values can be calculated for various potential scrub radii, shown in figure 3.2.2 graph.

[32] (Carvajal, 2009)

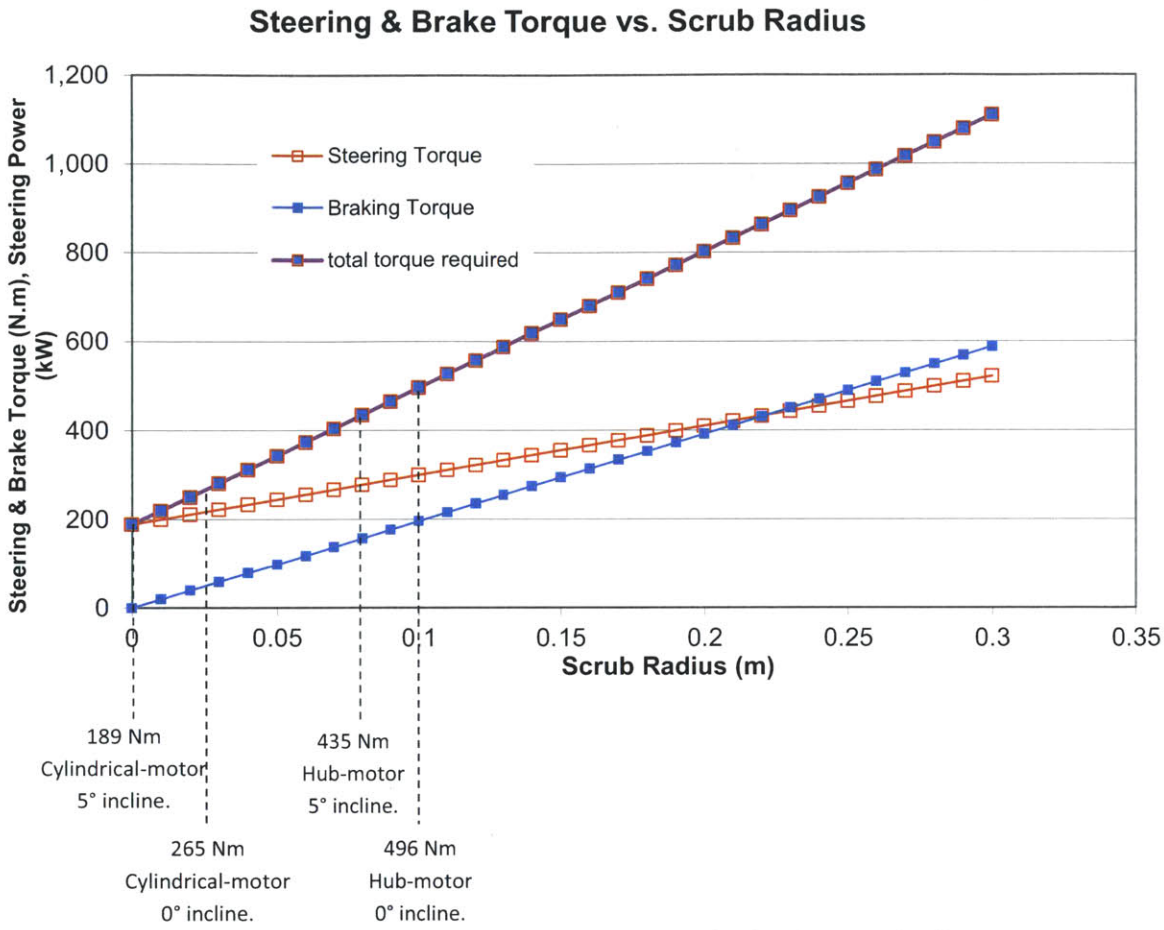


Figure 3-11: Steering and brake torque vs. scrub radius (steering offset)

At minimum, 189Nm would be required by each steering motor in the case where the center of the wheel's rotation resides in the center of the contact patch, 0mm scrub radius. The value of the required steering torque more than doubles once scrub radius approaches 100mm. Therefore it becomes extremely important to package the Robot Wheel components in a manner that minimizes the scrub radius by keeping the steering axis, or "kingpin axis," central to the tire contact patch. Selecting the drive motor type (hub or cylindrical) plays a large part in the final scrub radius length since each motor's form-factor heavily influences the packaging options of the kingpin axis. The larger size of the hub-type motor tends to conflict with the desired location of kingpin elements while the cylindrical-type and its transmission can be more flexible to accommodate desired packaging constraints.

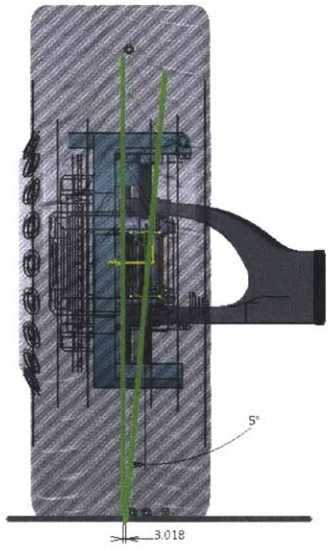


Figure 3-12: Zero scrub radius

3.2.2.3 Iterative Developments of Hiriko Robot Wheel

MIT Initial Proposal

The initial Hiriko Robot Wheel proposal was designed to incorporate essential key features previously addressed. It included an electronically actuated disc caliper brake, a vertically positioned cylindrical motor (which improves packaging, allows for a level of decoupling from the road impact, and provides scalability), a vertical rail suspension with a through-shaft damper and a rigid steering arm. This single arm maximizes modularity and provides us an opportunity to house the ECU's on the arm local to the robot-wheel.

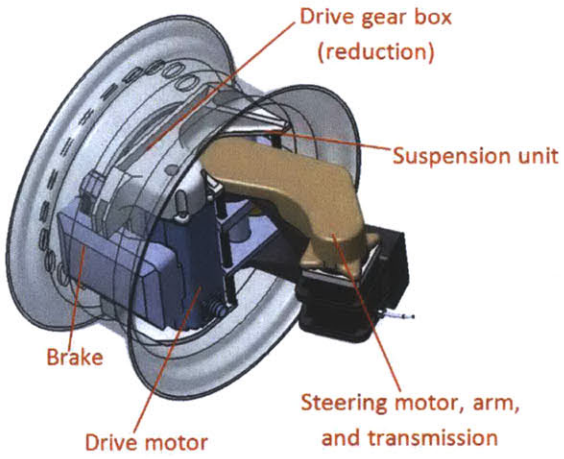


Figure 3-13: Initial MIT Robot Wheel proposal

The orientation of the drive, brake, suspension and steering components allow for a high level of scalability. The electronic brake has space to grow without conflicting with other components. The drive motor power and torque can be increased by lengthening the motor (it's diameter of course will be limited up to a point, but its length can be purely a function of incorporated rim diameter). The scalability of the vertical suspension is similar to the drive motor whereas this can also be increased with a larger diameter rim – still in both drive and suspension, the tire/rim width does not change. Moreover, the steering component may be removed if the robot wheel is only needed for propulsion and braking – in this scenario, space needed for storage or other components may be maximized. With a zero scrub radius, this proposal proved to be the overall most compact, but complex solution.

Supplier Initial Proposal

Early proposals from the initial prospective Robot Wheel supplier embraced a completely different architecture. Striving to incorporate an alternating-current asynchronous hub motor, that had previously been developed in-house, created packaging challenges for the other supporting subsystems. As opposed to an external rotor to attach the wheel, the motor contained an internal rotor whose axial output resulted in additional assembly depth. Therefore, no room remained to bundle steering or suspension within the corner unit. Additionally the proposed double-wishbone suspension solution required three complex connection points – eliminating plug-and-play capabilities. Although the proposal did offer potential dynamic handling benefits, the relatively large size of the suspension elements considerably encroached upon the space of the battery compartment.

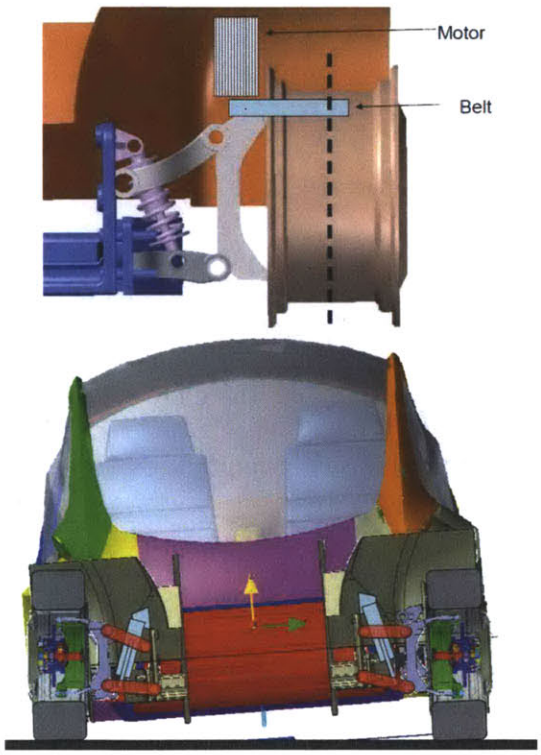


Figure 3-14: Initial supplier Robot Wheel proposal

3.2.2.2 Satisfying Functional Requirements

The propulsion system of the Robot Wheel can utilize different types of motors – from cylindrical shaped high-speed brushless direct current (BLDC) commercial motors, to specialty high-torque hub motors. With several types of independent suspension options at disposal (MacPherson, wishbone, trailing- and leading-arm), the configuration of subcomponents can take on many forms also. When crossed with even more options for brakes and steering actuation, the net number of options quickly escalates. The folloing image illustrates just some of the design options for Robot Wheels. Over a dozen versions of Robot Wheel concepts have been developed either by the MIT Media Lab research group or through collaborative projects, each with different tradeoffs.

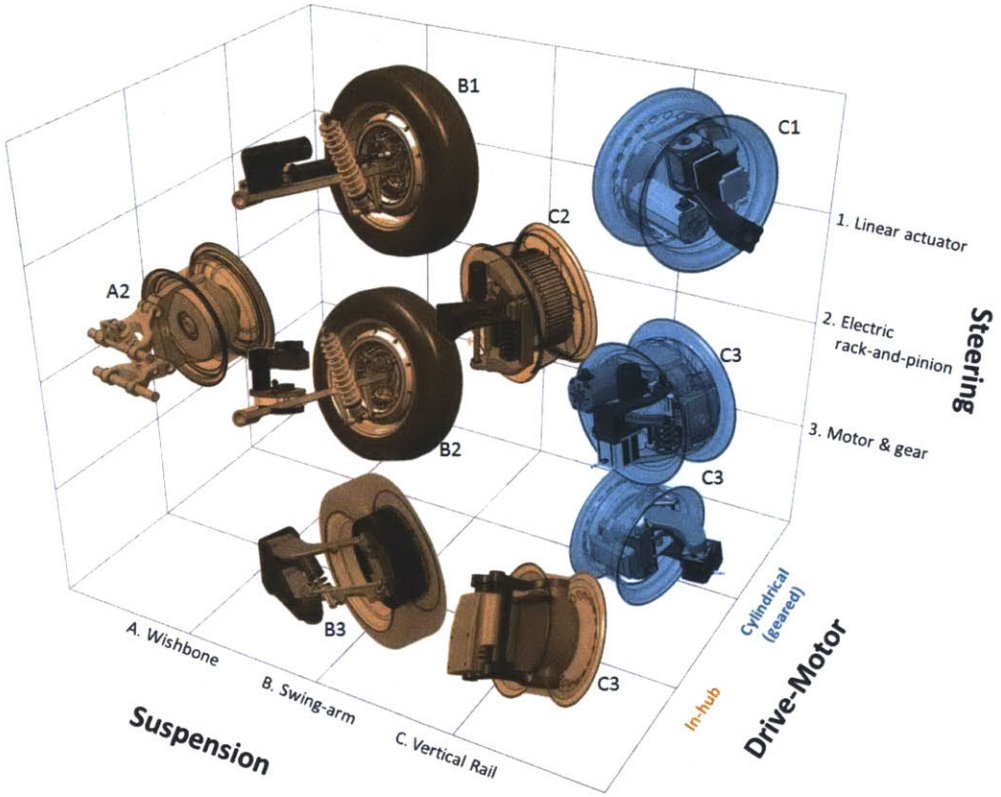


Figure 3-15: Robot Wheel matrix

Aside from optimizing the packaging and motor specifications of the Robot Wheel, considerations of the module's effect on the vehicle's other functions must also be preserved. Therefore an evaluation matrix was developed during the CityCar industrialization to ensure all core features and functional requirements were met. The most promising designs A2, C3, C2, and B1 were assessed respectively. The following establisehed CityCar core features from were used as a baseline guide for all evaluations:

1. Wheel Robots - In-Wheel electric motor module with embedded suspension, electronic braking, and independent electronic steering system.
2. Front Egress - Frontal entry system that integrates front windshield, driver controls, and accommodates easy ingress/egress for passengers.
3. Folding Chassis - An actuated folding mechanism connects the front passenger cabin with rear storage module.
4. Drive-by-Wire - Vehicle control system built upon FlexRay and CAN bus technologies.
5. (Included characteristics) Communications with GPS integration in the city – Smart Interface inside vehicle (not interlinked with points 1 thru 4). Plus sensing necessary for autonomy.

Brief desciptions were generated within a matrix for the lead Robot Wheel designs that were up for debate – analyzing each one's benefits and drawbacks according to the following fucntional requirements. Matrix Topics addressed design & packaging, development & manufacturing, function/capabilities, and modularity

The analysis highlighted some of the following conclusions:

- Compact suspension solutions would be critical to accommodate the large rectangular battery packs.
- Suppliers were most interested in owning and controlling the propulsion motor technology
- An additional connection plate was unlikely to be used, so a suspension type that was inherently simple in its connection would have to be used to expedite module swapping.
- Steering solutions were continually addressed last in the design process of the Robot Wheels. This misdirected focus typically resulted in incomplete and incompatible proposals. [Steering integration was the most difficult challenge.]
- Ability to manufacture within the supplier's capacity quickly became more paramount than reducing part count and simplifying the module. Many compromises were accepted to enable manufacturability.
- The O-turn feature would require each wheel to turn ~70-degrees – skid-steering would provide inaccurate movement since it relies on slip movements.
- 200 mm minimum suspension travel would be required from the Robot Wheels
- Although the simple elegance of the hub-type motors is an attractive solution, there are significant weight disadvantages that may be unacceptable for a 450 kg micro-vehicle. (The Hiriko vehicle was developed under the European quadricycle[33] classification which set particular weight and power limits.)

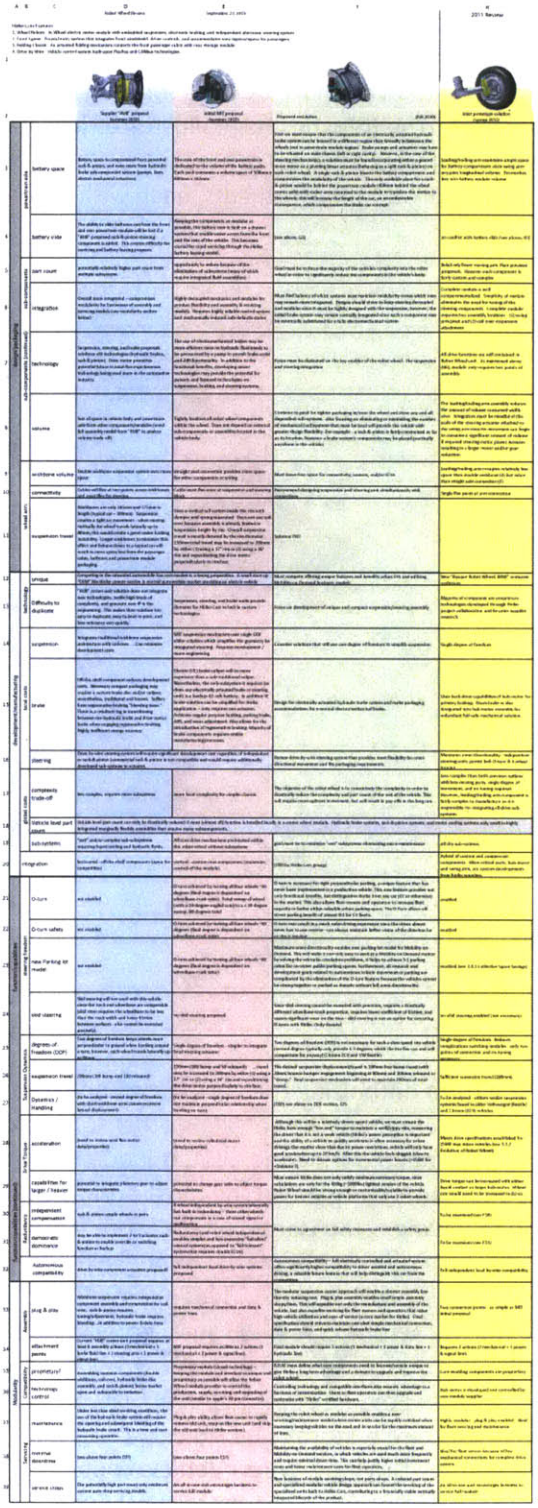


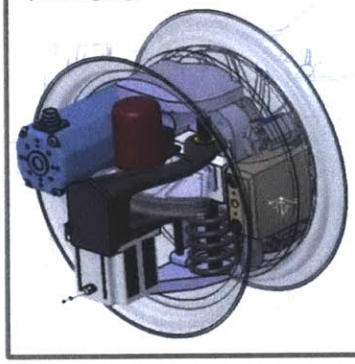
Figure 3-16: Robot Wheel analysis chart

[33] (European Commission, 2009)

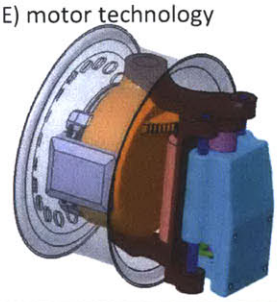
The following chronologically illustrates some of the major design milestones of the Robot Wheel during the Hiriko project:

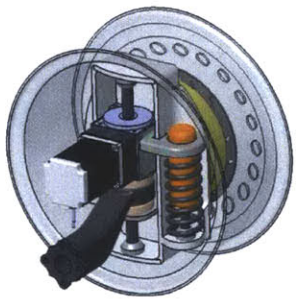
Will Lark & Raul-David Poblano build and ship Robot Wheel prototype to Spain to demonstrate general features.

Will Lark designs vertically suspended Robot Wheel in order to minimize scrub radius and maintain compact packaging.



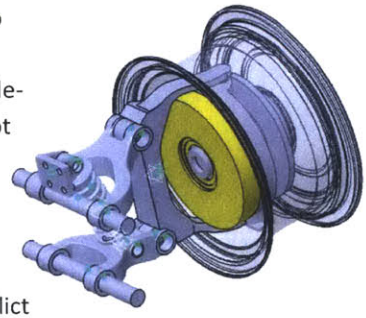
Patrick Hasselt from Epsilon/Hiriko designs vertical suspension RW with Will Lark in order to incorporate supplier's (CIE) motor technology

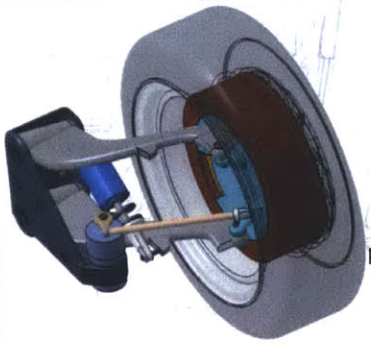




Will Lark adjusts design of vertical suspended Robot Wheel to incorporate supplier's (CIE) motor technology.

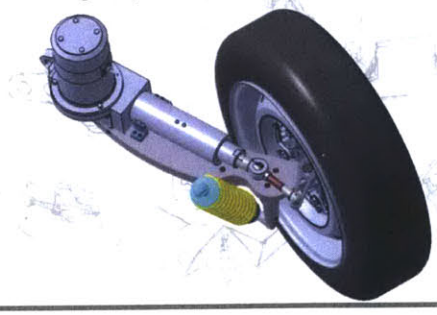
Potential Hiriko supplier (CIE) proposes double-wishbone Robot Wheel that utilizes their hub-motor. Design creates packaging conflict





Will Lark works with Eduardo Perez from Epsilon/Hiriko to develop dual-leading-arm suspension solution to reduce packaging conflict and accommodate hub-motor from supplier.

Will Lark, Eduardo Perez, David Cameron, and Raul-David Poblano collaborate on leading-trailing arm RW that decouples steering suspension uses 2 connection points.



Hiriko supplier, SAPA, develops prototype robot wheels for testing based on prior leading-trailing suspension solution

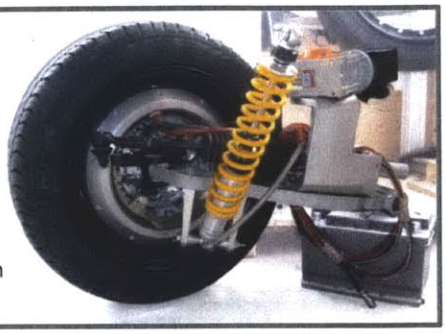


Figure 3-17: Development milestones of Robot Wheel during Hiriko project

Final Robot Wheel Developed

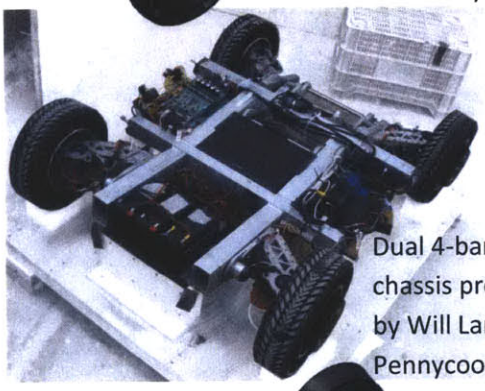
Through further understanding of all core functional requirements of both the Robot Wheel and its surrounding modules of Hiriko, a unique solution was developed to capture the most essential benefits previously established.

Figure 3-18: Final Robot Wheel developed

The Leading/Trailing arm type of Robot Wheel demonstrated all of the following potential advantages:

- Plug-and-play: single primary mechanical connection with suspension strut (2 connection points)
- No need for tuning or adjustment of steering or suspension (once module is optimized)
- Integration of commercial half-rack-and-pinion – robust and reliable steering assembly
- Outward rotor hub motor provides inner space for central kingpin (reduce steering motor loads)
- Scrub offset equaled 20 mm which required 280 Nm of steering torque
- Packaging compatible for safety redundancy of mechanical drum brake
- Sufficient space for front and rear accessible battery modules
- Use of commercial suspension coil-over
- Compatibility to commercial steel wheel
- All dry components reduce maintenance and need for additional auxiliary subsystems
- Repeatable swing arm: front right & rear left are same and can be reassembled for mirror side

Initial 4-bar folding chassis by Will Lark



Dual 4-bar folding chassis prototyped by Will Lark & Nick Pennycooke

Refined digital chassis design by Nick Pennycooke

Final chassis by Hiriko engineers using prior designs

3.2.4 *Folding Chassis Implementation*

Previous folding chassis concepts for the CityCar have been developed at MIT, and other commercial concept concepts have addressed the issue of vehicle folding for reduced space while parking (*reference: Renault Zoom 1992*). However, most of these concepts exploit a single pivot arm to lift and tilt the body of the vehicle. This method, while perceived as simple, is by nature very limited and poses greater technical difficulties in execution. In order to achieve the wheelbase reductions garnered by the proposed invention, a long single pivoting arm is needed, which will lift the majority of the vehicle's mass up significantly, and restrict chassis packaging and steering maneuverability. The dual 4-bar linkage system instead decouples the rear cabin onto the rear 4-bar mechanism which conserves energy since it translates many of the heavy load components, all while maintaining the relative kingpin (wheel steering axis) position - giving the vehicle total maneuvering capabilities during any state of its fold.

Also early empirical experiments of scaled models show that the distribution of weight between the front and rear cabin allows the folding mechanism to behave as an energy absorbing component for front and rear impacts/crashes. Although more thorough and extensive testing is required to prove commercial viability, preliminary testing shows that exploiting this type of folding chassis in a front or rear impact scenario may be able to reduce the rate of the deceleration in the passenger cabin. Particular linkages may also be strategically designed to compress or fail, acting as dynamic crumple zones, thus reducing crash force transmission to the passenger cabin.

Figure 3-19: Folding chassis development

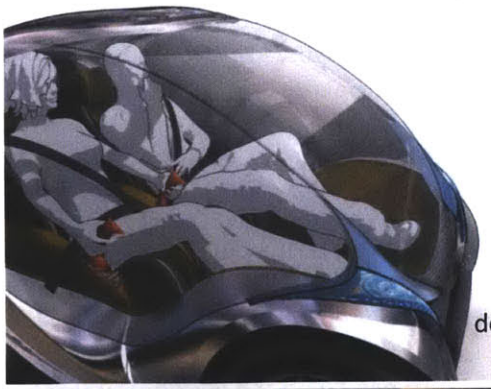
The folding chassis of the Hiriko reinforced that such a feature would sufficiently reduce the footprint of the vehicle without compromising the mission-critical components. The kinematic model of the chassis was adjusted to accommodate a repeatable powertrain axle assembly. This mirrored axle assembly allowed for savings in development costs; however this adjustment to the geometry resulted in consequences in its space savings. With each powertrain assembly 750 mm in length and 170 mm of front and rear buffer space, the 2,630 mm vehicle length was only able to shorten to 2,000mm (15% less than the initial CityCar chassis).

Folding Chassis

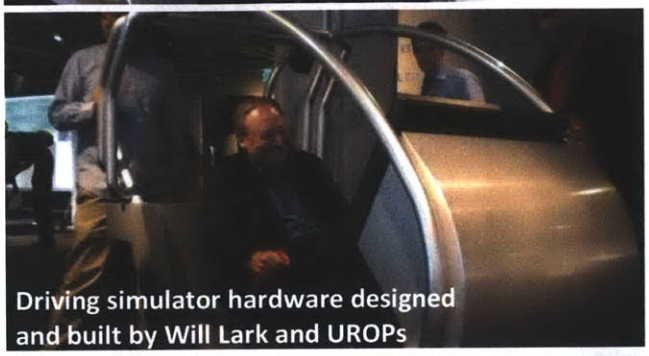
	CityCar concept design	Hiriko commercial prototype
Space Savings	40%	25%
Manufacturing method	Ladder frame	Tubular space frame
Dual 4-bar linkage	Primary rear powertrain with rotating front axle	Mirrored powertrain axle
Actuation	2 linear actuators	2 linear actuators
Fold time	5 seconds	20 seconds

Table 3-2: Folding chassis comparison

The folding feature is a core element of the Hiriko vehicle. Although it also contributes to the eased front entry and exit, improving the percentage of footprint reduction will be essential to justifying its complexity. Reducing the length of each battery module is one method to compressing the vehicle even more. One other aspect that can benefit from design improvements is the actuation of folding. The current Hiriko linear actuator each require up to 10kN of force to initiate the fold, costing over $1000 for suitable linear actuators. However passive tension springs could drastically reduce the load requirements of each of the actuators in a similar manner that a garage door spring counterbalances the door's weight.



Joystick driver interface designed by Will Lark



Driving simulator hardware designed and built by Will Lark and UROPs

Joystick test conducted by Hiriko

Electric wheel sketch for SAPA by Will Lark

Electric wheel by SAPA on prototype

Figure 3-20: By-wire driver interface development

3.2.5 *Electronic Driver Interface*

Since the CityCar is a full drive by-wire vehicle (throttle, brake, and steering), the human machine interface (HMI) had to also be developed since a traditional mechanical rack-and-pinion wheel would serve incompatible. The initial CityCar design incorporated a dual-joystick driver interface in which the operator would simply press forward, backwards, left and right to navigate the vehicle. The interface also opens up much of the space within the passenger cabin, allowing a relatively micro sized vehicle to feel much larger (no steering wheel, steering shaft, or dashboard). The joysticks that frame the driver's seat also ease front entry and exit. The minimal controllers create a more seamless transition to eventual automated driver's assist and complete autonomous systems.

This interface was tested by means of a museum installation in which visitors could interact with a driving simulator to get a feel of how a potentially novel controller would behave. Both in concept and in the driving simulator, the left and right joysticks moved in unison, allowing the driver to control the vehicle at any time with either hand. From observing dozens of volunteered visitors that tied the dual joystick simulator, it became clear that a similar type of controller would be suitable for a slow speed city vehicle. Young teenagers adapted to the interface the quickest as middle-aged participants were more apprehensive. Surprisingly, more elderly participants were fairly comfortable with the unique controllers as it required reasonably little dexterity.

During the design phases of Hiriko different studies were conducted to test the feasibility of a joystick-type controller. Therefore driver tests and surveys were conducted on a retro-fitted automobile that incorporated a small joystick (5" in length) in the center of the console used for disabled drivers. The left and right steering were mapped normally to the left and right tilting of the joystick; whereas the throttle and brake were inverted to ensure that forward-generated g-forces when braking only reinforce the braking motion and do not induce acceleration. With the throttle and steering oppositely mapped, controlling a full sized automobile with a mini-sized joystick proved

confusing and intimidating. Most participants in the study felt fairly uncomfortable with the interface. Afterwards, the driving instructor did inform that most users that become trained to drive this vehicle require around 50 hours before they can become competent and comfortable. Ironically, similar to the museum simulator, the best driver from the 30+ participants on the test track was a 12-year-old who obviously had never driven an automobile before, but was very familiar with video game controllers.

Electric wheel design by Will Lark and Marie Le Monnier (ETUD)
Built by SAPA

Figure 3-21: Hiriko human machine interface

The final driver interface that was on Hiriko utilized wheel-like HMI. The wheel incorporated both a thumb activated throttle paddle and a brake paddle on the back of the wheel activated by the drivers fingers. The wheel turns only 90-degreed in each direction, compared to a traditional steering wheel that offers three to four times more rotation. The limited angle of rotation requires a more precise input from the driver since the smaller angle range must be mapped onto the same driving wheel movement. Additionally, placing a wheel in front of the driver now created an obstruction of the front entry and exit. A pivoting cantilevered arm was integrated into the middle console to move the controller in and out of position as needed.

As developers performed driving test with this new Hiriko interface, a couple of key points were learned:

- Small steering angles were sufficient for directional control in open environment. This interface would need to be tested on more narrow street/paths.
- Lag in steering system requires driver to project and predict trajectory.
- Lack of force-feedback proved uncomfortable and unsettling for vehicle control.
- The throttle and brake by hand is suitable for short distances; however, fatigue could set in after about 15 miles.

Electronic Driver Interface

	CityCar	Hiriko	Conclusions
Core platform	Full electric by-wire No mechanical connections	Full electric by-wire No mechanical connections	1. Feasible for commercial applications 2. Micro-vehicle category provides more leniency 3. Redundant system in need of development
Human machine interface	Dual joystick Open interior	Haptic Wheel Pivoting cantilever arm	1. Wheel more intuitive than joysticks 2. steering wheel pivot arm complicates design of interior 3. steering wheel and arm create inconvenient obstruction for entry and exit 4. joysticks can be easily adapted by too expensive and requires more precise input from driver
Driver feedback	**Driver simulator developed for MIT museum** 1. Fairly intuitive 2. Youth: simple for to learn 3. Middle-age: more apprehensive 4. Elderly: simple to use because of eased dexterity **Retro-fitted automobile with single central joystick for disabled drivers** 1. Similar findings from museum simulator (easily adapted by young drivers) 2. Inverting steering and throttle make vehicle difficult to drive 3. Small joystick requires too much precision for full size automobile	**Electronic wheel on Hiriko** 1. Small steering angles are sufficient. 2. Lag in steering system requires driver to project and predict trajectory. 3. Lack of force-feedback uncomfortable and odd to control. 4. Throttle and brake by hand is suitable for short distances. Fatigue could set in after 15 miles.	1. Electronic interface (joystick or wheel) needs some type of force feedback 2. Cruise control feature could assist in reducing hand fatigue from throttle and brake paddles 3. Increasing the steering angle from only 90-degrees clockwise and 90-degrees counterclockwise to 120-degrees in each direction could improve steering precision

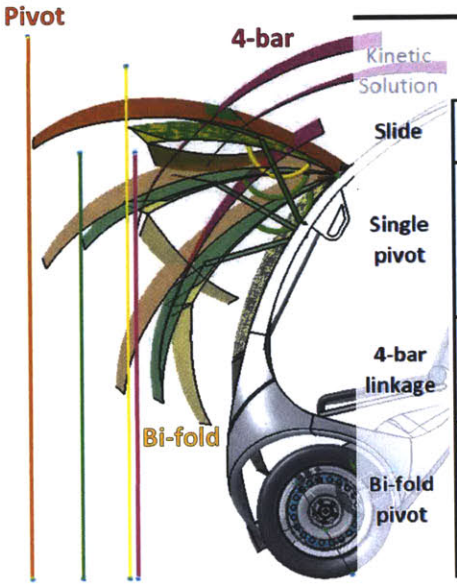
Table 3-3: Electronic driver interface comparisons

3.2.6 *Front Entry Solution*

In an effort to reduce the cost of the Hiriko vehicle, the front door utilized a single upper pivot to rotate it upwards in a similar fashion to an SUV's tailgate. Gas dampers were used to assist in the lifting of the door. However with the large size of the door, this solution results in considerable consequences of weight and size.

Figure 3-22: Front entry development

Even though the folding chassis reduces the size of the vehicle, the door requires over 800 additional millimeters of space in front of it. This can cause a conflict with elements on the sidewalk such as trees, parking meters, mailboxes, or other objects within the city. The single pivot door also creates an awkwardly large sweep that the occupant must back up from when entering the vehicle. Closing the door once in the vehicle becomes even more difficult since passengers must stretch out to reach the raised door.



Front Entry Solution

Advantage	Drawbacks
Most compact. 0 mm opening sweep.	Requires uniform curve (consistent guide rail).
Most simple. Robust.	Heavy. Large opening sweep - 825 mm Requires most room in front. Most awkward - difficult to open from outside and inside the vehicle.
Second most compact solution. 300 mm opening sweep. Single door panel.	Laterally less stable. Awkward path of movement for users.
Similar robustness as single-pivot solution. Comparable door sweep as 4-bar linkage solution. 300 mm opening sweep.	Split in door requires additional seal.

Table 3-4: Front entry solution

3.3 Stakeholder Feedback

3.3.1 Automotive Expert Interviews

Following the CityCar developments – designs, prototypes, and Hiriko – multiple senior automotive experts were interviewed in order to gain qualitative feedback concerning various aspects of the vehicle. All interviewees have over 30 years of experience working directly for American automobile original equipment manufacturers. Each participant was informed that their identities would remain anonymous in order to maintain frank and open discussions for the purpose of gaining constructive feedback. Each interview lasted roughly one hour; therefore key quotes were extracted for the purpose of evaluation. A more comprehensive version of the discussions can be found in appendix 7.K.

3.3.1.1 Industrial opportunities for CityCar

Most of the automotive interviewees share the belief that we are approaching a time where alternative modes of personal transit are needed in overcrowded cities worldwide. Their perspectives do vary however on how urgent the need will impact the fundamental technologies within the automobile. While some believe that supporting markets will mature enough to proliferate the amount of fully electric vehicles over the next five years, others pragmatically expect incremental shifts over the next 10 to 15 years.

	Topic	Feedback Summary	Quotes	Conclusions
MIT CityCar/Hiriko Industrial Effort	Unique Hiriko business model	Potential exists for small companies to break ground in electric vehicles. Recommends approach similar to consumer electronics industry.	"Those models (small EV companies like Tesla and Fisker) are becoming more feasible and possible."	There are opportunities for new business models in the electric vehicle sector. Just as most new or disruptive technologies, smaller newer companies have the flexibility to assume the risks and can prove to be a real advantage if they can be first to market and own the new domain.
			"This initiative in the Basque region is pretty interesting to see how it plays out ...because if it does work out to be safe robust reliable system that they can actually deploy it then that removes some of the excuses to why you shouldn't do it that way."	
			"The main theme was maintained throughout the project. ...The concept was faithfully done in the Basque region. I thought they really did a great job."	
	Disruptive Technologies found in CityCar	Established industries have less incentive to risk resources on disruptive technologies.	"They (OEMs) don't handle it (disruptive technologies) well. ...The guy that's going to do the best, is the guy that's desperate. The guy on top isn't going to risk it. And it's good form. It's true, if you're the leading manufacturer ...what is the motivation to gamble when you're on top?"	The newer business who has less to lose will be at an advantage if the development of CityCar/Hiriko's modules is executed properly.
	Alternative mobility solutions	CityCar features are appropriate for cities, just may be a longer time to see them in effect. Change happens slow in automotive industry.	"But in terms of working inside of a city center like the MIT car – the folding , the grid, being able to get into the car, being able to move to your individual spots – I think those things will happen – as you know in Europe there already areas that you can't bring your car into the city center ...but it's still going to take a long time"	The technologies in the CityCar have real potential for success particularly in crowded cities in which their current modes of transit are proving unsustainable. Although unique, each of the CityCar features are feasible and if properly developed, viable. However, making a significant impact in the automotive sector is extremely difficult. Because of long established supply chains and infrastructures, changes will only be seen slowly and incrementally. Fundamental radial changes will only come from newer start-ups who define their own processes.
			"Finding creative solutions to handle personal requirements within the city I think you know- the vehicle that was developed by MIT does a great job at that [with] the stacking, the charging, and contributing back to the grid..."	
			"Now from a transportation standpoint, if you're talking about urban areas, there are going to be more constraints on cars and parking and road pricing. ...so twenty years out there are range of scenarios, one of those being people are going to be doing more car sharing, pay-per-use type thing; but one has to figure out what are the inflection points to do that."	

Table 3-5: Automotive feedback - Industrial opportunities

Most do agree that there are currently strong opportunities, now more than ever, for new business models in the electric vehicle sector. But just as with most new and potentially disruptive innovations, such a venture will likely be taken on by a new player to the market – such radical vehicles will not come straight from the automotive sector. If an enterprise can master particular technologies for future electric vehicles – such as the Robot Wheels, by-wire platform, or methods for micro-footprints – they will be at a significant advantage when larger markets are ready to embrace them, such as growing cities in China. Larger manufacturing markets overseas are ramping up their competencies within the electric vehicle sector. The aggressive securing of battery technologies by multiple Chinese companies demonstrates this foresight.[34]

[34] (Ramsey, 2012)

Similar opportunities for technology buy-outs can become present for electric vehicle propulsion systems and other equipment supporting urban vehicles.

Participants believe that the core technologies within the CityCar/Hiriko, such as the Robot Wheels, by-wire platform, and micro-footprint will eventually make their way to the mainstream market, but as before, it may take a substantial amount of time to do so.

Key Points from interviewees concerning industrial opportunities

- CityCar's platform architecture can be viable more so for a new small business as it is lower risk and satisfies niche needs in crowded cities.
- CityCar's disruptive technologies can be at an advantage for small EV market, but it will be difficult to gain significant shares of automotive market which has well established supply chain
- More time will be needed to observe the successes of small EV companies like Tesla and Fisker before fundamental transformations trickle to the automotive sector

3.3.1.2 Exploiting Opportunities Granted from Modularity

Discussing the potential opportunities that could come from the vehicle's high level of modularity unveiled more benefits internal to the manufacturer than the individual customer. Assemble-to-order vehicles however can be very valuable to larger customers, such as fleet operators for shared mobility services, as roughly two-thirds of participants expressed practical value in the ability to customize their vehicle features (appendix 7.M). Single end users are less likely to take advantage of the combinatorial options. The business advantages perceptible to customers will instead come through the form of electronic personalization - being able to customize to behavior and integration of the vehicle to each driver.

The modular core electric backbone allows the uMEV vehicles such as the CityCar to achieve a high level of platform flexibility. However, there are still substantial risks involved in substituting mechanical components for all electronic ones. Multiple redundancies must be incorporated and fail-tolerant countermeasures need to be employed to ensure at least the same, if not better, reliability is achieved than today's traditional automobiles. It may just be a matter of time before the replacement of mechanical systems is more commonplace since they are increasingly present in many complex systems, such as aeronautics. The success of autonomous drive systems may be a key technology needed to proliferate by-wire vehicle systems. Done successfully, autonomous navigation will reduce the error from the human element and its need for electro-mechanical actuation will further reinforce the reduction of mechanical components.

One of the key benefits of the uMEV vehicle architecture, and modular products in general, is the accelerated parallel development. Clear boundaries between subsystems allow different modules to be worked on concurrently. As witnessed throughout the Hiriko project, the all-electric modular architecture did reduce necessary interactions between the suppliers. Suppliers were able to execute design and engineering relatively independent of each other, only requiring the occasional update of shared specifications where the modules would intersect.

	Topic	Feedback Summary	Quotes	Conclusions
Exploiting Modularity	General Benefits of Modularity	Have to take advantage of modularity for (1) cost savings and (2) customization	"I think you have to, it's like evolution – there's variation, and then natural selection follows. If you don't, it's like the Model-T issue. Ford ran [the Model-T] wild because everyone was buying it, but after a while people were like that's not what I want because these alternatives are better. ...there was like an 18 month period to retool beyond the Model-T just to get back relevant in the market."	The initial benefit of modularity are likely to be employed behind the scenes in the manufacturing and integration processes of the vehicle. The business advantage perceptible to customers will come through the form of electronic personalization - being able to customize to behavior and integration of the vehicle with each driver. Exploiting modularity to offer assemble-to-order vehicles may not be important as initially perceived. However, assemble-to-order vehicles can be very valuable to fleet operators for shared mobility services (as roughly two-thirds of participants expressed practical value in the ability to customize their vehicle features).
			"...however the electrification aspect; some of the designs that you guys have done are actually compelling because it's like a whole clip - the propulsion, steering, the suspension are all one module that you just hang on the vehicle and those are interchangeable corners so that's good. ...which is dramatically different than an internal combustion engine so there could be some savings from that standpoint."	
			"Much more customization. The days of just picking a car from these nine options – I think someone is going to decouple that and say here's 800 apps that you can have for your car, each one cost you $2/year. Which ones do you want? ... I think you're going to see it customizable on the initial purchase, I don't think you're going to see it reconfigurable."	
	Electrification & by-wire systems	Electrification does have the potential to reduce cost but you have to find other compelling motivations, like autonomy, to justify the safety risks.	"It's my opinion and experience that the electrification of al lot of these traditional mechanical elements is actually in the longer run lower cost – initially it might be a bigger investment but if you get the volumes up – like the cell phone or consumer electronics industry ...the analogy is similar, not exact, but similar. ...They might be some players that say "I will own the space around wheel robots ,or whatever it is," and they get the cost down and the industry to adapt it perhaps and then it becomes less of an impediment."	There are still substantial risks involved in substituting mechanical components for all electronics one. Multiple redundancies must be incorporated and fail-tolerant countermeasures need to be employed to ensure at least the same, if not better, reliability than today's traditional automobiles. Electronics systems are evermore present in many complex systems (aeronautics for example); therefore, it may just be a matter of time before their replacement of mechanical systems is more commonplace. The success of autonomous drive systems may be the technological inflection point needed to proliferate by-wire vehicle systems.
			"You're not just going to see it just because. ...Now with by-wire systems, unless you're going to get into autonomous vehicle systems where the car can drive itself, now the motivation for by-wire becomes much greater. ...Unless it's better or more reliable, why would you do it?"	
	Challenge of Integration, verification, and liability	Very difficult to change supply chain. Incentives from modularization must be for manufacturers because customers are not concerned with how it gets built.	"If you modularize things you can speed up production. ...for example the supplier responsible modules showing up at the plant – the whole instrument panel cockpit or the whole propulsion system for example."	The Hiriko project reinforced some of the feedback from the automotive experts - it is very challenging to change approaches and procedures between manufacturers. However, the completely new platform of the CityCar, enabled the collaborative efforts to start from a clean slate, and the all electric modular architecture did reduce necessary interactions between the Hiriko suppliers. Suppliers were able to execute design and engineering relatively independent of each other, requiring occasional update of shared specifications (interfaces/borders).
			"...the biggest issue is the legacy issues around [the modules] – supplier agreements, labor unions ... and then how do you design the interfaces.	
			"...as long as it performs to a prescribed specification I'm not sure people care where it comes from. The most critical part of a car is integration."	
			"[To the consumer what's important is] what is looks like, how to integrate all the componentry, and how to establish, nurture and promote the brand"	
	Expanding the Supplier's Role	Few components (perhaps only engine and body panels) are built in house anymore - suppliers build everything. More horizontal integration.	"From and OEM's perspective you'd rather have fewer suppliers involved in larger contributions"	Clearly the Model-T days of vertical integration are long gone and dozens of players are involved most complex products. The Hiriko project begins to hint at potential open development in which a module supplier could take the initiative to innovate a variety of solutions that are compatible with the interface and greater functional requirements. However the necessity of an integrator to verify that all systems are functioning and communicating properly will remain crucial in systems where safety is paramount. Therefore the role of the integrator, be it an OEM or its equivalent in the case of Hiriko, will always be necessary even in the most open technologies.
			"...the vertical integration has continued to become more and more flattened out and horizontal and certainly the future I think is more horizontal integration where a number of players have a responsibility, commitment, and investment into the final product."	

Table 3-6: Automotive feedback - exploiting modularity

As we see an era where manufacturing is global and product development is more horizontal than ever, the Hiriko project begins to hint at potential open development strategies. A module supplier has a platform at their disposal to innovate a variety of solutions that are compatible with the interface and overall functional requirements. Still, an essential integrator must verify all system functions and communications to ensure robust reliability. Therefore the role of the integrator, be it an OEM or its equivalent (in this case of Hiriko) will always be necessary even in the most open technologies.

Key Points from interviewees on modularity

- CityCar's modular platform can reduce development costs
- Semi-open vehicle platform enables suppliers or core module manufacturers to initiate innovation
- All electric platform will reduce costs over time but must be made reliable
- Autonomous driving technologies may be an assisting key technology for future commercial development of by-wire systems
- Modular uMEV can speed up production and reduce development costs, and increase contribution from supplier; however, integrators must be careful about legacy issues that result from modules

3.3.1.3 Expanding the Role of the Supplying Manufacturer

It was stated best that interactions between original equipment manufacturers and their suppliers are "hostile at least and downright war at best." The last section of the interviews focused on improving the relationships between both parties by finding opportunities that could be found in the uMEV CityCar modular platform. One of the key motivations behind the CityCar and Hiriko projects was to enable bottom-up innovation – allowing suppliers to initiate new technologies in a relatively more open manner.

	Topic	Feedback Summary	Quotes	Conclusions
Further integrating the Supplier into the development process	OEM-Supplier Relationships	Contentious	"It's hostile at least and downright war at best"	Model must be reexamined to keep local manufacturing of high-quality products.
	Profit Sharing	Modular ownership requires business model equity based on contribution	"...Also how do you balance the profit sharing if the supplier is taking on more responsibility"	In order for suppliers to change from their traditional roles and become proactive module manufacturers, they will have to become invested stakeholders. Module developers must be properly incentivized in order to innovate on the behalf of the CityCar.
			"The only way that you can have a fully integrated supplier is if the amount of money that the supplier get is a combination personal earning of his products and the vehicle profit. If he doesn't have a stick on both of those games, he's only going to play in the game he's got money in."	
	Supplier Driven innovation	Given the proper environment, innovation can and does come from the bottom up in the automotive sector	"...in fact depending on the financial climate that OEMs and supplier will be working on in the future and how much more responsibility that the supplier takes I think that we'll see more innovation coming from the suppliers."	Suppliers are at the ground level of most technologies and well equipped to lead new innovations. However their priorities focus resources on driving volume and maintaining their already razor-thin profit margins. Given the right incentives, whether it be (1) a percentage of unit profits, (2) greater amount of subcomponent responsibility, or even (3) participation in the design and development process of the vehicle, R&D efforts may be refocused and reinforced. Combining all three incentives could create the best lab environment for new module technologies.
			"We've done things like integrated suppliers at the design phase, at the engineering phase, and at the build & assembly phase we've run those trials. And Volkswagen has also done similar tests. ...it's feasible. On a lower volume it might be a safer lower risk way to go. And that's why this initiative in the Basque region is pretty interesting to see how it plays out. ...because if it does work out at that level where the stakeholders are getting their value capture it a robust reliable system that they can deploy, then that removes some of the excuses that have been thrown out to why you shouldn't do it that way."	

Table 3-7: Automotive feedback - Expanding the supplier's role

In many cases the suppliers are more than competent to lead the innovative efforts as they are on the ground level of most technologies and well equipped to lead new advances in vehicle components. However because of their relatively less stable position in the automotive sector and razor-thin profit margins, the overwhelming majority of their resources focus on driving volume and maintaining the slim revenues. Some incentives to encourage and justify larger R&D efforts could include: a percentage of unit profits, greater amount of subcomponent responsibility, or even participation in the design and development process of the vehicle. Moreover, combining all three incentives could create a more ideal scenario for a test lab environment of new CityCar module technologies.

<u>Key Points from interviewees on supplier's role</u>

- Automotive suppliers are struggling to survive even more so than OEMs with slim profit margins
- In order for suppliers to change from their traditional roles and become proactive module manufacturers, they will have to become invested stakeholders.
- Module developers must be properly incentivized in order to innovate on the behalf of the CityCar.

3.3.1.4 Key Concluding Points

- Although opinions are mixed on the perspective of rate of emergence, electric vehicles will continue to proliferate. Companies that master the key technologies such as the Robot Wheel (or similar modules) will be at a substantial advantage.

- Most key benefits from CityCar's modular platform can be advantageous to Hiriko's business model. Still developers will have to be very attentive to integration and validation. Also, embracing to rigorous a standard can lead to binding legacy issues down the road.

- End users will be less concerned or even interested in the flexibility of the modular platform. Manufacturers can leverage this feature to provide custom fleet vehicles to larger service providers. Modules are unlikely to be exchanged during the lifecycle of the vehicle for customization purposes. Servicing however can still prove beneficial.

3.3.2 *Input from Module Manufacturer*

Following the development of the CityCar concept, Hiriko, the core Basque engineers from each of the module developers were asked to participate in an online survey. The twenty questions addressed potential benefits of modularity, opportunities for customization, prospects for leveraging and expanding their core competencies, and details on their perspective modules. The survey was offered in both English and Spanish (Castellano).

Concerning the features of the CityCar, Hiriko manufacturers had mixed perspectives on the viability of each. The core features of folding and maneuverability from the robotic wheels are generally viewed positively. Three-fourths of the Hiriko manufacturers do believe that the folding chassis is a business benefit; however, only one-third of those same respondents feel that it is an essential feature. The remaining quarter believe there is little to unfavorable impact on the vehicle. As far as the high level of maneuverability of the robot wheels (O-turn, tight turning radius, and 4-wheel steering), manufacturers unanimously agree that it is a beneficial feature. Nevertheless, 37% do believe that the benefit is marginal. The front entry of the vehicle holds similar opinion to the robot wheel maneuverability – all agree that it is a net benefit, but a little over a third of the manufacturers find the benefit marginal. Lastly, while over 62% of the module developers believe that the rear module adds value for customization, the remaining proportion believes there will be little to no impact from this module.

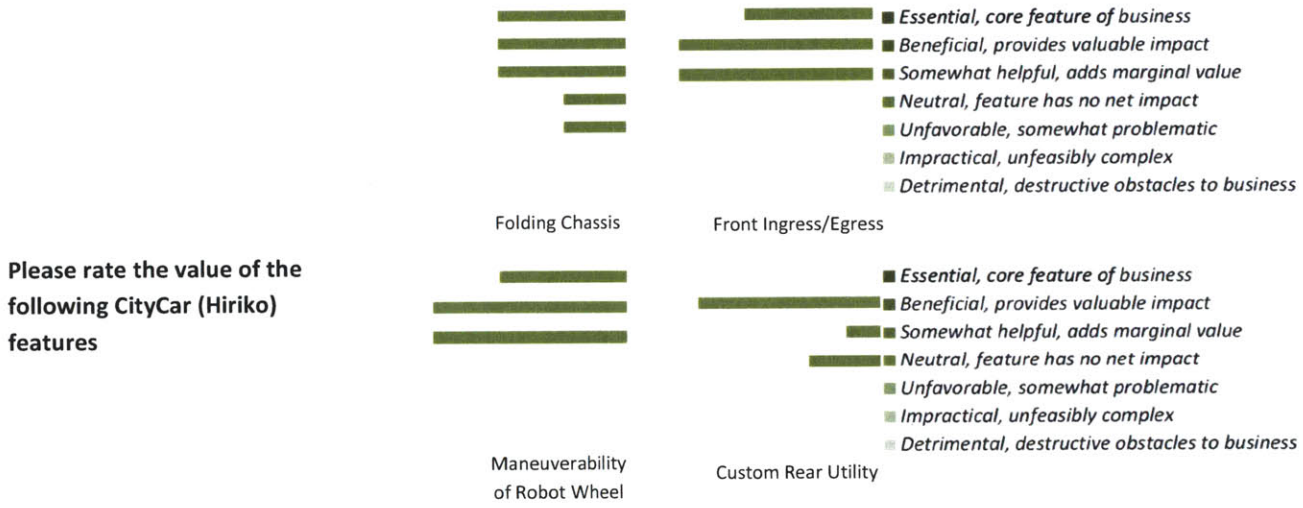


Figure 3-23: Module manufacturer survey feedback - CityCar features

Most manufacturer suppliers believe there are strong opportunities to customize their modules, especially the performance characteristics of the robot wheel and design aesthetics of the surfaces. This is especially important for most end users, as senior automobile designers will reinforce, that end users maintain an emotional attachment to the look and performance, or "feel," of an automobile. System control developers do see opportunities in after-market services that may be deployed to their modules. As control systems are software based, there are many opportunities to provide applications or "apps" to supplement their units. Using the vehicle as a platform for customized applications is an attractive approach as the vehicle becomes more and more electronic and mechanically flexible.

Figure 3-24: Module manufacturer survey feedback - chief questions

In general, most module providers believe there are opportunities in servicing their modules once they are in use. Nevertheless, they have mixed perspectives on the lifecycle management of their modules. While those involved in the robot wheel, chassis, and surfaces believe they can continue involvement throughout the lifespan of their modules, those responsible for energy management and control systems do not see the need for further interaction once the vehicle is assembled. This response is logical, considering control standards and energy platforms must remain robust, reliable and do not require alterations within the vehicle. Additionally, the electronics control backbone is not subject to the same wear and tear of traditional mechanical elements that require routine maintenance. Once electronic protocols are modified, these improvements are usually implemented in the next version or model of a vehicle.

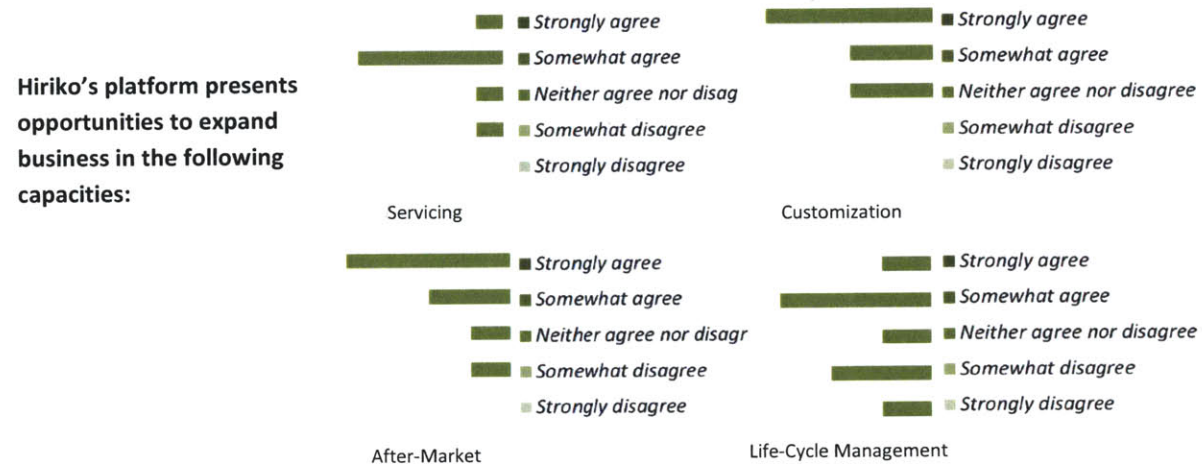
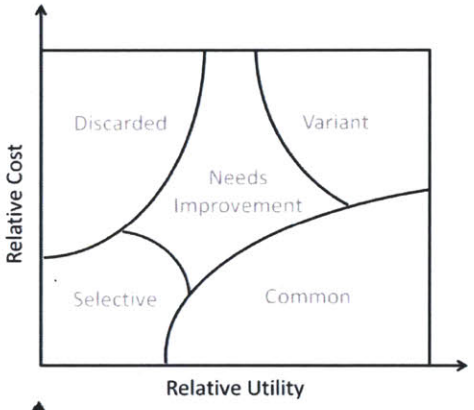


Figure 3-25: Module manufacturer survey feedback - business opportunities

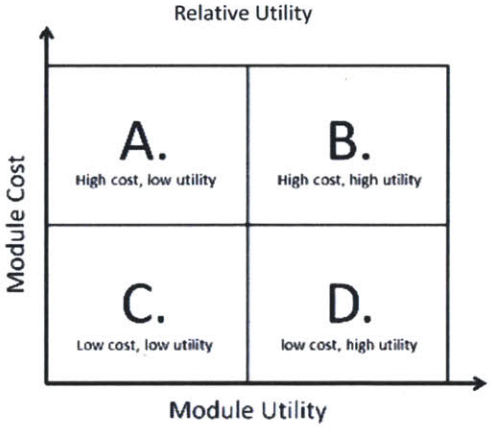
The battery module in a shared mobility vehicle is subject to much more frequent utilization. Shared mobility system experts insist that vehicles will need to be used at least 6-7 times more frequently in order for the service to be profitable. This frequency of utilization results in a higher turnover rate for its lithium polymer battery pack that typically needs to be replaces after a little over 1,000 cycles (charge and discharges). In order to maximize usage during the day, battery module specifications strive to accommodate a full day's use from one or two charges (for example 70 miles range per charge if given and average rental distance of 10 miles). Such frequent use of the vehicle's battery will result in module replacements every couple of years. This presents an opportunity for battery module manufacturers to be closely involved in the supply, servicing, and repurposing of these units.

3.3.2.1 Cost Utility Measurement

One of the metrics used to relatively compare each of the module's value is the "cost-utility plot," addressed previously in section 2.3). This measurement associates the relative functionality of a module at its comparative production cost. Modules that are low in cost but maintain high utility are viewed as "common" as they are cost-effective and enable stability within a product. Such modules should be reused as often as possible. More expensive modules with high utility are viewed as "variant" – they maintain their importance but are used more seldom because of their larger costs. Modules that are comparably expensive to develop but have significantly less function or utility are subject to being "discarded" since they maintain little value and are not cost effective. Cheaper modules with little utility are considered "selective" and are of low priority. They are generally less effective but can still be useful considering their low cost. Lastly, components that fall right in the middle maintaining significant utility but slightly higher cost than common modules fall into a vague category that "needs improvement." These modules require clever tactics to lower their cost or drastically improve their utility; otherwise they cannot be cost-effectively justified.



Manfucturer participants were asked to associate each module with a quadant in the following chart. For example, if a survey participant felt that the robot wheel module was reletively very expensive but added significant utility to the vehicle, they are likely to select quandrant "B." (Note, more answers could have been used in the survey by adding a mid-range options both in cost and utility, providing nine answers to chose from instead of just four. However, concerned that too many participants would select the easy middle ground, four options remained to solicit a concrete answer.)



Results from the survey entries reflect that most manufacturer tend to view most modules as expensive as 72% of all answers were in the "high cost" zone. Their perspective on utility was slightly more balanced as 57% of manufacturers

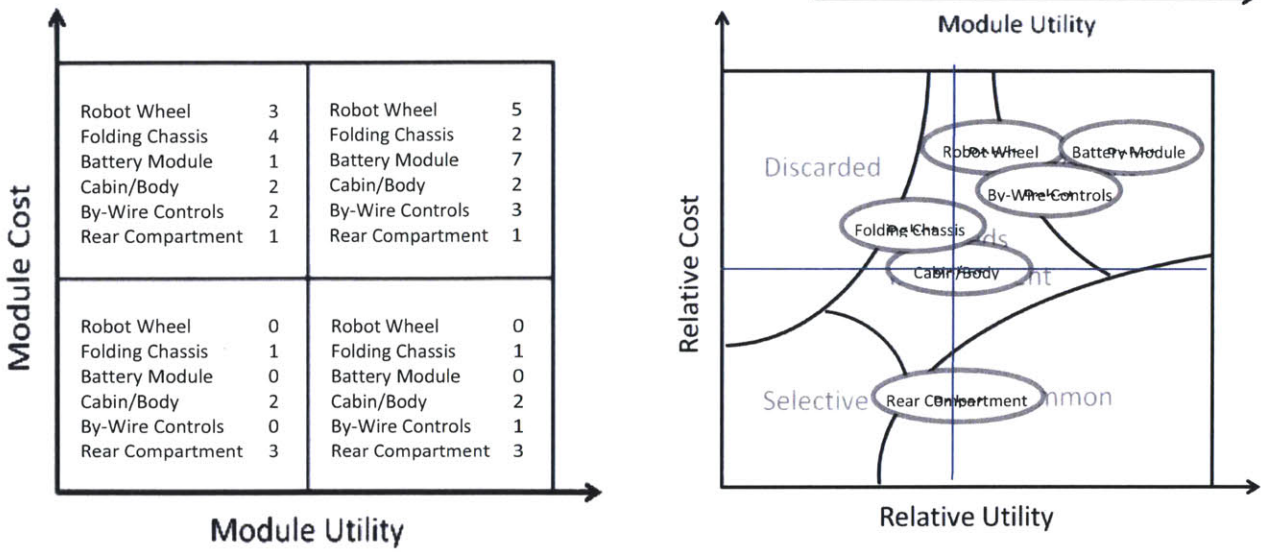


Figure 3-26: Module cost-utility plots from manufacturer feedback

viewed the various modules "high utility." When further analyzing the responses, each manufacturer tended to reflect a cost bias towards their module, each more likely to rate their model as high cost than others.

Since the measures of costs and utility are relative comparisons, the plot was adjusted to balance the majority of answers considered "high-cost" – resulting in most answers to be lowered and widened across the area. For the most part, the rear compartment and body are considered common modules, and the battery and by-wire units are viewed as "variant." The Robot wheel needs improvement as it is barely considered a variant module. The Robot Wheel is at risk of being discarded as the suppliers continue to value engineer many of the high tech functions. Unless costs are reduced or its functionality is significantly improved, the folding chassis is likely to be the first module to be discarded from the perspective of Hiriko suppliers.

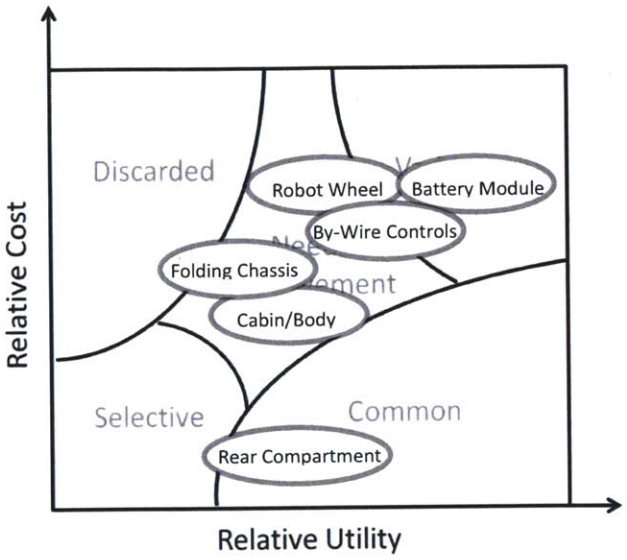


Figure 3-27: Module cost-utility plot from survey

As features continue to be improved and engineers frivolously find ways to reduce costs, there are strategies that may improve cost efficiency across the board. The most conservative approach would suggest that the folding chassis be discarded, robot wheels rethought and simplified in order to drastically reduce costs, many by-wire systems defaulted back to more mechanical solutions, and that the lithium-ion battery technology be substituted for an older established chemistry such as a nickel-metal hydride (despite its high weight and low energy density).

Conversely, striving to preserve most core features of the CityCar/Hiriko, a progressive approach to improve may also serve as a viable option:

- Reducing the cost of the robot wheel may be the most difficult challenge. Current supply chains do not provide enough compatible mechanical components for the novel module. The demand for hub motors is low as they are used on niche vehicles and concepts; therefore, low economies of scale keep the prices for these typically custom built units high. Robot wheel designs that instead use lower-cost commercial high-speed cylindrical motors may help the module remain more economically viable. This choice will require a geared reduction, but finding the right combination of commercial

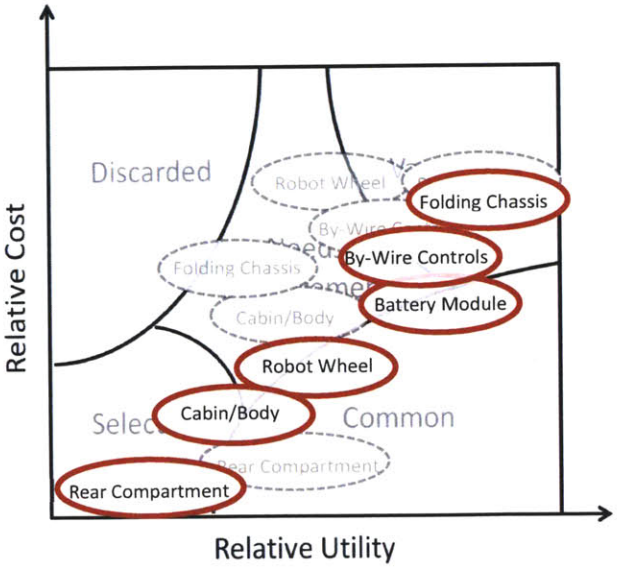


Figure 3-28: Recalibrated module cost-utility plot

components that are compatible with the module's form factor will be the key to reducing costs.

- The folding chassis presents a significant challenge to the overall vehicle design. Although the cost of the folding chassis itself may not be relatively high, there are external implications to the design of its surrounding components. The structural components of the chassis itself are simple and inexpensive; still the linear actuators are the most expensive component of the system. Commercial linear actuators equipped to handle up to 10,000N of initial force for folding are currently priced around $1,000 USD. Given the target price of Hiriko $16,000 USD,[35] a more economical solution must be found. Counteracting some of the weighted force with inexpensive passive tension springs serves as one approach that will significantly reduce the load upon the linear actuators and subsequently reduce costs. Still another approach to justify the folding chassis among its other modules is to increase its utility by adding a substantial safety feature that could justify higher costs, as addressed in *Reinventing the Automobile* – dynamic deceleration.

- Further simplicity to both the body and rear compartment can ensure both modules remain in the common and selective categories respectively. Currently the framing for both the cabin and rear compartment consist of over a hundred manually bent and welded aluminum tubing members. Such an assembly process requires high labor costs and is not scalable. Most of the curved aluminum tubes follow the general form of the body and support the thin walled plastic covers. Instead many of these complex tubes could be substituted for straight simple members combined with more rigid exterior panels.

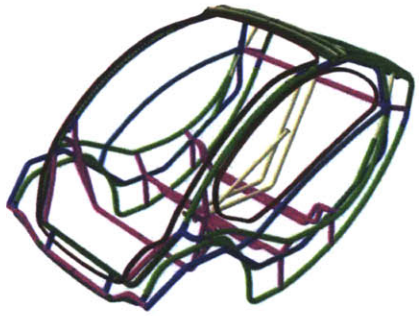


Figure 3-29: Hiriko cabin tubular framing

- Lithium-ion technologies are still relatively new and more expensive than its less energy- and power-dense competitors. The cost of advanced electric vehicle batteries can expect to continue reducing over time. Lithium-ion battery costs dropped 14% between 2012 and 2011, up to 30% since 2009.[36] Similarly, as by-wire control systems become more common, economies of scale will continue to pull down costs.

[35] (Alvarez, 2012)
[36] (Doom, 2012)

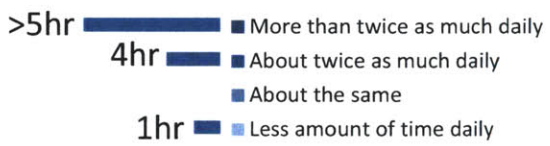
3.3.3 *Input from Shared Mobility Specialists*

Throughout the development process of the Hiriko vehicle, numerous associations were formed with groups and individuals closely involved with urban planning and shared mobility systems. Crefutur, BCN Sharing Projects, Inno-Z, Better-City, Public Bike System, Opinno, and Barcelona Activa were some of the major participating groups. Various experiences in system development, fleet operation, municipal services, utility services, system management, and research offered keen insight on best practices for the emerging Mobility on Demand service utilizing the Hiriko vehicles.

In similar fashion, following the unveiling of the Hiriko in Brussels, each of the contacts was asked to participate in a brief online survey. In this case, questions focused on characteristics and vehicle features particularly relevant to shared mobility services. Out of over 30 questions, four predominant factors of the Hiriko CityCar stood out: customization, range, reducing maintenance time, and concentrated parking (through a reduced footprint size).

If the average personal vehicle is used only an hour or two each day, about how much more do you believe vehicles in a shared mobility service are used?

"Must be used at least for 6-7 per day to be economically viable." - survey participant



Fleet operators would consider employing more expensive vehicles if these vehicles saved them time in servicing and maintenance.

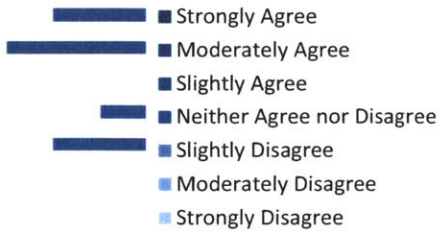
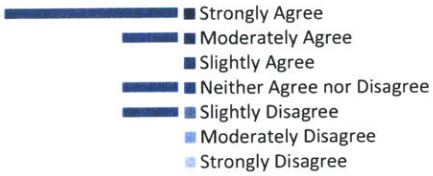
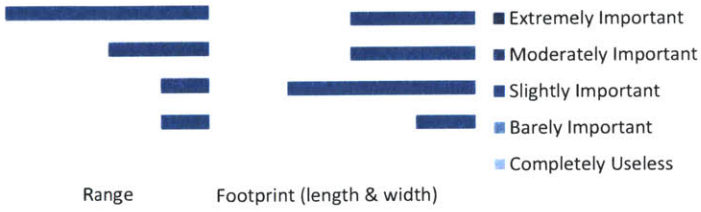


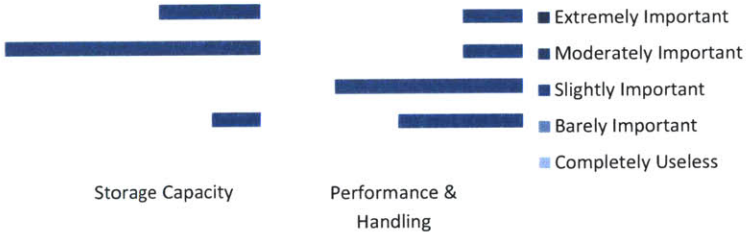
Figure 3-30: Shared mobility survey responses (1 of 3)

Fleet operators will likely utilize the opportunity to customize the rear compartment for their own utility or service. (For example: delivery, maintenance/utility, cooled or heated compartment).

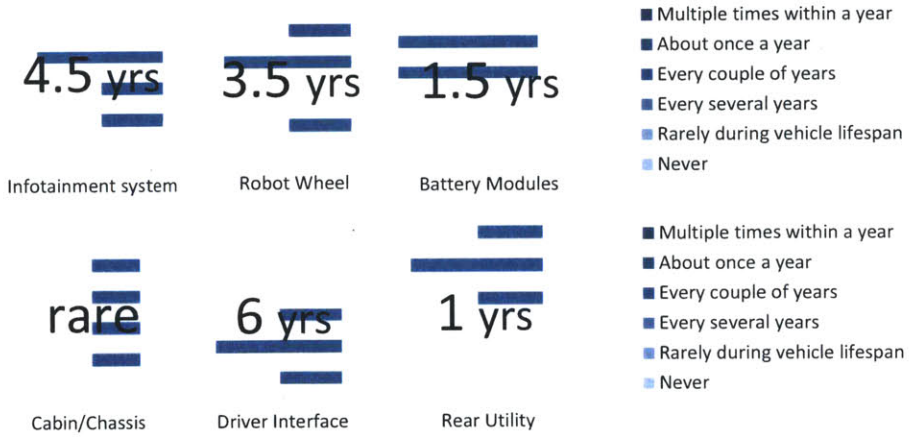


When selecting vehicles for a shared mobility program, it would be valuable to be able to customize the following features:





In a shared mobility fleet, how frequently are the following modules likely to be changed?



Shared mobility programs typically use identical vehicle models within their fleets (although Zip Car does employ a variety of automobile models). How important is it to have a variety of vehicle types in a shared mobility service?

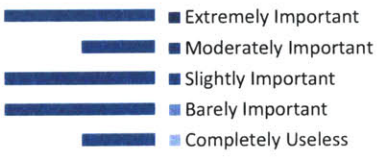


Figure 3-31: Shared mobility survey responses (2 of 3)

Incorporating folding into the CityCar to reduce its footprint by 40% and enable a 3:1 street parking ratio can be worth the added expenses in a shared mobility service.

Mobility on Demand services can operate without CityCars, just as existing enterprises do today.

Vehicles with micro-footprints (less than 30 sq-ft) are very valuable in crowded urban environments

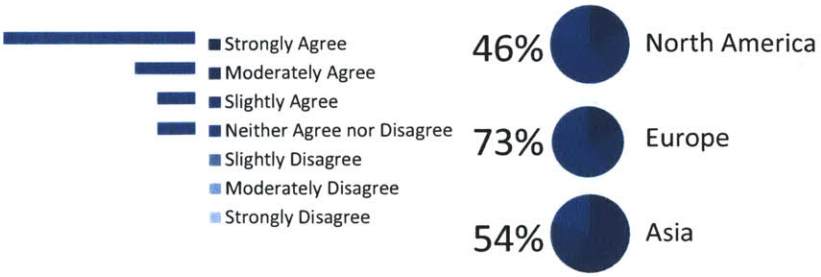


Figure 3-32: Shared mobility survey responses (3 of 3)

Mobility on Demand services can operate without CityCars, just as existing enterprises do today. Still, some of the CityCar's unique features may assist these services by easing operations and offering specialty urban personal mobility options to their members. According to interviews conducted with senior developers of shared mobility services, there are particular vehicle factors that can assist the effectiveness of the service and the transit of their vehicles. The most important factors of the vehicles in the fleet of MoD are the following:

- Price of vehicles in fleet
- Utilizing premium space
- Reducing maintenance
- Maximizing uptime
- User Customization

The feedback from the online surveys revealed strong favorability toward the ability to customize their fleet vehicles in some manner. Consistent with the interviews, reducing the necessary maintenance, extending the vehicle's range, and reducing the occupied parking area remain paramount features of the shared mobility fleet. A strong majority of participants believe that each of the fleet vehicles would be used more than twice as often as personally owned automobiles. Increased rental factors over six were recommended to maintain a profitable service. Given that vehicles in car2go's rental service are used on average at least 4 times a day, utilization frequencies around 4-6 times a day is a reasonable target.

Lastly the folding feature of the CityCar was well favored among shared mobility managers and researchers. However, most believe such a feature would be significantly more beneficial in European cities as opposed to more spread out American cities.

3.3.4 *Stakeholder Feedback Summary*

In order to gain a comprehensive view from the perspectives of all participating stakeholders, automotive manufacturing, module suppliers, and shared mobility system, all responses have been combined into a summary chart. The summary chart combines questions of similar topic and their relative favorable or unfavorable opinions.

		Response Value (Most favorable = 10, Least favorable = 0)			
		Manufacturer	*Shared mobility*	Avg	Question
CityCar Features	**Folding**				
	Q1	6.6	9.7		Incorporating folding into the CityCar to reduce its footprint by 40% and enable a 3:1 street parking ratio can be worth the added engineering complexity.
	Q2	6.6	-	7.3	Incorporating folding into the CityCar to reduce its footprint while also easing entry and exit of passengers can be worth the added engineering complexity.
	Q3	7.3	-		Please rate the value of the following CityCar (Hiriko) features: Reduced footprint from folding chassis
	RW manuverability	-	-		For the CityCar (Hiriko) vehicle, please rate the importance of the following maneuvers:
	Q4	5.4	5.4		O-turn
	Q5	4.2	5.4	6.1	Translation
	Q6	6.3	5.8		4-Wheel Steering
	Q7	8.1	-		Please rate the value of the following CityCar (Hiriko) features: Maneuverability from Robot Wheels
	Front entry/exit				
	Q8	8.1	-	8.4	Please rate the value of the following CityCar (Hiriko) features: Eased entry and exit from front door
	Q9	-	8.6		Permitting entry and exit from the front of the vehicle is a worthy benefit to challenging the traditional vehicle architecture (given support/demand from the end user).
Industry benefits	**Custom rear module**				
	Q10	7.3	-	7.4	Please rate the value of the following CityCar (Hiriko) features: Customized utility from rear compartment.
	Q11	-	7.5		Exploiting Hiriko's modularity to have vehicles of various storage capacity, range, size, and performance can be an effective solution for shared mobility fleets.
	Design & manufacture				
	Q12	4.1	-		Does the decoupled (modular) vehicle platform liberate design and manufacturing decisions?
	Q13	7.5	-	5.8	Are you likely to propose changes, improvements, or variation to your module, or wait until it is requested?
	Q14	5.9	-		Compared to your previous supplier roles developing other automobile components, does your role now within Hiriko permit you to be more empowered in module development?
	Q15	5.8	-		Hiriko's modularity will expedite future versions of this vehicle.
	Servicing				
	Q16	6.9	-	6.9	Hiriko's modular platform presents [service] business opportunities.
	After-market products				
	Q17	7.8	-	7.8	Hiriko's modular platform presents business opportunities to expand into [after-market products].
	Customization				
	Q18	4.4	-	6.3	The modularization of the drive train in the RobotWheel provides the opportunity to customize its performance characteristics more easily than a traditional vehicle platform.
	Q19	8.1	-		Hiriko's modular platform presents business [customization] opportunities.
Shared mobility (MoD)	**Lifecycle management**				
	Q20	5.3	-	5.3	Hiriko's modular platform presents business opportunities [for lifecycle management of the modules].
	Micro-footprint				
					Vehicles with micro-footprints (less than 30 sq-ft) are very valuable in crowded urban environments.
	Q21	-	4.6		American cities
	Q22	-	7.3		European cities
	Q23	-	5.4	7.6	Asian cities
	Q24	-	5.4		How complex of a challenge is land acquisition when developing or expanding a shared mobility service?
	Q25	-	9.7		Utilizing a fleet of vehicles that have a small footprint or take little space while parked can ease the development and expansion of shared mobility systems.
	Q26	-	9.4		Hiriko's folding capability (3-to-1 parking ratio) is uniquely valuable to shared mobility management.
	Ability to custoize fleet				
	Q27	-	7.8		If managing a fleet of shared vehicles, the option to customize your vehicle features would be: (varying levels of value)
					When selecting vehicles for a shared mobility program, it would be valuable to be able to customize the following features:
	Q28	-	7.8		Range
	Q29	-	7.5	7.4	Storage Capacity
	Q30	-	6.6		Footprint
	Q31	-	4.7		Performance
	Q32	-	7.8		Fleet operators will likely utilize the opportunity to customize the rear compartment for their own utility or service. (delivery, maintenance/utility, cooled or heated compartment).
	Service & Maintenance				
	Q33	-	7.1	7.7	Fleet operators would consider employing more expensive vehicles if these vehicles saved them time in servicing and maintenance.
	Q34	-	8.3		The modular architecture of Hiriko is likely to reduce maintenance burdens to shared mobility fleet operators.

Table 3-8: Stakeholder feedback summary - average weighted responses

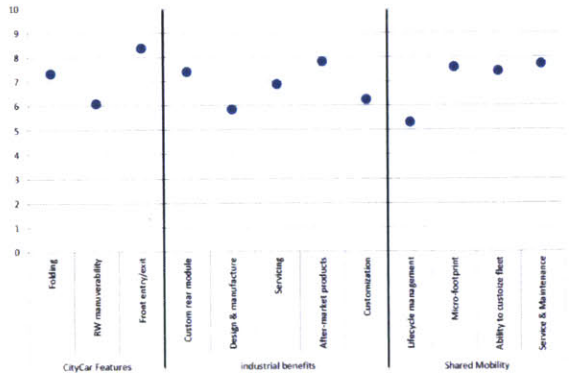


Figure 3-33: Summary plot of weighted responses

At first glance, there seems to be general favorability towards the front entry feature, potential to expand into after market services (modules and electronic applications), and the vehicle's ability to achive a micro-footprint through folding. Relatively, most apprehensions or disinterest involves the lifecycle management of the worn modules, the desgin and manufacturing challenges, and the complex manuverability of the Robot Wheels. Nevertheless, most of the feedback was generally positive. As the novelty of particular features face-off with the reality of manufacturing cost, supply chains, system reliability, other methods to achieve similar features may be expored (such as combining left and right Robot Wheels to create a more robust "Robot Axle").

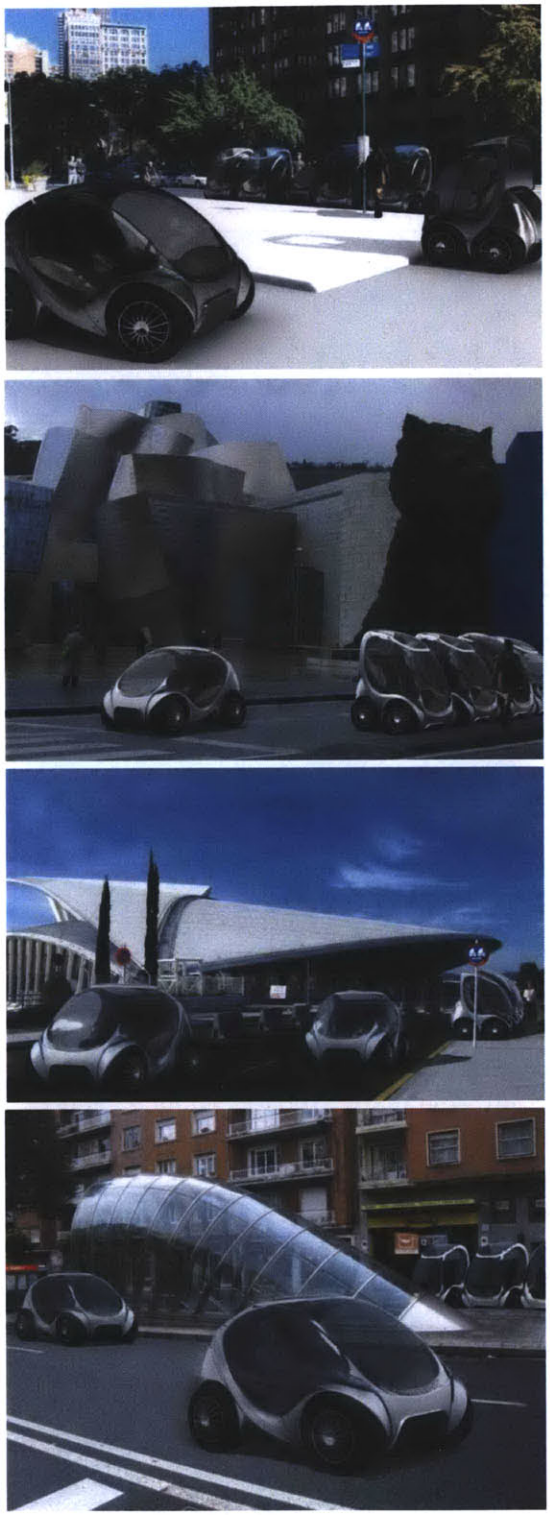


Figure 3-34: CityCar in Mobility on Demand

3.4 CityCar in Mobility on Demand system

Even though City Cars can work well as privately owned vehicles, they can provide greater sustainable benefits when integrated into a shared-use model, like Mobility-on-Demand. The system operates through a network of vehicle stacks at major destination points throughout a city, such as subways, shopping centers, airports, office complexes, residential areas, sport facilities, and universities.

The user can expeditiously rent one of the CityCars by swiping their pre-established membership ID card, removing a charged vehicle from the stack to run their errands and finally returning it to any of the conveniently located charging/parking stations. Vehicles automatically recharge while they are in these stacks. This one-way shared-use rental system provides an urban-friendly embodiment of a ubiquitous valet service that complements surrounding transportation options.

Instead of replacing private automobiles or mass-transit systems, Mobility-On-Demand systems equipped with CityCars supplement each of these modes of transportation and expand multi-modal capabilities through a lean vehicle tailored specifically for city environments. Major efficiencies are gained by reconfiguring the relationships of urban mobility, energy management, and information networks so that each transportation option can function in a more harmonious fashion.

Key factors to keep in mind with mobility-on-Demand

- High utilization
- System monitoring
- Land acquisition
- Vehicle redistribution
- Vehicle maintenance
- Recharge/refill
- Power management
- Repairs
- Fleet purchases and turnover

3.4.1 *Collective Space Savings*

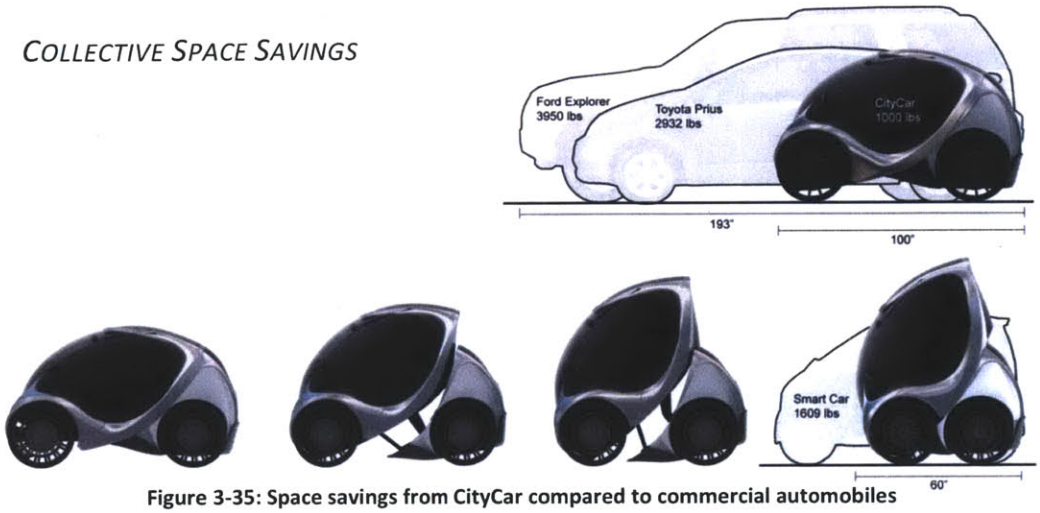


Figure 3-35: Space savings from CityCar compared to commercial automobiles

The CityCar's folding chassis reduces its foot print by 40% in order to occupy less than 25 square feet when parked (precisely 24' 2"). When folded the vehicle's length matches its width, which is typically equal or even slightly narrower than most full sedans. This small dimension allows the CityCar to fit in parallel parking spaces in two orientations, normally parallel and perpendicularly nose-in. The front access of the vehicle encourages drivers to park the vehicle perpendicular to the curb, allowing both passengers to exit gracefully onto the sidewalk as shown in Figure 3-36. Also, since the vehicle utilizes a single front entry and exit face, less buffer space is required on each of it sides.

The combination of the folding chassis and front entry/exit lets at least three CityCars to fit within one parking space designated for an automobile. The three vehicles fit within the parking space even while maintaining two feet of space between each of them. This buffer allows the CityCar to perform an O-turn and exit from the space, letting the driver always operated the vehicle safely in a forward direction. The CityCar's micro footprint, which enables a 3:1 vehicle concentration for parallel street parking, can also be well utilized within exterior lots and multi-level parking structures.

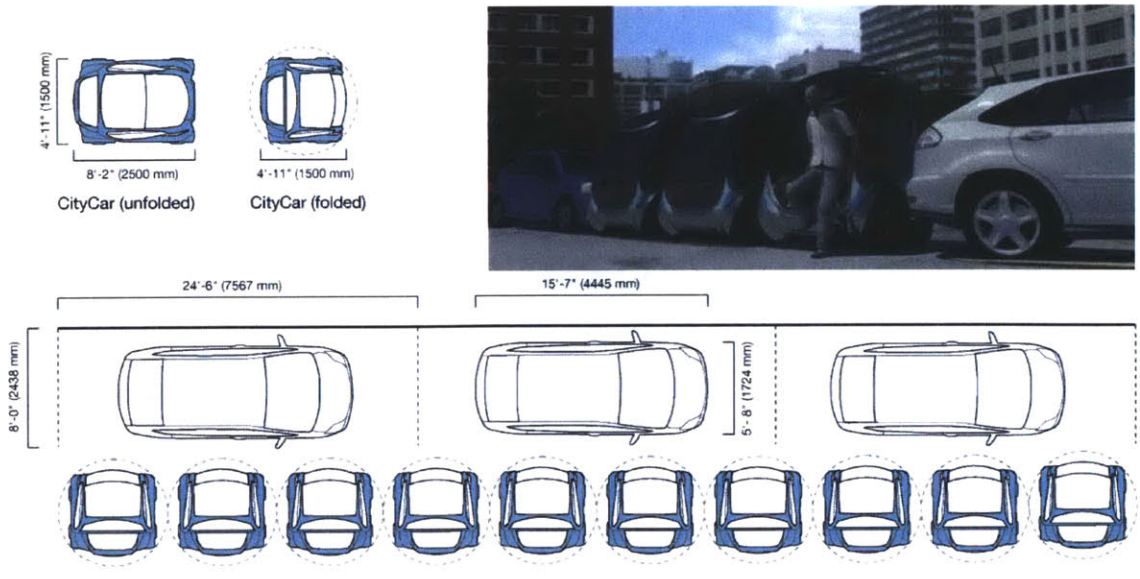
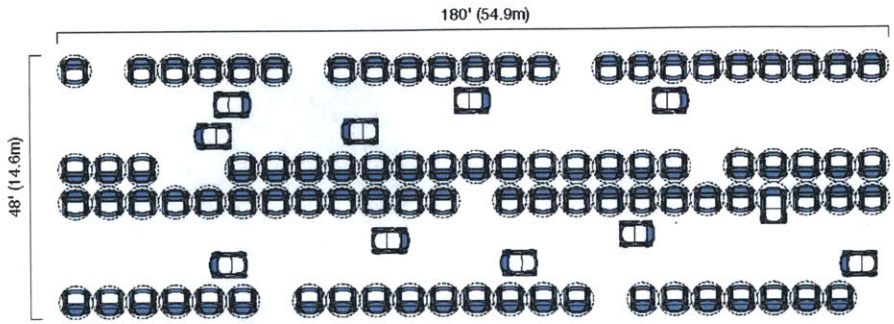


Figure 3-36: CityCar 3:1 street parking ratio, by Ryan Chin & Derek Allan Ham



This comparison shows how the compact footprint from folding combined with O-turn maneuverability allows the same number of vehicles as a traditional parking lot to consume over two-thirds less surface area.

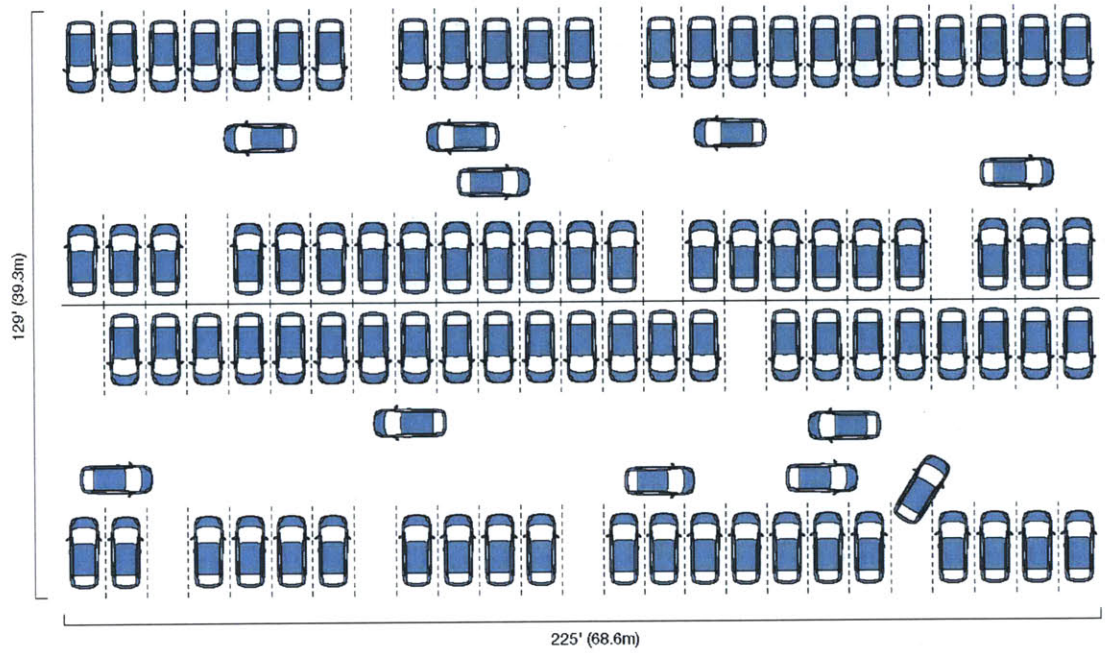
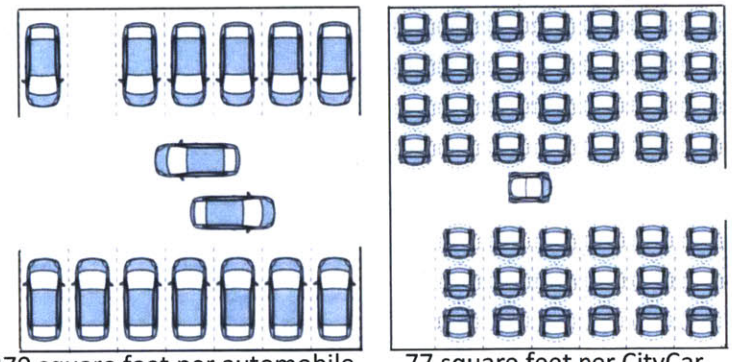


Figure 3-38: Comparative surface area savings in parking lot, by Ryan Chin

Another strategy to condense the parking layout of CityCars takes advantage of the benefits of autonomous navigation systems.. Unmanned CityCars that are equipped with appropriate proximity and position sensing coupled with vehicle-to-vehicle communications may be permitted to park themselves in tight spaces typically inaccessible by drivers. Such a solution would only require a single access point at minimum (Multiple entry and exit locations may be added to increase vehicle flow). This reduction of pathways would enable over three times as many CityCars to fit within the same space (3.2:1 ratio).



270 square feet per automobile
14 automobiles

77 square feet per CityCar
45 CityCars

Figure 3-37: Compressed lot from autonomous parking, by Ryan Chin

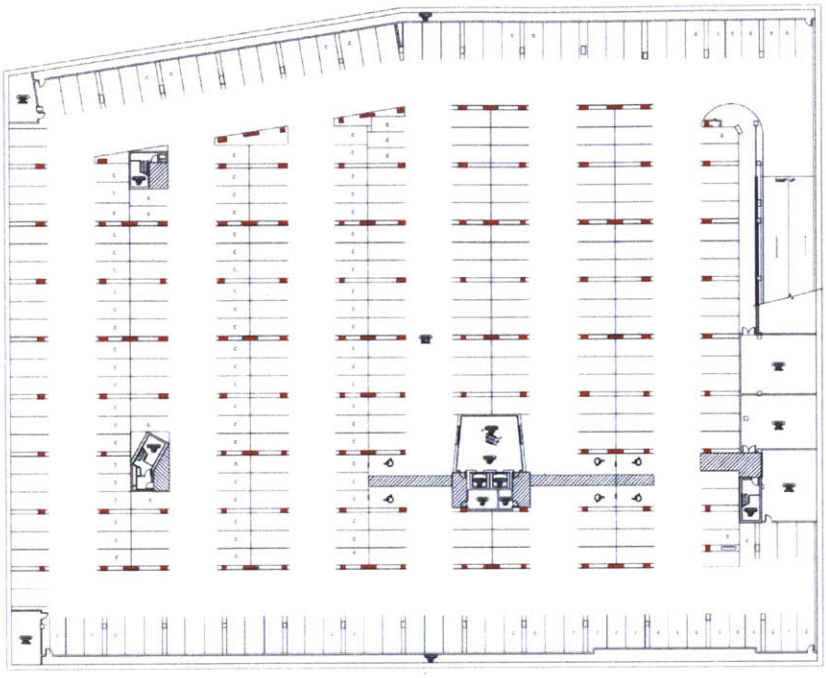


Figure 3-39: MIT Stata Center parking lot.

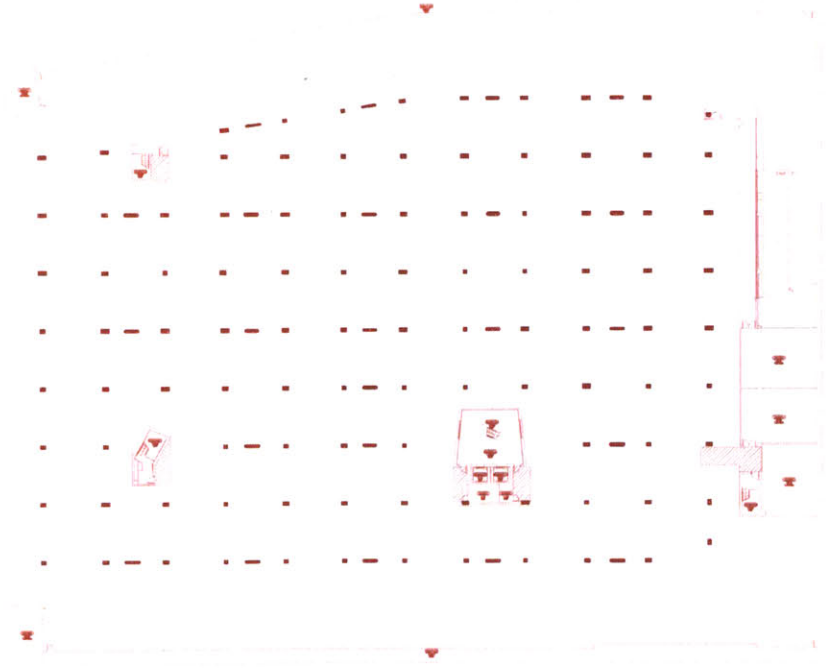


Figure 3-40: Parking lot structure and barriers - 122 load bearing pillars

Preliminary studies reveal that the three to one parking ratio benefits illustrated for street parallel parking can be preserved within an outdoor lot setting. And in an outdoor parking lot scenario the redesign of the paint boundaries would enable an easy transition of vehicle types. This ratio may be increased around 4:1 if the two foot spacing is reduced.

However the conversion of a parking lot to contain dozens or even hundreds of CityCars becomes substantially more challenging in an underground or multi-level above ground structure. All larger covered parking lots, whether they are above or below ground, contain many load-bearing pillars. The location of each of these structural pillars can be seen in red in the MIT's Stata Center parking lot for example in Figure 3-39.

Unlike the paint that outlines all the spots and lanes, the pillars are obviously permanent. Figure 3-40 illustrates each of the immovable structural elements in the Stata Center lot. This layout is typical of many multi-level underground parking lots, around which over a hundred columns must be navigated.

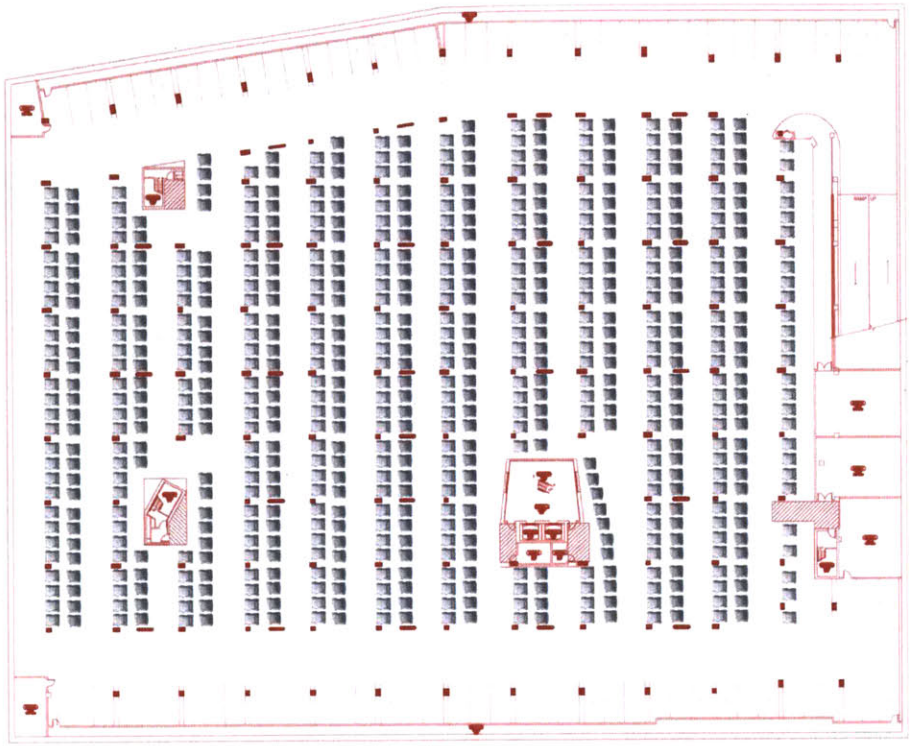


Figure 3-41: Majority conversion of lot for individual parking of CityCars

Taking advantage of its footprint and narrowing the access lanes allows 597 CityCars fit in the space of 234 traditional automobiles (2.5:1 ratio). In this scenario 76 parking spots remain to accommodate traditional automobile options.

Figure 3-42: Rendering of CityCar stacks in underground parking garage

Since CityCars do not require left or right access, each can be parked closer side by side. This allows four CityCars to fit in the space previously occupied by three automobiles. Drive pathways to access the parking spots can be significantly narrowed down even more so than simple one-way paths since the CityCar's O-turn permits an extremely small seven foot turning circle (whereas most automobiles have a 30-35 foot turning circle). The significantly larger turning circle (also referred to by "turning radius") requires either a wider pathway or parking space to accommodate the automobile's vehicle sweep.

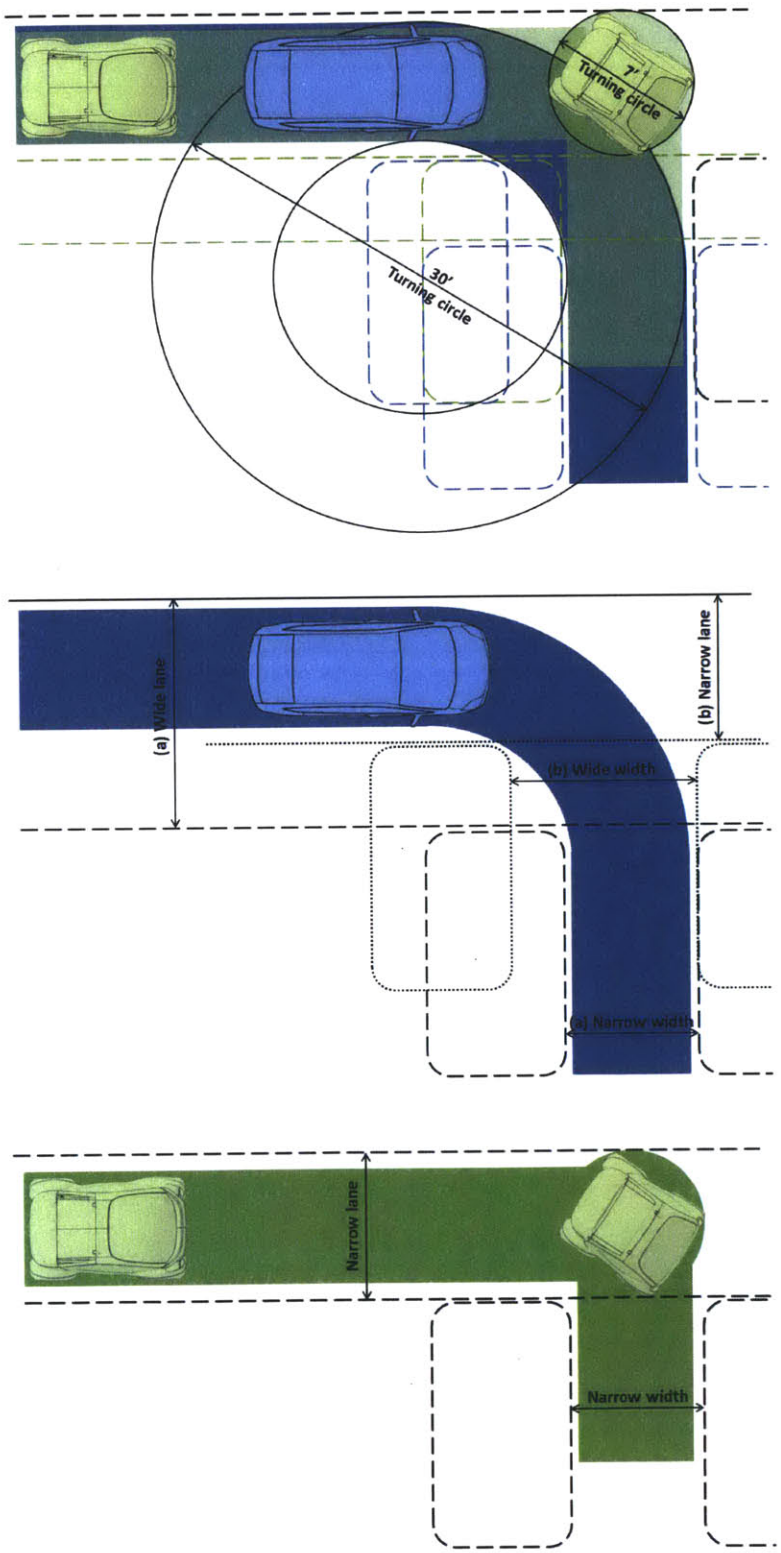


Figure 3-43: Comparison of CityCar vehicle sweep to automobile

The combination of the CityCar's micro footprint and high maneuverability create an extremely lean "vehicle sweep." This sweep encompasses any surface area required for the vehicles to travel to and from their desired spots. Figure 3-43 illustrates the resultant vehicle sweeps from the turning circle of a traditional automobile and the CityCar.

While some of the most maneuverable automobiles have turning circles (curb-to-curb) around 30 feet, the combination of the CityCar's micro footprint and O-turn capabilities enable a mere seven feet, only two feet greater than the vehicle's body width. These differences have implications not only in the eased navigation through crowded cities, but also their supporting infrastructures, like parking lots.

The middle section of Figure 3-43 demonstrates that the space to accommodate an automobile's relatively larger turning radius must be granted by either a wider lane with a narrow spot width (a.), a narrow lane coupled with a wide spot width (b.), or a combination of both. In any case, significant square footage is being dedicated and unoccupied for the means accessing a parking space.

In the case of the CityCar however, the last section of Figure 3-43 demonstrates how lean the vehicle's sweep can be – consuming 33% to 57% less area in order to navigate its way into its parking space. Such tight maneuverability results in significant benefits for increasing the density of vehicles in a parking structure – especially one whose structural layout is already established.

In the converted parking structure two rows of parking for automobiles can accommodate up to four rows of parking for CityCars. The distribution of structural columns, in the Stata Center for example, allows for new drive paths to be utilized once the painted barriers are redesigned. (Note: The original painted barriers remain in upper image to show and compare the previous parking locations.)

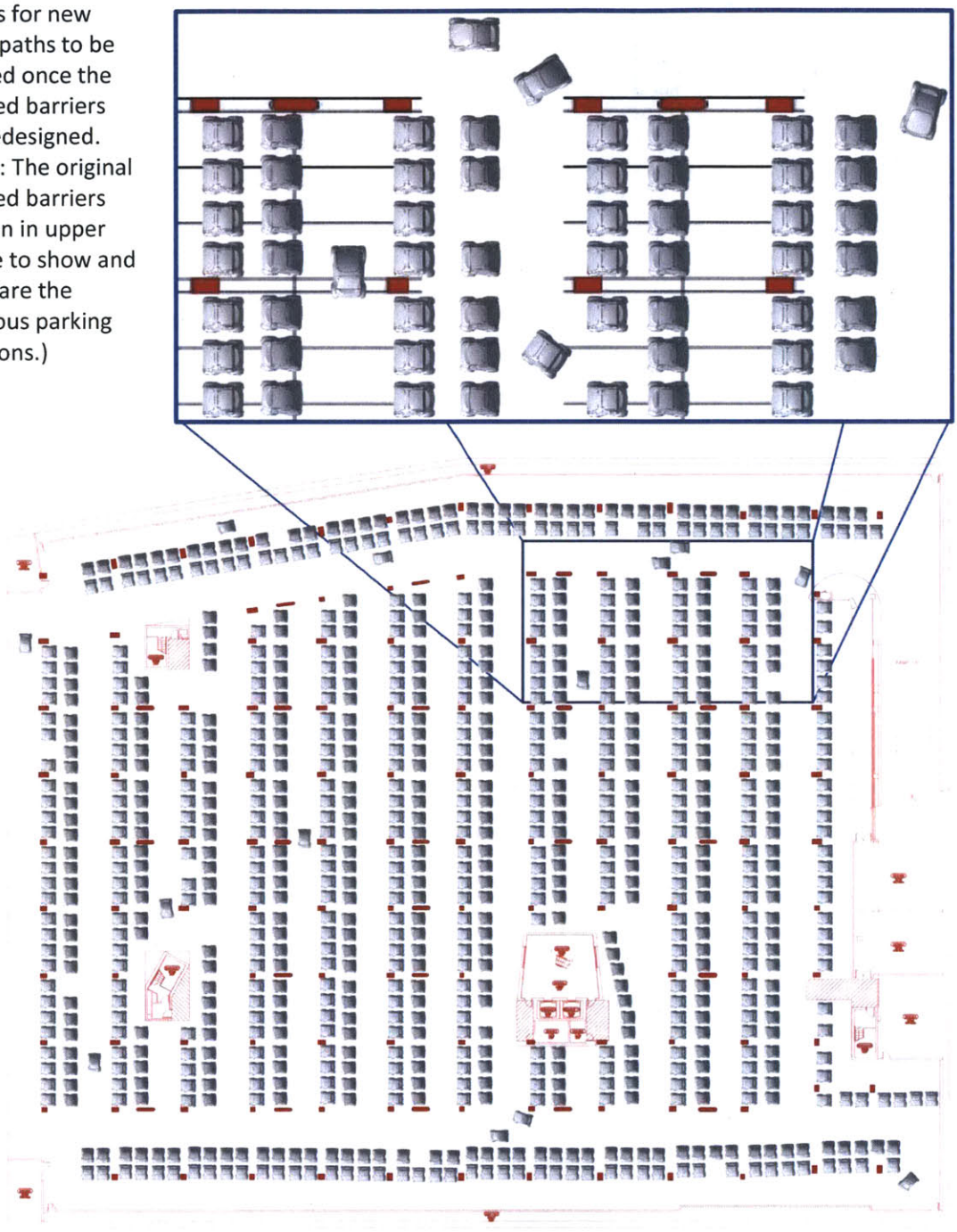


Figure 3-44: Total conversion of Stata Center lot for individual parking of CityCars

Figure 3.43 shows the complete conversion of a single level of the Stata Center parking structure. 843 CityCars fit within the space of 340 traditional automobiles to enable a 2.5:1 ratio. Alternating one-way paths are surrounded by two-way driveways.

As in the preliminary study (Figure 3-39), many more vehicles CityCars can be condensed into the surface area of a parking lot when vehicles are autonomously shuffled and relocated. The same Stata Center parking lot that would typically fit 340 automobiles or 843 individually parked CityCars could accommodate up to 1,545 CityCars if operated through an auto valet system, as shown in Figure 3-45. This ultra-dense parking configuration yields a 4.5:1 parking ratio. The rows four to six vehicle deep of CityCars self could self-organize about through six pathways to enter and exit their spots. While the number of pathways could be reduced to cram in an extra vehicle or two within each row, flow patterns would be significantly hindered.

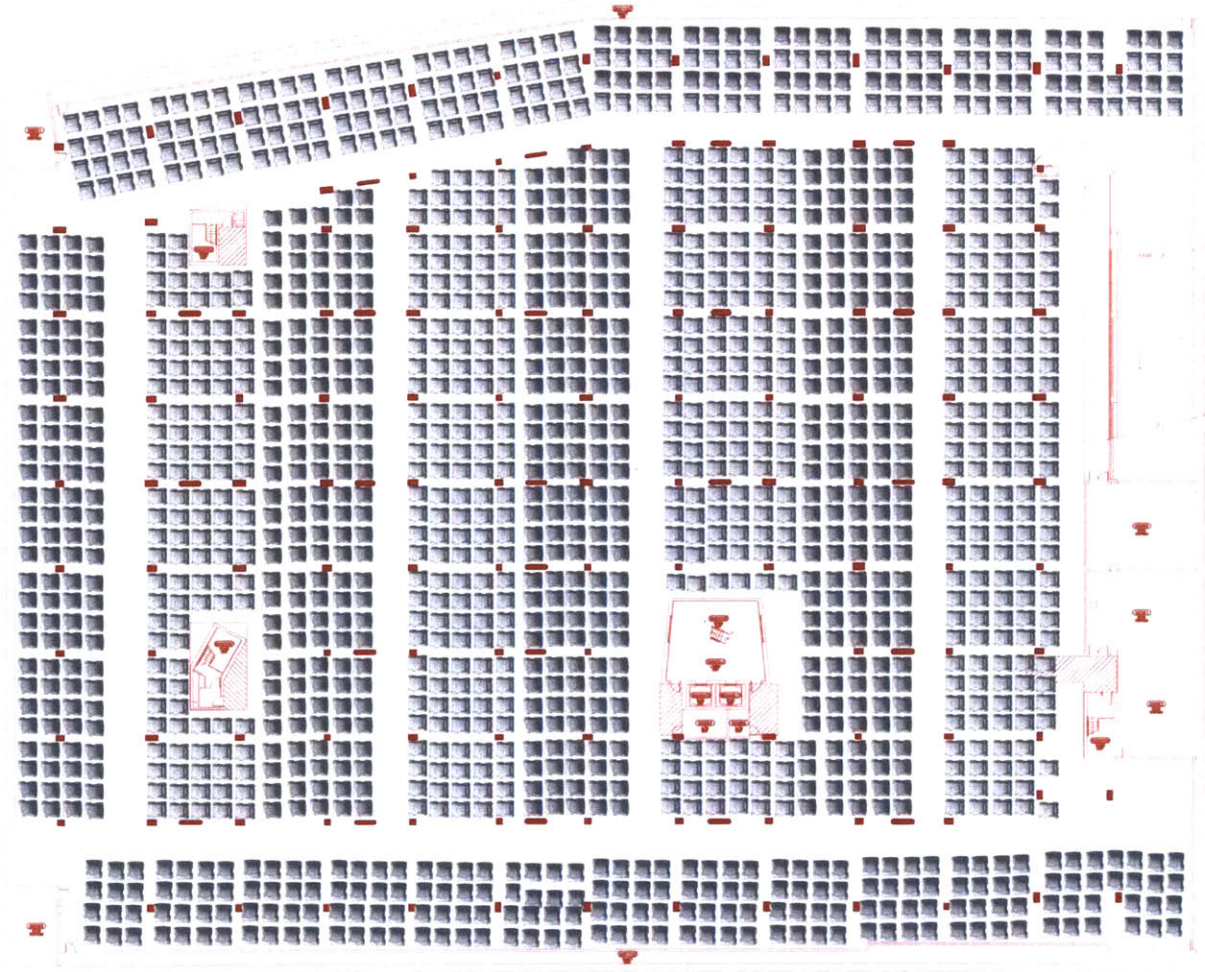


Figure 3-45: Total conversion of Stata Center lot for autonomous parking of CityCars

1,546 CityCars occupy the space of 340 traditional automobiles (4.5:1 ratio). Most rows are stacked five vehicles deep.

The ability to convert older parking structures to house a plethora of CityCars in a highly-dense manner presents an intriguing business opportunity for operators of shared vehicle fleets. Whether they employ technologies that enable autonomous navigation within the controlled enclosed environment, or simply offer the structure for individual parking, fleet operators can now concentrate 2.5 to 4.5 times more vehicles within the level to offer their service to more customers. On the other hand, if shared mobility operators were not looking to offer such a large fleet service (such as over 1,500

CityCars), their smaller quantity fleets could occupy significantly less space instead. Given a conservative city parking rental rate of $2,000 a year per space, this two-thirds to three-quarter space saving may result in over a hundred-thousands of dollars in annual parking rental costs for a fleet of 100 vehicles in a major metropolitan area (given the fleet operator can negotiate rental rates based on the square footage occupied by roughly 30 automobiles).

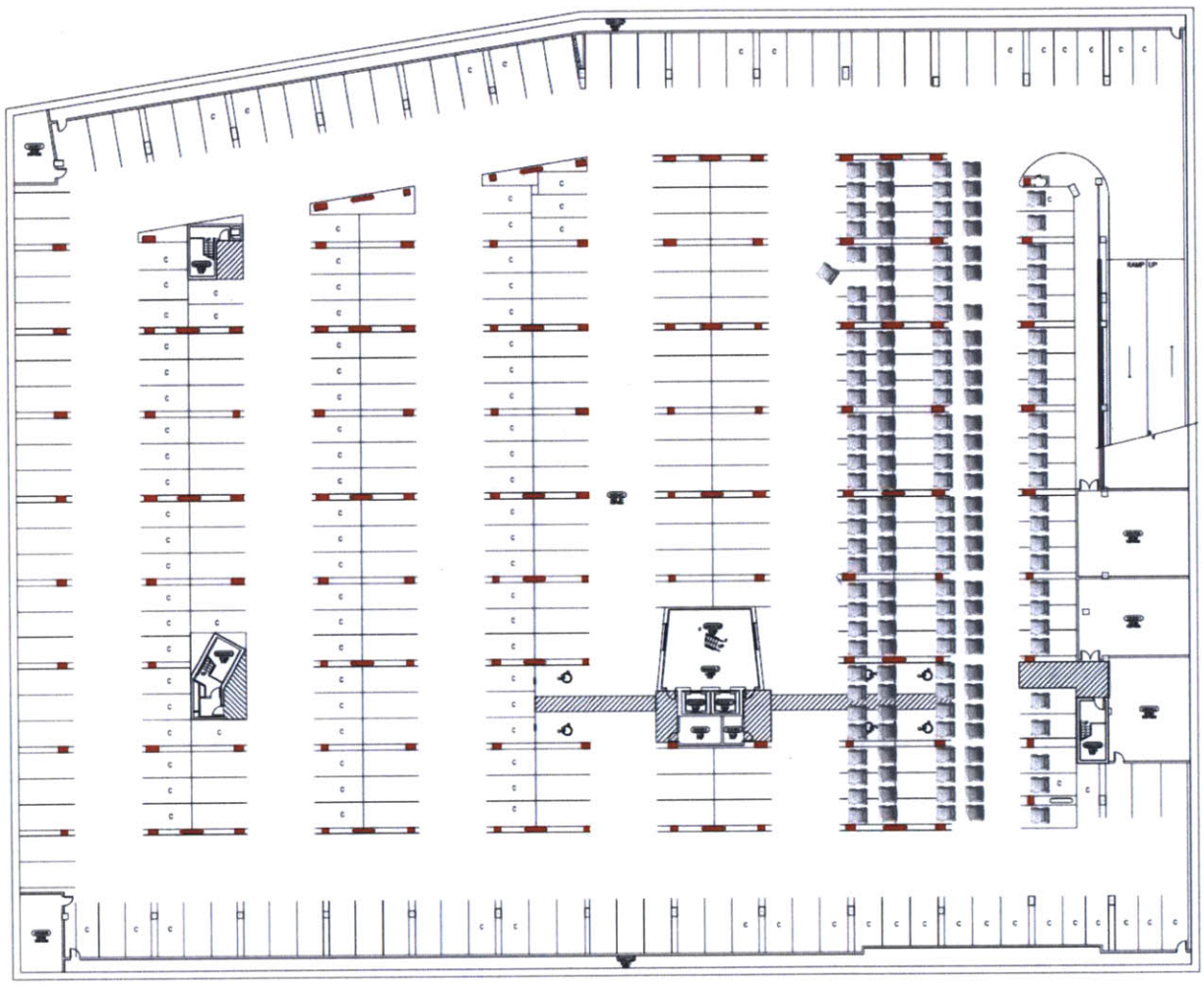


Figure 3-46: Partial conversion of Stata Center parking lot for shared mobility fleet

Even in the most moderate conversions, figure 3.45 illustrates how 114 CityCars in a shared mobility fleet may fit within the space of 68 automobile parking spaces in an underground lot. Such utilization of this section would reduce annual operational parking cost by 40%.

Overall, with the increased density ratio gained from the CityCar there are two general paths from which operators can benefit – one, increasing the quantity of vehicles within the area or two, reducing the area needed by the vehicles.

Opportunities from Increased Parking Density Ratios

model	parking density	Increased revenue	or	Reduced capital investment		Reduced Lot size	
Parallel Parking	Location example:	Fenway park block, 25 automobile spaces					
		$18/day		4,000 sq-ft			
	3 to 1	$328,500 extra/year (full utilization) $1,31,400 *		160 sq-ft per automobile $100/sq-ft, $16,000/automobile	50 sq-ft per CityCar $100/sq-ft, $5,000/CityCar **$275,000 savings**	1,250 sq-ft for 25 CityCars	**2,750 sq-ft savings** 12 vending trucks
Under/above-ground multi-level lot	Location example:	MIT Stata Center (one floor), 340 spaces					
		$20-30/day		122,000 sq-ft (per floor)			
	2.5 to 1	**$4,653,750 extra/year** (full utilization) $1,861,500 *		360 sq-ft per automobile $200/sq-ft, $72,000/automobile	145 sq-ft per CityCar $200/sq-ft, $29,000/CityCar **$14,620,000 savings**	49,000 sq-ft per floor for 430 CityCars	**73,000 sq-ft savings** 200+ NYC micro apartments
	4.5 to 1 automated valet	**$10,858,750 extra/year** (full utilization) $4,343,500 *			79 sq-ft per CityCar $200/sq-ft, $15,800/CityCar **$19,108,000 savings**	26,918 sq-ft per floor for 430 CityCars	**95,000 sq-ft savings** 300+ NYC micro apartments
Outdoor parking lot	Location example:	MIT Westgate lot, 320 spaces					
		$15-$25 / day		90,000 sq-ft			
	3 to 1 automated valet	**$4,672,000 extra/year** (full utilization) $1,868,800 *		270 sq-ft per automobile $100/sq-ft, $27,000/automobile	90 sq-ft per CityCar $100/sq-ft, $9,000 per CityCar **$5,760,000 savings**	28,800 sq-ft for 320 CityCars	**61,200 sq-ft savings** softball field
	5 to 1 automated valet, 12" spacing	**$9,344,000 extra/year** (full utilization) $3,737,600 *			54 sq-ft per CityCar $100/sq-ft, $5,400 per CityCar **$6,912,000 savings**	17,280 sq-ft for 320 CityCars	**72,720 sq-ft savings** 10 tennis courts
	6.5 to 1 automated valet, 6" spacing	**$12,848,000 extra/year** (full utilization) $5,139,200 *			41 sq-ft per CityCar $100/sq-ft, $4,100 per CityCar **$7,328,000 savings**	13,120 sq-ft for 320 CityCars	**76,880 sq-ft savings** 14 basketball courts

* moderate revenue calculations made from 80% utilization with 50% subsidies

Table 3-9: Revenue and space opportunities created from dense parking ratio

3.4.2 *Modular Impact on Vehicle Maintenance*

Maintenance and servicing is another operational cost that can be reduced from the uMEV's modular architecture. For an individual owner, keeping up on the manufacturer's recommended maintenance schedule is only a slight inconvenience since most automobile manuals recommend regular service merely on a six to twelve month basis. Nevertheless, the compartmentalized drivetrain (the Robot Wheel) can expedite regular services for individuals leasing the vehicles or even the Robot Wheels themselves. Instead of requiring the owner to deliver their complete vehicle to service shops and wait several hours or even a day for repairs, performing maintenance on the drivetrain can now be as simple and quick as changing a tire. The snap-on connection of the Robot Wheel can allow individuals to waste little time waiting for repairs. Still more, active service models would not even require individuals who lease their CityCar, or the modules that make it up, to visit the repair shops. Instead maintenance trucks that carry Robot Wheels on board could service the complete drivetrain in a similar manner to AAA roadside service. While this may be a desirable convenience for individuals who own or lease a CityCar, the benefits become profoundly more influential for shared mobility fleets.

For Mobility on Demand service operators it is important to minimize downtime during vehicle maintenance and the associated labor cost, while maximizing the accessibility of each of their vehicles. Ideally each vehicle would be rented and used six times more frequently than individual cars according to shared mobility experts. While regular maintenance is only a slight inconvenience for individuals, the increased utilization of each of the vehicles would cause each one to be sent to service shops several times a year. This frequency of repair per vehicle can result in a significant burden for fleet operators of many hundred or even thousands of vehicles. In order to analyze the cost and labor implications for a shared vehicle under high-utilization, maintenance schedules of both a full electric (2011 Nissan Leaf) and a small urban (2001 Smart ForTwo) vehicles were studied.

Although multiple subsystems could have been analyzed, this study only focused the maintenance of drivetrain elements which can be functionally substituted by the CityCar's Robot Wheel. Therefore all recommended services (B1 and B16 in Table 3-11) and inspections (B6 and B25 in Table 3-11) relative to the drivetrains of two vehicles were listed over the recommended schedule span of six years (60,000 miles). The study anticipates utilization rates six times that of personal automobiles; therefore each vehicles used within the shared mobility system would be subjected to 60,000 driven miles a year. This annual projection of mileage is derived is reinforced from multiple factors. First, using the manufacturer suggested pairing of mileage per year (10,000 miles/year) multiplied by the increased utilization rates recommended by the shared mobility feedback. Vehicles in existing shared mobility programs such as "car2go" experience at least 4 rentals each day.[37] Secondly, another method takes the net average speed within cities (20 mph) over a continual annual usage within a shared mobility service. With peak transport hours between 6am to 9am and 3pm to 6pm, and infrequent usage in-between throughout the day, 8 hours of daily usage is anticipated – resulting in roughly 58,000 a year.

Lastly by observing annual mileage rates of rental car companies, quantities around the same order of magnitude can be found. Hertz rent-2-buy program, for example, provides vehicles one to two years old starting at 23,000 miles reaching up to 48,000 miles. Expecting at least twice as much frequency of use may be reasonable for a Mobility on Demand system located in prime locations of busy city centers.

[37] (car2go, 2009)

The following table Table 3-11 highlights the maintenance schedules for a Nissan Leaf and Smart ForTwo and illustrates the compressed labor costs and time relevant to a more frequently used MoD service:

				Individual Owners Manual			Mobility on Demand (utilized 6 times more frequently)						
				Scheduled Maintenance			number of times serviced over the course of:			Automobile Drivetrain		CityCar Robot Wheel	
				9-12 mo.	24-36 mo.	48-72 mo.	1 year	2 years	3 years				
		service time (hr)	labor cost (USD)	10,000 miles	30,000 miles	60,000 miles	60,000 miles	120,000 miles	180,000 miles	annual service time (hr)	annual labor costs (USD)	annual service time (hr)	annual labor costs (USD)
2011 Nissan Leaf	**Service**												
	Rotate tires	0.4	25.99	1	1	1	3	6	9	2.4	155.94	2.4	155.94
	Replace brake fluid	1.7	141.10	1	1	1	3	6	9	10.2	846.60	~~10.2~~	~~846.60~~
	Wheel Alignment	2.2	89.99	1	1	1	3	6	9	13.2	539.94	~~13.2~~	~~539.94~~
	Inspection												
	Axle & Suspension	1.7	141.10	X	X	X	0	1	1	1.1	94.07	~~3.4~~	~~282.20~~
	Brake pads and rotors	0.8	66.40	X	X	X	2	4	6	3.2	265.60	3.2	265.60
	Front suspension ball joints	3.3	273.90	X	X	X	0	1	2	3.3	273.90	3.3	273.90
	Steering gear and linkage	5.5	456.50	X	X	X	0	0	0	0.0	0.00	~~0.0~~	~~0.00~~
	Steering linkage ball joints	0.4	33.20	X	X	X	0	1	2	0.4	33.20	~~0.4~~	~~33.20~~
	Brake lines & cables	1.7	141.10	X	X	X	0	0	1	0.6	47.03	~~0.6~~	~~47.03~~
	Reduction gear oil	1.3	79.99	X	X	X	0	1	2	1.3	79.99	~~1.3~~	~~79.99~~
										total	total	total	total
										35.7	$2,336.27	8.9	$695.44
2011 Smart fortwo	**Service**												
	Rotate tires	0.4	25.99	1	1	1	3	6	9	2.4	155.94	2.4	155.94
	Replace Brake fluid	1.7	141.10		1	1	2	4	6	6.8	564.40	~~6.8~~	~~564.40~~
	Wheel Alignment	2.2	89.99	1	1	1	3	6	9	13.2	539.94	~~13.2~~	~~539.94~~
	Engine oil and filter	0.5	39.90	1	1	1	3	6	9	3.0	239.40	~~3.0~~	~~239.40~~
	Spark plugs	1.0	83.00		1	1	2	4	6	4.0	332.00	~~4.0~~	~~332.00~~
	Engine coolant	1.4	89.99			1	1	2	3	2.8	179.98	~~2.8~~	~~179.98~~
	Flat belt	0.5	41.50			1	1	2	3	1.0	83.00	~~1.0~~	~~83.00~~
	Inspection												
	Brake lines	1.3	107.90	X	X	X	0	0	1	0.4	35.97	~~0.4~~	~~35.97~~
	Disc brake pads	0.8	66.40	X	X	X	2	4	6	3.2	265.60	3.2	265.60
	Engine coolant	1.4	89.99	X	X	X	0	0	1	0.5	30.00	~~0.5~~	~~30.00~~
	Parking brake	5.3	439.90	X	X	X	0	0	0	0.0	0.00	0.0	0.00
	Front axle ball joints	3.3	33.20		X	X	0	1	2	3.3	33.20	3.3	33.20
	Steering linkage ball joints	0.4	33.20	X	X	X	0	1	2	0.4	33.20	~~0.4~~	~~33.20~~
	Drum brake pads	1.3	107.90			X	0	0	1	0.4	35.97	0.4	35.97
										total	total	total	total
										41.4	$2,528.59	9.3	$490.71

Table 3-11: Drivetrain maintenance evaluation

Following the compilation of every drivetrain service and repair over the course of 180,000 miles (increments of 60,000 miles), or three years within a shared mobility fleet, services irrelevant to the Robot Wheel were removed. Since the Robot Wheel drastically reduces many of the mechanical parts and does so within a dry manner (no hydraulic subsystems), many repairs like brake fluid (C3), wheel alignment (C4), and spark plug replacement can be eliminated.

Significant savings in both labor costs and time are reduced by exploiting the plug-and-play capabilities of the Robot Wheel drivetrain module. Compared to a commercial all-electric vehicle, the CityCar could require only one-fourth of the annual service time (N15) as the 2011 Nissan Leaf. This would reduce the annual labor costs of each vehicle from $2,336 (M15) to $695 (O15). Compared to a small relatively simple automobile like the Smart ForTwo, the CityCar would save a similar order of time while cutting annual labor cost from $2,528 (M35) to $490 (O35) per vehicle. Overall the CityCar's Robot Wheel has the potential to cut the labor cost at a rate of 4.25:1.

While the reductions in service time hold a similar 4:1 ratio, these savings can be increased even more by using a roadside repair model. Table __ lumps the complete amount of drivetrain services into

a total service time (L15 and L35); however, clusters of these repairs would spread out over the course of three days or so throughout the year. Each of these service appointments would require that the vehicle be removed from operation for at least half a day. When comparing that to the 10 minutes it would require to switch the Robot Wheel, essentially swapping the corner drivetrain, it's reasonable to assume reductions in downtime by over 90%. This huge reduction in vehicle service time is not completely eliminated, it is instead shifted to unit repairs on the Robot Wheel modules in a separate refurbishing shops. While some time may be saved focusing the repairs of Robot Wheels in a streamlined shop; the most important benefit comes from keeping each vehicle in the MoD fleet in operation as much as possible.

3.4.3 Reduced Operational Costs

Although consumers are fairly sensitive to the cost of automobiles and current gas prices, seldom do they have a full grasp of all the expenses that actually go into car ownership. Automobiles require many accompanying expenses that in some cases can almost double the actual cost over the course of five years. Vehicle depreciation, interest from financing, taxes and fees, insurance, fuel, maintenance, repairs, and any available federal tax credits all contribute to what is known as the "true cost of ownership," or TCO.[38]

3.4.2.1 General Observations from Operational Costs

- Parking consumes a significant proportion of total cost for individuals within a city.
- Energy/fuel play the biggest factor for highly utilized fleet vehicles
- It is difficult to justify the purchase of an electric vehicle as an individual given its higher depreciation and insurance. The recuperated cost savings only serve as a benefit when the vehicle is utilized much more frequently, as in MoD. However if the CityCar *is* able to lower its maintenance and depreciation cost, it can be a cost effective option for individuals as it is for shared fleet services.
- Even if the reduced annual parking cost only marginally improve profit margins for shared fleet operators, the ease to compress more vehicles in highly desirable and difficult to obtain areas may still be the most substantial benefit. Shared systems can support 3 to 5 times more rentals in compact areas. This is especially important in shared services that typically need to maintain over twice as many parking spaces as vehicles within the fleet (excess parking spaces ensure capacity during fluctuations throughout the day).

According to the American Automobile Association (AAA), the average person spends about $9,000 each year to own a vehicle. Still, this calculation does not consider even more factors that are present in crowded cities such as parking. In 2011, the average monthly cost of parking was $155.22 in North America,[39] which results in $1862.64 a year and over $9,313.20 over five years for parking alone. Still, this is a fraction of the cost for most major cities worldwide (top 25 cities globally average at about $600/month). This number is expected to keep rising, considering the price of parking has continued to escalate over the past five years. Additionally, given other urban issues, such as poorly maintained pot-hole ridden streets, higher taxes on gasoline, higher insurance premiums, and the general abuse automobiles are subjected to during daily exchanges in highly populated areas, the actual cost of vehicle ownership within a city is greater than suburban, rural, and other less populated parts of the country. Factoring in these differences, the urban true cost of ownership (uTCO) takes into account the higher costs of parking and other variances that make vehicle ownership within a city unique.

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[38] (AAA, 2009)

[39] (Moore, 2011)

3.4.2.2 uTCO parameters:

Parking – The largest unique variant compared to traditional TCO calculations. As property value is at a premium in US cities, parking increases the annual true cost of ownership by 22% on average. In major cities such as Boston and New York, parking easily doubles the annual cost of ownership and even triples in other global cities like London. Although not all residents within these cities own vehicles and not all employees reside within the city, this overwhelming cost of parking is not an option for shared mobility services. Services similar to Mobility-on-Demand must rent or own spaces to accommodate their fleets of vehicles. Baseline estimates would cost a fleet of only 1,000 vehicles over five-million dollars a year.

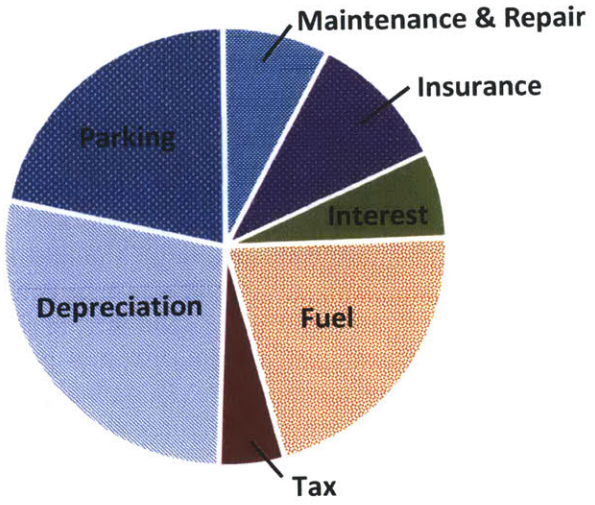

Figure 3-47: Urban true cost of ownership (uTCO)

Fuel/Electricity – Gasoline is a significant annual cost for automobiles, averaging at $1,950 a year considering 2011's price average of $3.83 per gallon. In the case of shared mobility, the refilling of frequently used fleet vehicles combined with slightly higher gasoline costs makes this expenditure even more significant. A fleet of 1000 vehicles utilized 6 times more often throughout the day than individual cars (recommended minimum for profitability) would cost 12-million dollars to the MoD operators annually. *(5% increase on gasoline price from city taxes)* Fleets providing electric vehicles on the other hand would save the operators, and therefore the end-users, by a factor of 2.67. Electric recharging for a Nissan LEAF, for example, requires only $731 for an individual annually and therefore would cost a similar fleet about 4-million dollars.

Maintenance & Repair – In most TCO calculations, the maintenance of the automobile accounts for 4-10% of the total annual expenses within the first five years of ownership. These yearly upkeep and repair cost continue to creep up as the vehicle adds mileage and components are worn down. Most conservative calculations estimate the vehicle being driven for 15,000 miles a year, resulting in an average of roughly $500 a year. However in shared mobility services, in which the vehicles are ideally utilized six times as often, maintenance and repairs can run a couple thousand a year (a couple million dollars a year per 1000 vehicles). One of the design goals for the CityCar was to minimize maintenance by reducing its part count, decreasing its number of subsystems, utilizing a practically all-dry drivetrain platform, and cleverly replacing hardware with software wherever possible. This strategy would drastically reduce or even eliminate the following automobile procedures: oil & oil filter change, wheel alignment, fuel filter, radiator flushing, and transmission maintenance. Besides the cost savings, perhaps more important for MoD operators is the reduced downtime of their fleet vehicles. Less maintenance over the lifespan of the vehicle results in longer periods of time with the vehicles in operation, lower repair costs, and lower labor costs.

Depreciation –This often unrecognized factor costs the average car owner in the US $3,728 a year and can be more expensive on models that are subject to oversupply, hold limited appeal, or compete with similar rebated models. Although millage has an impact on overall depreciation, timing plays a larger role; therefore, vehicles used frequently within a shared mobility service depreciate less per mile driven. For a MoD service operator, resale value of each of their fleet vehicles may be one of the less important

concerns within their business. However, vehicle appeal does influence the service. Regardless of a well maintained condition, customers prefer not to drive in cars that are considered outdated, obsolete, or don't contain the latest technology features. CityCar's modularity may be able to play a role here. Through clever management of module lifecycles, vehicles can appear new, or at least up to date, by swapping in the particular modules when necessary. Substituting the cabin or body panels every couple of years while conserving the same Robot Wheels and electronic backbone can keep the MoD fleet looking up to date while saving money, adding a higher perceived customer value.

Insurance – Automobile insurance varies around 10-20% of annual costs and is influenced by a number of factors. Insurance on rental vehicles can be generally higher because of the frequency of use by many multiples of drivers. It may be too early to speculate now the insurance will vary on a CityCar-type vehicle. While its conservative top speeds and increased visibility can lower its average rate, it's relatively small size and new supply chain can drive rates back upwards. Therefore, no net assumptions will be made on the changes in insurance rates for the CityCar or other uMEVs.

Interest from Financing – Financing interest accounts for about 10% of the total cost, during the first five years of individual ownership. This aspect remains independent of the vehicle type; therefore, there is no expected change for financing a CityCar or any other uMEV vehicles. Annual financing cost can be reduced and in some cases eliminated with large fleet purchases from service operators who receive bulk discounts and are better equipped to pay cash.

Taxes & Fees – Automobile taxes and fees are mostly state mandated and vary little from vehicle type. For the sake of this study, we will assume this 4% factor is equal across the board.

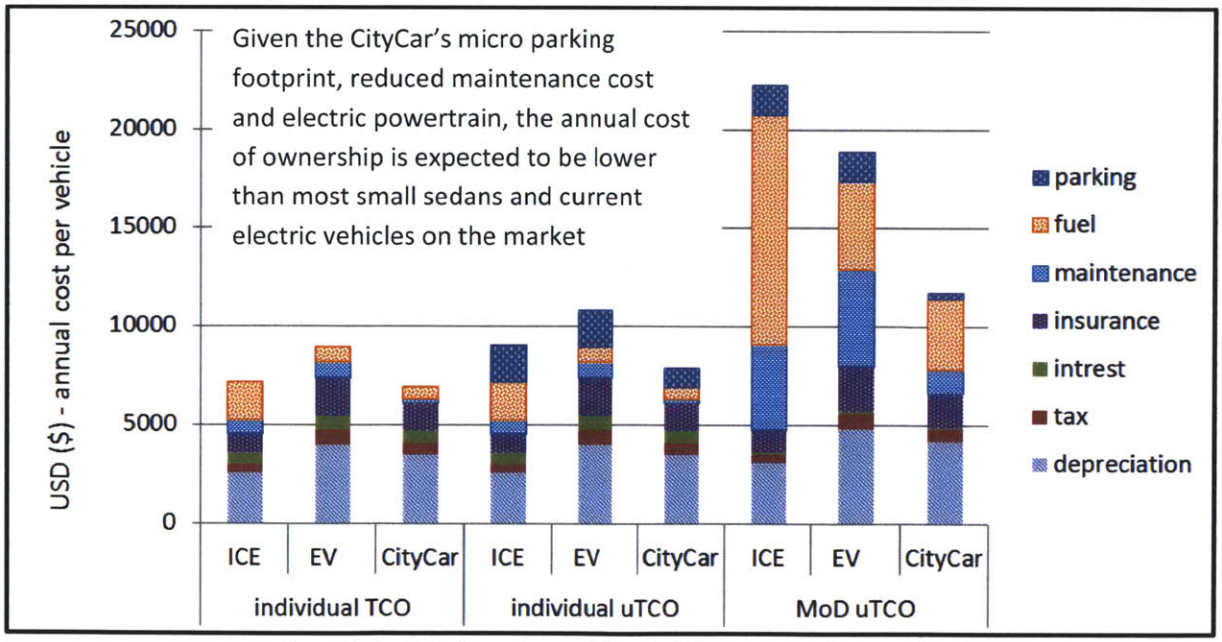

Figure 3-48: uTCO for various vehicles in different ownership models

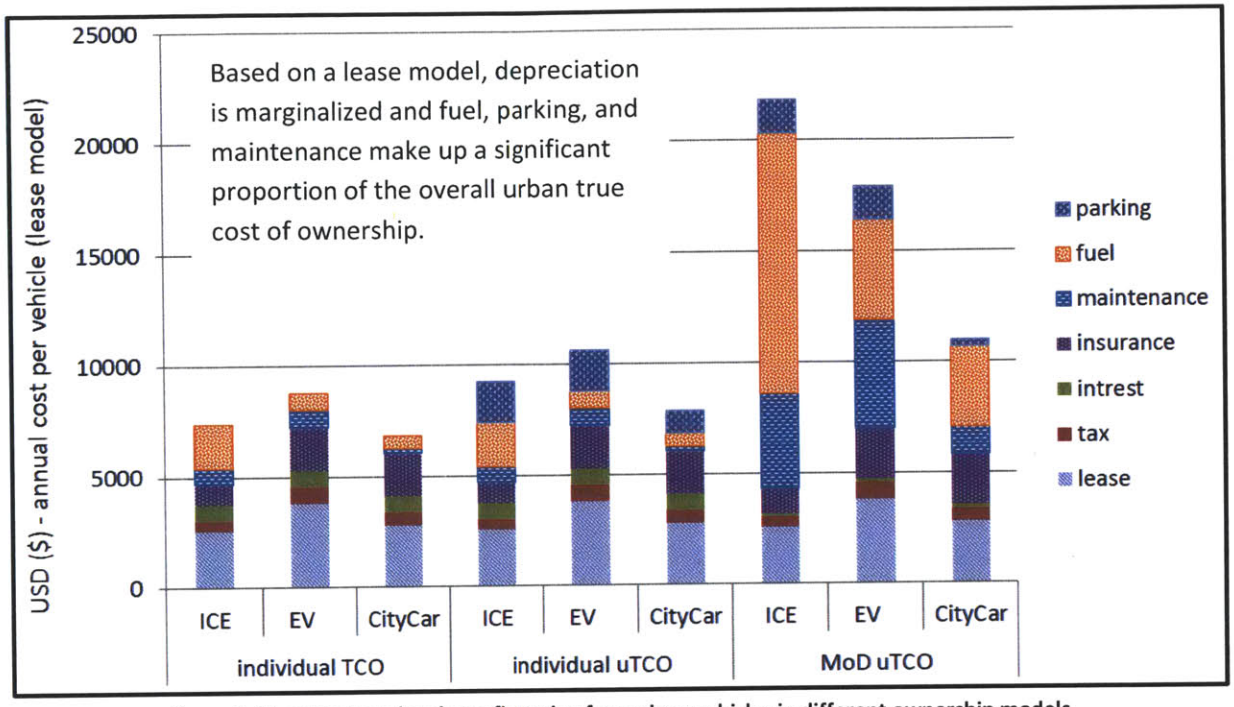

Figure 3-49: uTCO based on lease financing for various vehicles in different ownership models

4 CONCLUSION

The CityCar has served as a platform to explore numerous opportunities within urban mobility. The vehicle concept itself has engaged well over a million (Appendix 7.C) observers to rethink their means personal mobility. As the particular details of the design are focused on urban mobility and support goals of Mobility on Demand, the vision has also provided a springboard to explore supporting technologies such as recharging schemes & energy distribution, methods to manage vehicle fleets through intelligent dynamic incentives, and clever means of electronic customization.

The modular architecture of the CityCar uMEV stimulated new industrial ventures overseas. Basque automotive suppliers have joined efforts to expand their technological competencies in electric vehicles. Each of these core module manufacturers have been empowered to form their own consortium for vehicle development. Additionally, the electric platform of Hiriko can support many of the growing renewable energy sources flourishing in northern Spain and surrounding European cities.

As for operators of shared mobility services, the CityCar/Hiriko may relieve some of the major capital burdens that these startups face. Reduced maintenance demands may allow fleet vehicles to remain in operation for the maximum amount of time. Its condensed parking ratio, ranging from 3:1 to 6.5:1, can ease market penetration by greatly increasing the number of CityCars that can be located in prime areas throughout the city.

The cities themselves also benefit from the presence of CityCar fleets. Since they are lean on space consumption, significant surface area can be rededicated towards green spaces or other community based surroundings. The lightweight, zero-emitting electric platform provides local environmental benefits in crowded cities that suffer from overwhelming CO_2 automobile emissions. Furthermore, traffic flow can be improved by supporting increased ridership of public transit. The CityCar in a Mobility on Demand service supports seamless multi-modal options for end users, addressing first-mile, last-mile challenges.

Overall, the CityCar has served as a conduit between many of the major stakeholders that are essential to best address mobility challenges in a coordinated manner. Opportunities can be discovered for multiple groups indirectly involved in the development of the uMEV platform and CityCar vehicles. Suppliers and new automobile manufacturers can be reenergized through a unique business model. Shared mobility services are given a vehicle option that is tailored to urban environments. End users are provided a distinctive convenient driving experience that improves their interaction to the city. Urban developers are eased in the design of commercial and residential buildings as parking requirements have the potential to be relaxed. Finally, municipalities can be afforded new transit models to offer its residents while reinforcing support to their existing public transportation systems and growing opportunities for revenue.

4.1 Impact on other Stakeholders

Figure 4-1 illustrates the opportunities for interaction between many of the core stakeholders that may be involved in the CityCar development, management, and use.

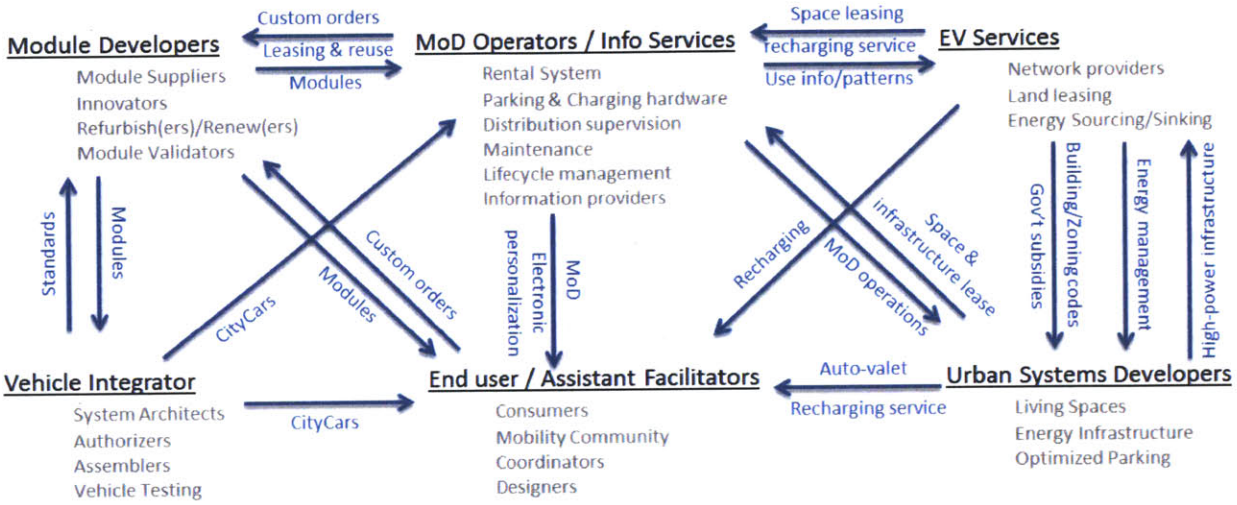

Figure 4-1: Interaction opportunities between stakeholders

4.1.1 Auto Suppliers

Challenges/Problems:

- Suppliers are subject to a one-way and hostile relationship with OEM. Automakers specify exactly which parts they need and how much they will pay for these parts.
- Suppliers are restrained to marginal profits and are greatly restricted to fit OEM pricing and scheduling.
- Many relatively smaller automotive suppliers are edging towards bankruptcy.
- Suppliers have little margins of resources for R&D, nor outlets for innovation

Advantages/Opportunities

- By expanding their engineering role to include design and innovation, suppliers assume more responsibility and become module designers instead of just part suppliers (modules – RWs, driver interface, power, rear utility) and expand their capabilities from just suppliers to also module sales, customization, and reuse.
- Develop amiable relationships and improved interactions with OEMs/Integrators (GM Gravatai, Brazil plant example, suppliers work within GM to design subsystems).
- Opportunity to establish a supplier network, in which they collaborate to meet industry standards while introducing their own ideas and innovations.

4.1.2 *Fleet Operators*

Challenges/Problems:

- High operating costs - Redistribution of the vehicles during the day is the highest cost to the service and prohibits the systems to becoming profitable (many hours of high cost manual labor).
- High utilization causes vehicles to wear down at a faster rate. Additionally, in some cases, users abuse vehicles in public/shared services.
- Services lack sense of ownership amongst end users
- Cost and demand of land is at a premium in major metropolitan cities.
- Acquiring land to develop vehicle stations presents initial challenge and difficulty for station flexibility.
- Commercial vehicles are difficult to monitor in real time (location, charge level, maintenance needs)
- Security monitoring - high utilization and 24-hr exposure presents vulnerability to vandalizing.
- Rental pricing models seldom reflect varying real-time circumstances

Advantages/Opportunities:

- Utilizing CityCar vehicles in a Mobility-on-Demand service can help fleet operators better service their customers while requiring less space to park each car at their stations (3:1 up to 5:1 ratio).
- The CityCar's drive-by-wire platform can better utilize embedded sensing and networking technologies within, allowing for real-time vehicle monitoring (location and security), and provide the potential for autonomous assistance in redistribution and automated valet services.
- The CityCar's modular platform allow fleet managers to rapidly substitute, service, and update modules separately from the vehicle as a whole, keeping operable CityCars in circulation for longer sustainable periods of time.
- Performance and design customization allow operators to provide unique local mobility solutions, optimized given each city's characteristics (the Boston CityCar w robust RWs vs. the LA w extended range).

4.1.3 *ORIGINAL EQUIPMENT MANUFACTURERS (OEM)*

Challenges/Problems:

Tight timelines with large proportions of responsibility. Business model built on annual commodity.

- Most OEMs are too big to be flexible and rapidly implement new technologies.
- Assume the majority of responsibility and risk – design, manufacturing, research, certification, marketing
- U.S. OEMs find it difficult to attract new innovative talent. Young graduates instead opt for silicone-valley type careers. Detroit is viewed as an industry that doesn't seem interested in doing new things.
- Lacks "open innovation" little outsourcing of its R&D to outside, small, nimble entities.
- Disruptive innovations threaten OEM's business model.
- Nasty labor and supplier relationships
- Lost brand loyalty from end users

Advantages/Opportunities:

- Through changing their role from a vertical manufacturer to an integrator (coordinator, assembler, and certifier), an OEM or new vehicle system architect can enhance product flexibility while improving their supplier relationships by empowering the suppliers to design and create new modules.
- By establishing and managing interfaces and their standards, the system architect can build an ecosystem of module suppliers which allows innovation to develop.
- Reduces risk of innovation and cost of failure by distributing responsibility

4.1.4 *End Users*

Challenges/Problems:

- Lack of new innovative products in mobility (automobile architecture has changed little over the past century).
- Long term increases of gas prices.
- True cost of ownership for automobile in major cities is often prohibitive
- Vehicles with new technologies tend to be too expensive to be embraced by the masses.
- End users tend to need multiple types of vehicles or multi-purpose vehicles (SUV), which results in inefficient use of resources and high costs.
- Parking in cities is expensive and often difficult to find.
- Vehicle customization is prohibitively expensive because it usually involves many hours of high labor costs
- Growing percentage of elderly population face difficulties maintaining the ability to drive

Advantages/Opportunities:

- CityCar in Mobility-on-Demand system offers the end user a high-tech transportation option without high capital costs (low risk to try new technology).
- In individual CityCar ownership, users can exploit customizable options.
- Eased parking in street (fitting into smaller narrow spaces like the Smart ForTwo), or designated MoD spots
- Reduced cost to refill from relatively less expensive electricity for lightweight short-range small CityCar
- With the combination of eased ingress/egress, custom driver interfaces, increased visibility, and the capacity for electronic driver assist, the CityCar not only improves the experience for the common motorists but also expands the potential for elderly and physically-limited drivers

4.1.5 *Municipalities/Utilities*

Challenges/Problems:

- Parking is significantly subsidized by local governments.
- Cities want to provide parking options from which they can generate revenue.
- Accordingly, relationship between drivers and municipal staff is hostile at minimum (only interaction is during payments and disputes).
- Public transit systems are underutilized in many cities and are rarely profitable. Additionally, infrastructure costs to expand or alter routes are extremely expensive and inflexible to adaptation.
- About a third to a half of the space is dedicated solely to automobile use and a large portion is used for parking; instead, much of these spaces could be used for parks or other socially inviting areas.
- Electric utility companies must manage changing energy demands throughout the day (mid-day peaks, renewable imbalances)
- Renewable and regenerative technologies with fluctuating outputs need energy storage solutions (wind turbine, solar, subway breaking).

Advantages/Opportunities:

- Cities have the opportunity to offer mobility services tied directly to their revenue resources.
- Municipalities can offer community mobility services and incentivize operation instead of solely relying on punitive revenue.
- Mobility-on-Demand services can supplement public transit by supporting established lines, expanding commuter range, and offer relatively more dynamic coverage.
- CityCar's 3:1 parking ratio allows for greater vehicle saturation, therefore more vehicles can be charged for parking per square foot and/or parking spaces can be repurposed for other uses (preferably green spaces).
- CityCar park-and-charge stations that incorporate a battery-bank buffer offer electric utility companies attractive options of sourcing power to the batteries during high output of renewables or sinking power from batteries during peak hours of demand.
- MoD stations located adjacent to electric public transportation not only complement each other by offering convenient multi-modal transport, but there are potential additional incentives of sharing electric infrastructures to efficiently manage high power exchanges.

4.1.6 *URBAN DEVELOPERS*

Challenges/Problems:

- Developers of new residential buildings are required to incorporate parking spaces for each of its residents (1:1 parking space to living unit)
- Parking structures are often an afterthought in design and are seldom desirable areas of dwelling (concrete surrounded, poorly lit, dirty, poor air quality).
- Parking structure surface area is poorly utilized as result of the average vehicle capabilities (turning radius, door clearance, parking capabilities of driver); therefore, much of the space in a given parking lot is dedicated to moving the vehicles and spaces in-between for ingress/egress access.
- Building zoning is prohibitive to mixed use complexes.
- Integration of EV charging posts are retro fitted to parking structures and buildings currently do not support infrastructure for high-power rapid charging.
- Live/work spaces are poorly integrated to parking.

Opportunities:

- Developers can offer mobility service as a unique option to their occupants.
- Residential and commercial complexes can offer CityCar MoD services as a portion of their overall parking and significantly reduce the amount of square footage dedicated to parking or permit more vehicles within their lots.
- Utilizing CityCars in an automated valet system can enable an 5:1 parking ratio compared to traditional car parking and provide a clean seamless drop-off for their occupants.
- The CityCar's clean electric platform can allow for unpolluted parking areas that may be better integrated to the living and work spaces.

5 FUTURE WORKS

The CityCar uMEV provides a clean, lightweight, micro-sized personal mobility option for today's growing cities. Moreover, the vehicle's features have been tailored to ease transit for end-users and to provide operational efficiencies for shared mobility systems, such as Mobility on Demand (MoD). As it has shown potential for new mobility ventures, it could benefit even more from the advancement and incorporation of particular technologies.

Including spatial sensing, vehicle-to-vehicle communications and some level of autonomous technologies can provide advantages to drivers and shared fleet operators. Occupants of the CityCar can be as ease with reduced or relieved vehicle operation while benefiting from potential safety improvements. Additionally, MoD operators can better manage their fleet by permitting vehicles to self-park in extremely tight spaces, and utilize the autonomous capabilities to redistribute the fleet across the city, meeting fluctuating demands. Given enough sensing, communications, and computational capabilities, each of the CityCars could coordinate throughout the city like a node in a network.

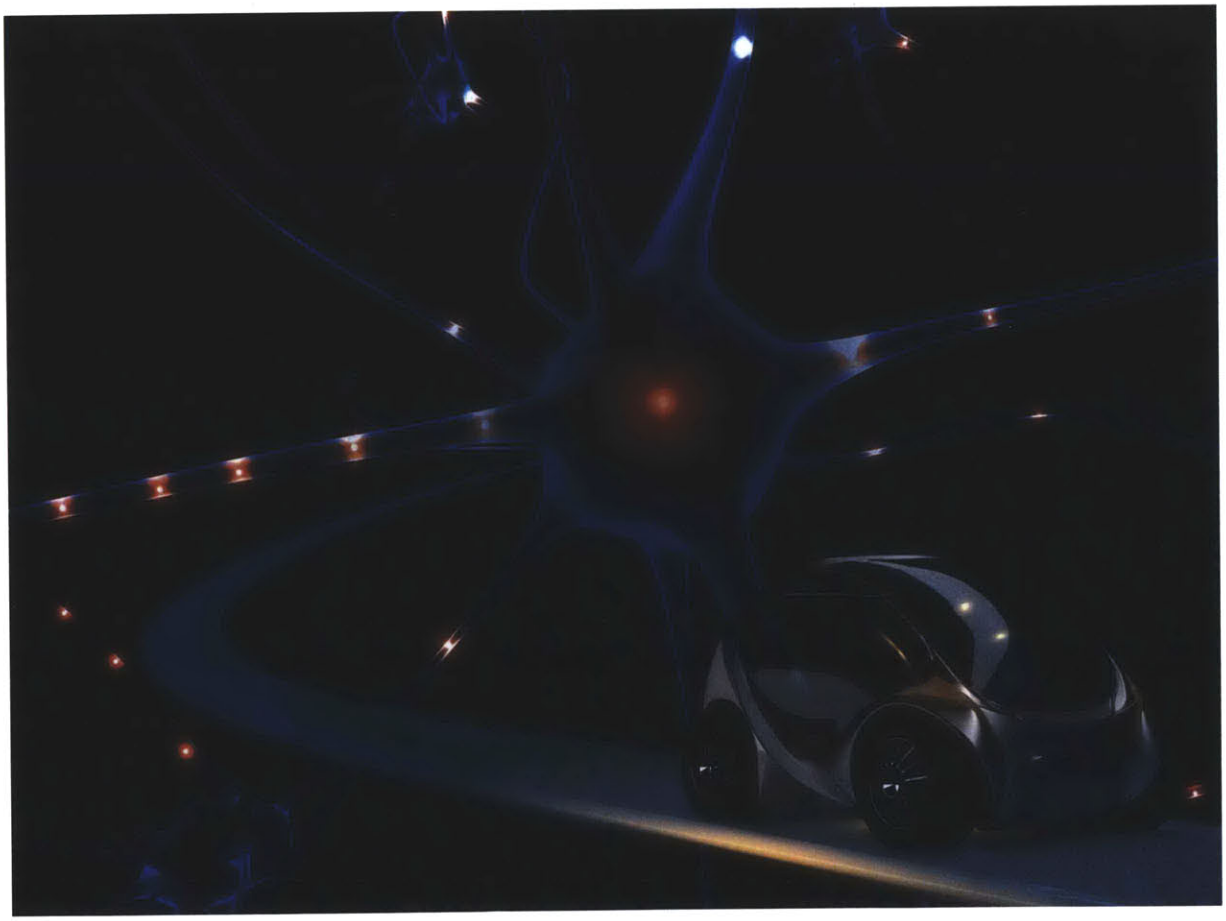

Figure 5-1: Networked CityCar

As the system grows, hundreds to thousands of electrically powered CityCars would benefit from the advancement of recharging infrastructures. Whereas supplying, redistributing, parking, monitoring, and maintaining the vehicles offers its own challenges, recharging a potentially large fleet of these vehicles can present an overwhelming complication. Even though it is feasible to have hundreds of these cars dock into parking spots and use conductive plug-in chargers (as done by some European municipal electric utility vehicle fleets seen in Figure 5-2), the potential entanglement of so many cables may soon become an unattractive resolution. Instead, utilizing inductive charging plates within the floor of the parking area can present a clean organized interface for the many CityCars to park over, recharge, and exit when needed.

Figure 5-2: Electric charging of Barcelona municipal service fleet

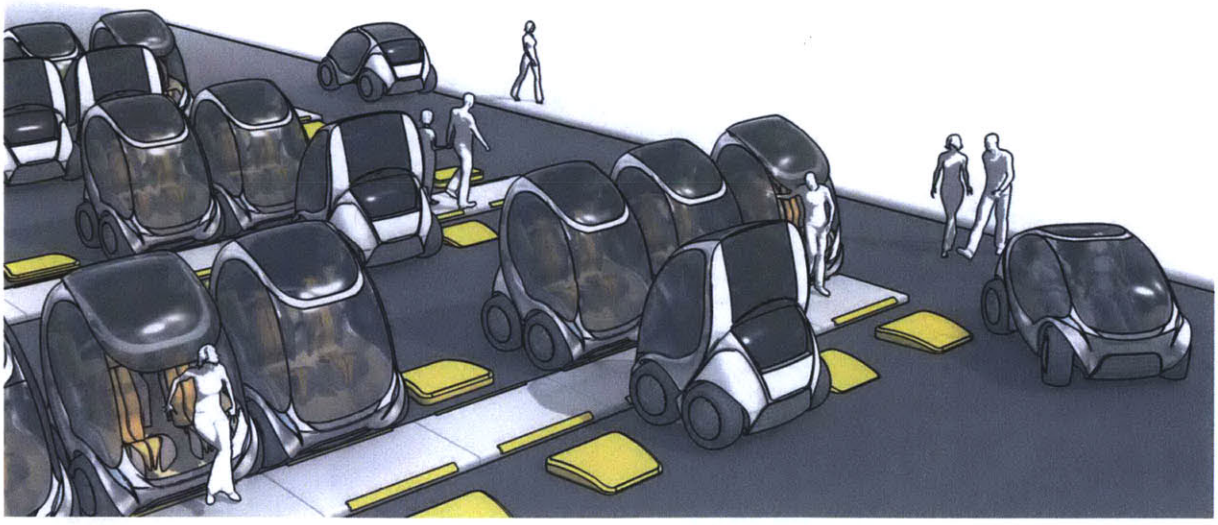

Figure 5-3: Inductive charging pads in CityCar parking lot

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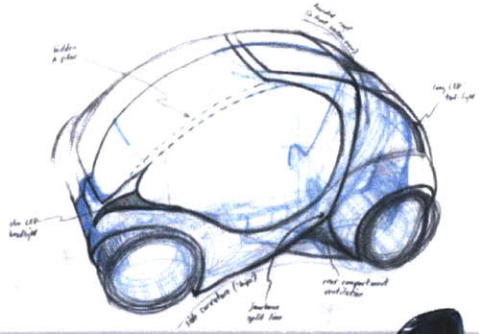
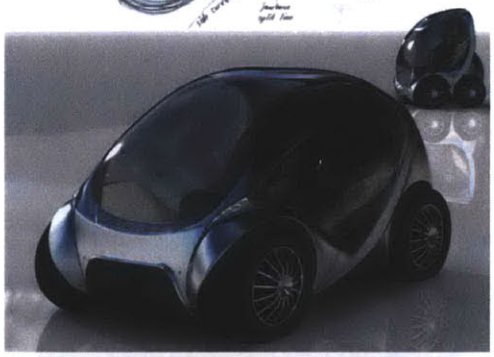
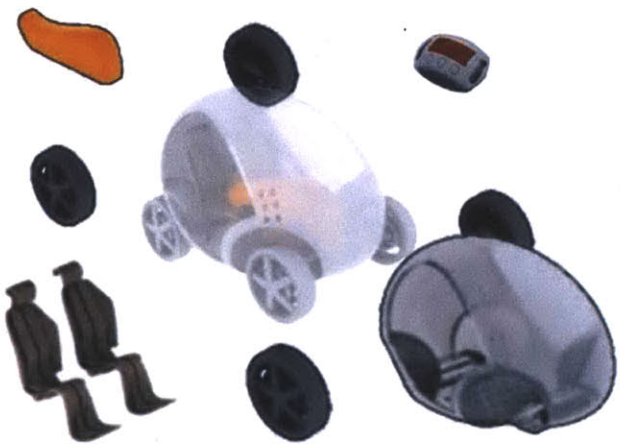
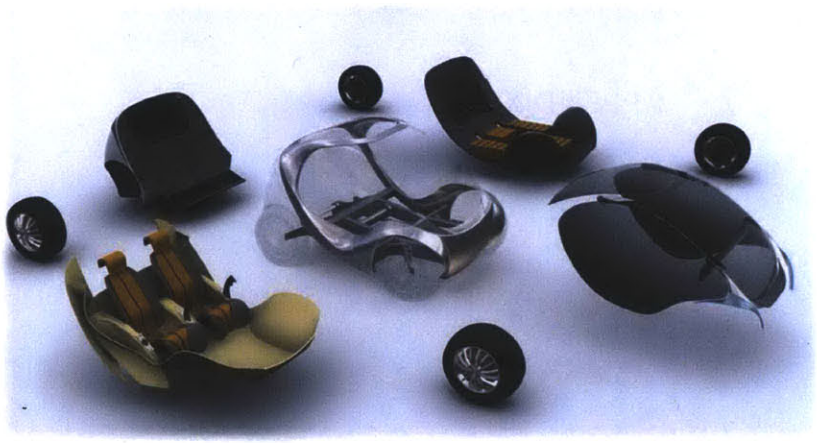
7 APPENDIX

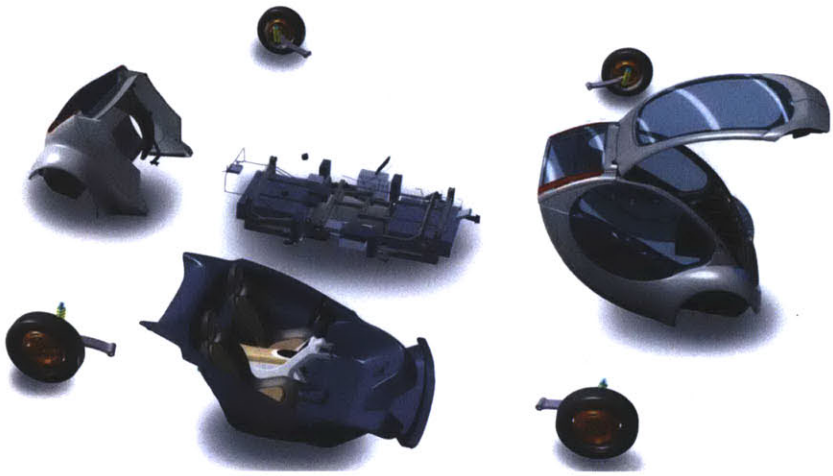
7.A CITYCAR: SKETCH TO PRODUCT





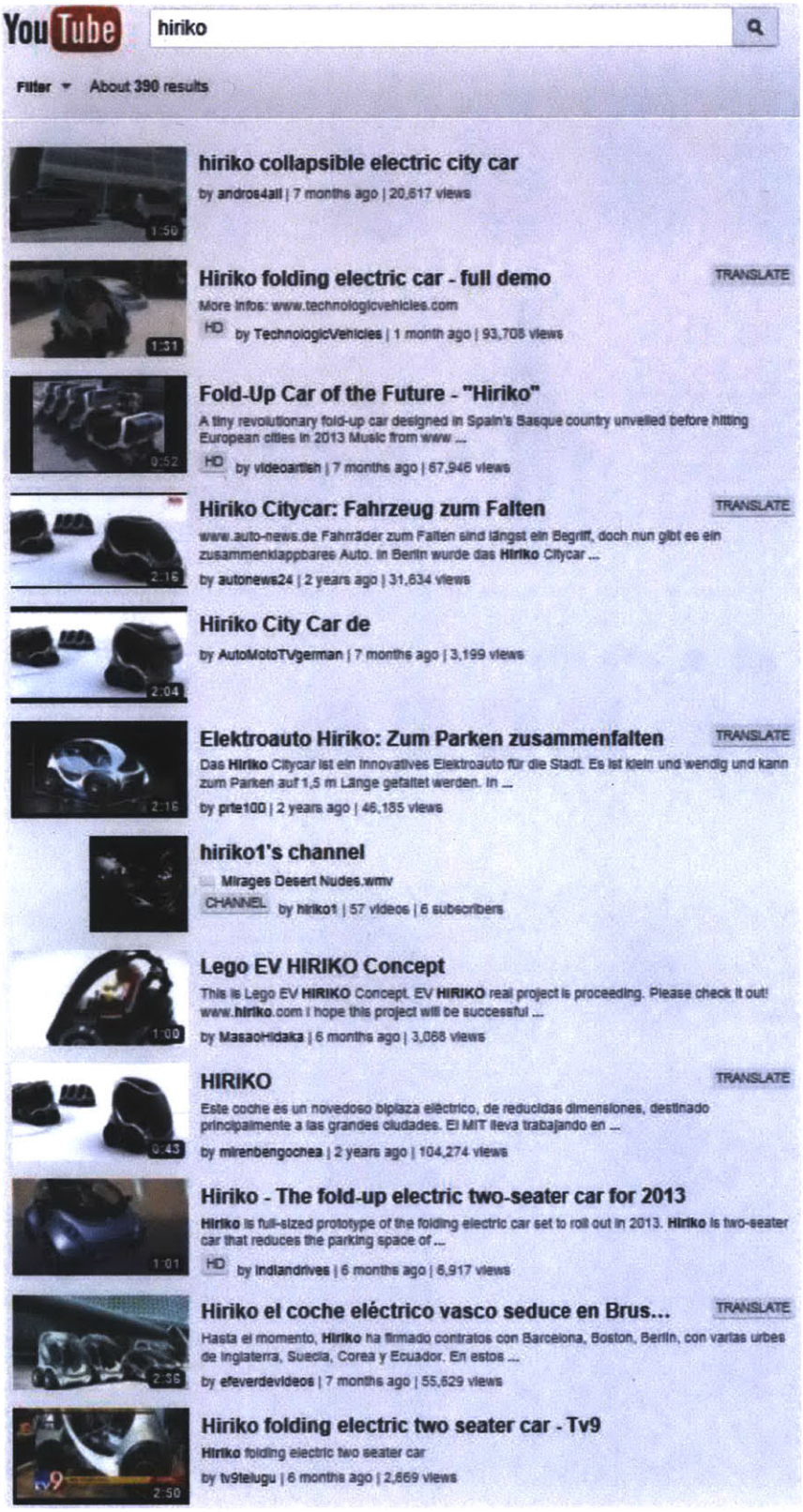






7.B MODULAR ENERGY SYSTEM – POWER PODS

7.C MEDIA EXPOSURE OF CITYCAR & HIRIKO



MIT Media Lab's folding CityCar

This 'folding car' from **MIT** Media Lab could change the way we travel in cities. We caught up with one of the team behind it at Media Evolution's ...

HD by **thenextweb** | 1 year ago | 174,461 views

MIT Media lab shows off urban, electric vehicles

MIT's electric vehicles for urban environments are showcases, including the folding **CityCar** and the electric bike attachment known as the ...

HD CC by **networkworld** | 2 years ago | 161,651 views

Why Design Now?: MIT CityCar

Why? Mobility on-demand and shared use are alternatives to private car ownership, and **CityCar** is a concept vehicle that combines the two. This two ...

by **cooperhewitt** | 2 years ago | 9,126 views

CityCar Changing Places Group

HD by **MITChangingPlaces** | 1 year ago | 187,829 views

mit citycar

by **cooperhewitt** | 1 year ago | 331 views

MIT's CityCar Concept

by **Pikinvent** | 1 year ago | 1,082 views

MIT shows off urban, electric vehicles.mp4

Here's an vehicle which I think will hit the market soon. I think this Hiriko is cool uncle-bugs.blogspot.com The **CityCar** or **MIT CityCar** is an ...

by **bugstan** | 6 months ago | 2,843 views

Green Revolution - CityCar

Lisa Van Pay of the National Science Foundation meets Will Lark, an **MIT** graduate student working on the **CityCar** project. The two discuss the ...

by **greentvgreentv** | 8 months ago | 885 views

City Car Apilable • MIT - Franco Vairani - Bill MI...

TRANSLATE

www.autoallas.com • El City Car, especie de microcar, llamado también smart car, desarrollado por un grupo de ingenieros y arquitectos del **MIT**` y ...

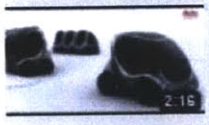
by **wwwautoallascom** | 4 years ago | 12,137 views

KAI Amokk Deep mit Citycar Darmstadt

TRANSLATE

Szeneflicker on tour KAI $ Amokk Deep.

HD by **CitycarDarmstadt** | 11 months ago | 1,252 views



Hiriko Citycar: Fahrzeug zum Falten

TRANSLATE

www.auto-news.de Fahrräder zum Falten sind längst ein Begriff, doch nun gibt es ein zusammenklappbares Auto. In Berlin wurde das Hiriko **Citycar** ...

by **autonews24** | 2 years ago | 31,634 views

CityCar prototype explained

A demo of the **CityCar** prototype at **MIT** Media Lab/Smart Cities, featuring an interview with one of the researchers working on the project.

HD by **liamont** | 1 year ago | 124 views

CityCar Driving

Half-Scale prototype showing off some of the cool stuff it can do.

by **ChrisMills90** | 2 years ago | 2,941 views

7.D HIRIKO CORE FEATURES:

1. **Wheel Robots** - In-Wheel electric motor module with embedded suspension, electronic braking, and independent electronic steering system.
2. **Front Egress** - Frontal entry system that integrates front windshield, driver controls, and accommodates easy ingress/egress for passengers.
3. **Folding Chassis** - An actuated folding mechanism connects the front passenger cabin with rear storage module.
4. **Drive-by-Wire** - Vehicle control system built upon FlexRay and CANbus technologies.

Characteristics of the Car to include:

5. Communications with GPS integration in the city – Smart Interface inside vehicle (not interlinked with points 1 thru 4). Plus sensing necessary for autonomy.

General Specifications:

Length (unfolded) =	2700 mm
Length (folded) =	1750 mm
Width =	1750 mm
Height (unfolded) =	1650 mm
Height (folded) =	2134 mm
Wheelbase =	1880 mm
Track =	1534 mm
Ground Clearance =	127 mm
"Dry" Curb Weight =	450 kg
Weight with batteries =	524 kg
Gross vehicle weight=	800 kg
Seating Capacity =	2 passengers
Luggage Capacity =	0.3 cu m (current)
Battery Technology =	Lithium nanophosphate
Battery Capacity =	10 kWh (scalable to 20 kWh)
Operating Power =	320 volts @ 30amps
Max. Drive Motor Power =	3.75 kW per wheel (15 kW total)
Drive Motor Torque (cont.) =	136 Nm (per wheel)
Drive Motor Torque (peak) =	185 Nm (per wheel)
Maximum Speed =	70 Km/h
Steering Torque required =	190 Nm (torque at steering axis)
Steering Motor torque (cont.) =	15 Nm
Max Steering Power required =	1.2 kW
Wheel size =	175/65/R15

Requirements for first prototype (optional features in grey):

Exterior

- Finished aluminum safety cell
- Folding Chassis - An actuated folding mechanism connects the front passenger cabin with rear storage module.
- Camera rear view system
- Photovoltaic powering auxiliary functions / comfort electronics
- Keyless front entry
- LED headlamps, brake lights, tail lights and turn signals
- Polycarbonate lower side-panel w/ operable glass windows
    - w/ silk printing to provide for privacy for lower panel
- Front ingress/egress system
    - w/ safety glass windscreen
    - w/ integrate display
    - w/ defrosting
    - w/ integrated wiper
- Proximity Sensing for autonomous parking and drive assist
- Emergency side exit (release latches)

Interior

- Dual drive-by-wire joystick control
    - w/ force feedback
- Interior lighting
    - automatic
- Adjustable power seats
    - w/ extended articulation for front ingress/egress
    - w/ seatbelts
- Side panel storage (briefcase, purse, or laptop bag size)
- Speakers
- Open mini-storage (shared use)
- Central/Main infotainment display
    - Rear view video display
    - OLED
- Electronic latches and door locks
- Ignition button
- Drive mode buttons (Standard, Park, O-Turn, Fold)

Rear Compartment

- Storage to two passengers (minimum two carry-on bags)
- A/C unit to provide heating and cooling to the back of passenger cabin (?)
- Tail and brake lights

Safety

- 180-degree passenger and driver airbag protection
- Emergency side panel release
- Demonstrable dynamic cabin safety
- 3-point seatbelts
- Reinforced side impact (polycarbonate and steel beams)

Drivetrain

- In-Wheel electric motor module with embedded suspension, electronic braking, and independent electronic steering system
- Four-wheel omnidirectional steering capability
    - O-turn
    - Mirrored
    - Translation
    - Parallel Parking
- Anti-lock brakes
- Electronic stability control
- Electronic brake-force distribution
- Modular, fail-silent wheel robots
- Drive, braking, steering and suspension integrated in wheel robots
- 10 kW-hr Battery Pack in two physically separated, redundant battery modules
- 15 minute rapid-charge times (Level III equivalent) at Level II 220VAC three-phase line power
- Onboard Level I charger compatible with standard wall outlet
- Zero power use electronic parking brake
- Redundant, fail-operational control system, using FlexRay

Information

- Infotainment (Nokia Meego)
    - Smartphone integration (Terminal)
    - GPS navigation system
    - Vehicle Instrumentation (Charge level, Speedometer, Odometer, Average energy use per kilometer)
    - Wi-Fi
    - Cellular network internet connection (Edge/3G)
- Autonomy sensors (laser field, radar)
- Parking assist
- Autonomous ability to operate in a constrained environment
    - Autonomous parking
    - Remote driving
    - Virtual towing (platooning)

7.E DERIVATION OF HIRIKO ROBOT WHEEL SPECIFICATIONS

Calculating Required Specifications for RobotWheel Drive Motor 6/29/10

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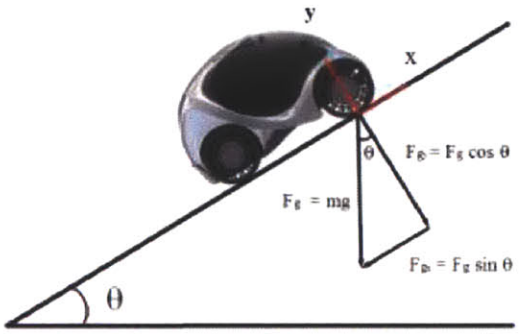
William Lark

Force Balance Diagram

$F_g = mg$
$F_{gx} = F_g \sin\theta$
$F_{gy} = F_g \cos\theta$
$F_{Rx} = F_{Ny}\, c_{rr}$
$F_{Dx} = \rho\, v^{\wedge}2\, c_{Df}\, A\, (1/2)$

$\Sigma\ F_x = F_{Vx} + F_{gx} + F_{Rx} + F_{Dx} = 0$
$F_{Vx} = -(F_{gx} + F_{Rx} + F_{Dx})$

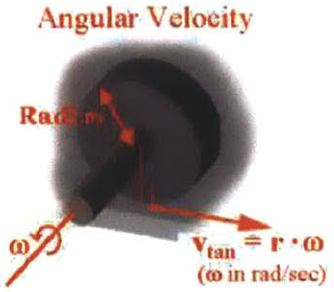
$\Sigma\ F_y = F_{Ny} + F_{gy} = 0$
$F_{Ny} = -(F_{gy})$



Moment Balance

Sum of the Moments in the Y direction
$M_{Ny} = F_{Ny}\, l_y = 0$
$M_{gy} = F_{gy}\, l_y = 0$
$\Sigma\ M_y = M_{Ny} + M_{gy} = 0$

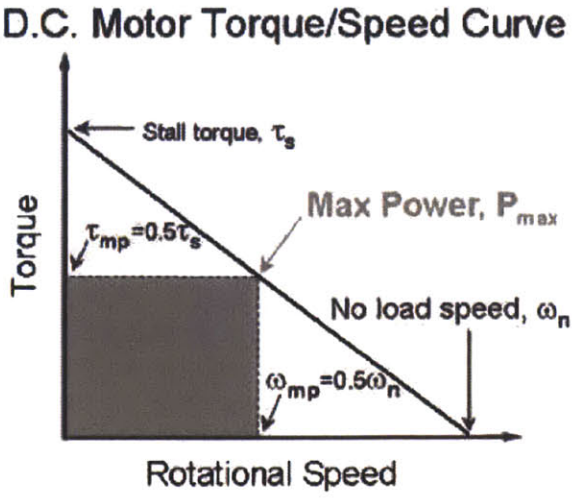
Sum of the Moments in the X direction
$\mathbf{M_{Vx} = F_{Vx}\,(l_x)}$
$M_{gx} = F_{gx}\,(l_x)$
$M_{Rx} = F_{Rx}\,(l_x)$
$M_{Dx} = F_{Dx}\,(l_x)$
$\Sigma\ M_x = M_{Vx} + M_{gx} + M_{Rx} + M_{Dx} = 0$
$\mathbf{M_{Vx} = -(M_{gx} + M_{Rx} + M_{Dx})}$



Torque vs. Speed

Motor Torque
$\tau = \tau_s - \omega\, \tau_s / \omega_{nl}$
$\tau_{nl} = 0$
$\tau_{mp} = 0.5\, \tau_s$
τ_s = stall torque (max torque)

Angular Velocity
$\omega = (\tau_s - \tau)\, \omega_{nl} / \tau_s$
ω_{nl} = no load speed (max rpm)
$\omega_{mp} = 0.5\, \omega_{nl}$
$\omega_s = 0$



Torque and Power vs. Speed

Motor Power

$P_{motor} = \tau * \omega$

$P(\omega) = -(\tau / \omega)\ \omega\ ^2 + \tau\ \omega$

$P(\tau) = -(\omega / \tau)\ \tau^2 + \omega\ \tau$

Motor Power: as function angular velocity

$P_{el}(\omega) = -(\tau_s / \omega_{bd})\ \omega_{bd}\ ^2 + \tau_s\ \omega_{bd} = 0$

$\mathbf{P_{mop}(\omega) = -(\tau_s / \omega_{bd})\ \omega_{mp}\ ^2 + \tau_s\ \omega_{mp}}$

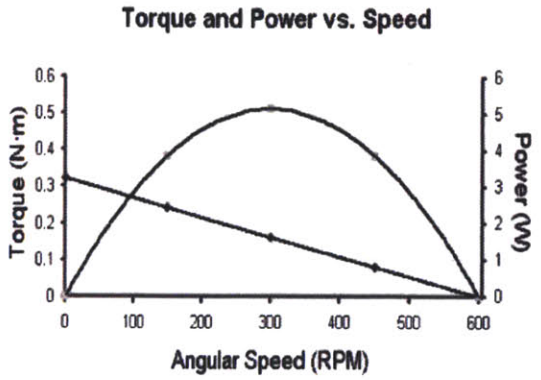
$P_s(\omega) = -(\tau_s / \omega_{bd})\ \omega_s\ ^2 + \tau_s\ \omega_s = 0$

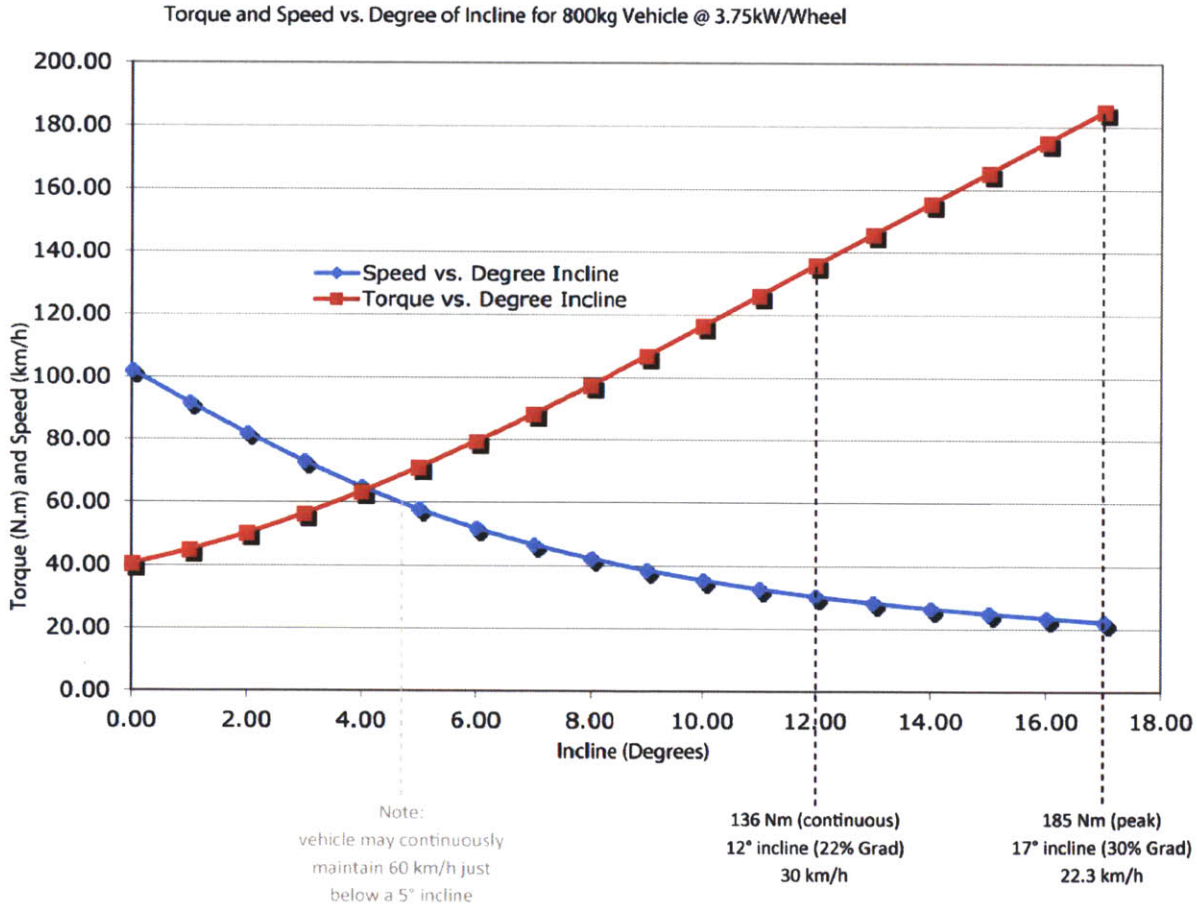
Motor Power: as function motor torque

$P_s(\tau) = -(\omega_{bd} / \tau_s)\ \tau_s^2 + \omega_{bd}\ \tau_s = 0$

$\mathbf{P_{mop}(\tau) = -(\omega_{bd} / \tau_s)\ \tau_{mp}^2 + \omega_{bd}\ \tau_{mp}}$

$P_{el}(\tau) = -(\omega_{bd} / \tau_s)\ \tau_{el}\ ^2 + \omega_{bd}\ \tau_{el} = 0$





Calculating Required Specifications for RobotWheel Steering Motor

Calculating Minimum Steering Torque for a variable scrub radius

τ_s = *steering torque*
x = *steering offset (scrub radius)*
F_N = *Normal Force*
P = *pressure at contact patch*
μ_s = *coefficient of friction*
A = *area of contact patch*
R_c = *radius of contact patch (1/2 tire width)*

$$F_N = PA$$

$$\tau_s = r\mu_s F_N$$

$$\tau_s = (x + r)\mu_s PA$$

$$d\tau_s = (x + r)\mu_s P \cdot dA$$

$$dA = r \cdot dr \cdot d\theta$$

$$d\tau_s = (x + r)\mu_s P \cdot r \cdot dr \cdot d\theta$$

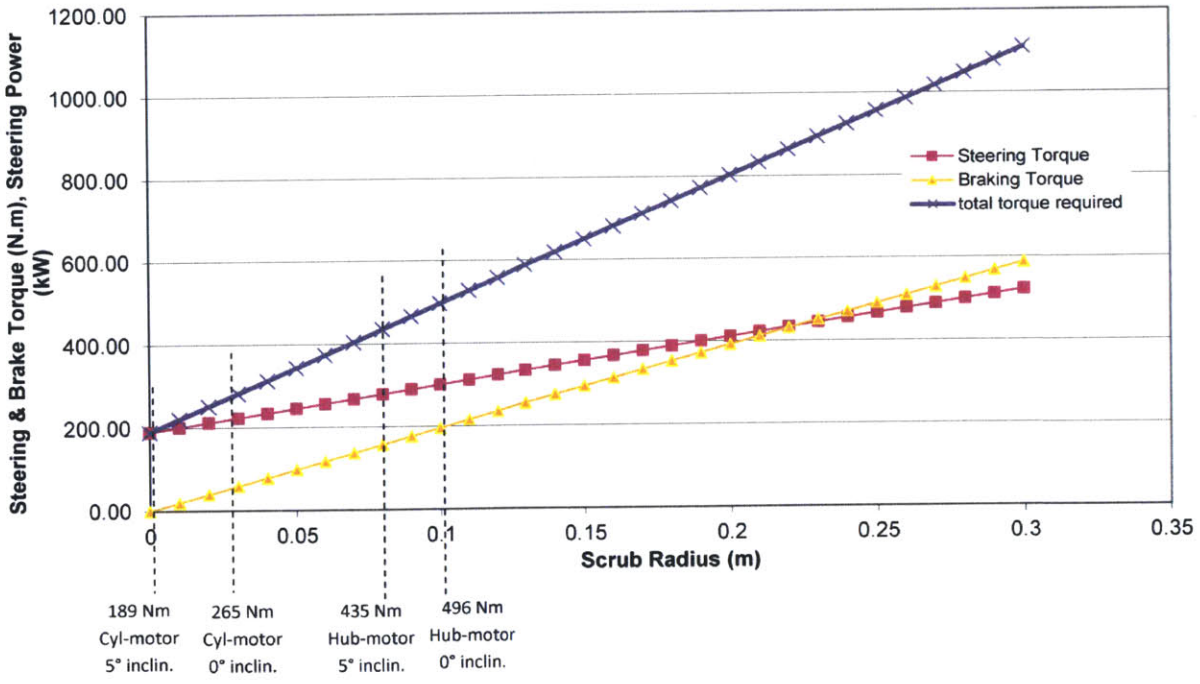
$$\tau_s = \mu_s P \iint (x + r)\ r \cdot dr \cdot d\theta$$

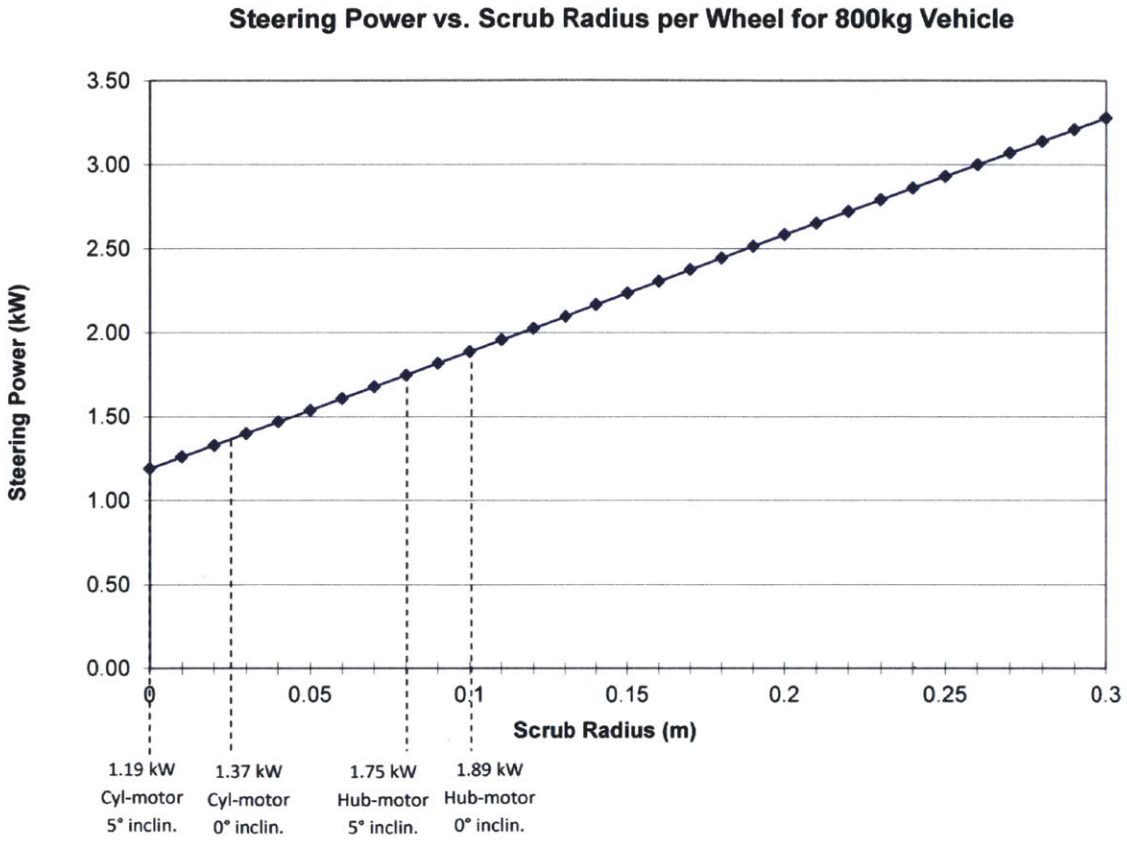
$$\tau_s = \mu_s P \int_0^{2\pi} \int_{-R_c+x_o}^{R_c+x_o} (x + r)\ r \cdot dr \cdot d\theta$$

$$\tau_s = \mu_s P \int_0^{2\pi} \left|\left(\frac{r^3}{3} + \frac{r^2 x}{2}\right)\right|_{-R_c+x_o}^{R_c+x_o} d\theta$$

$$\tau_s = 2\pi\mu_s P \left|\left(\frac{r^3}{3} + \frac{r^2 x}{2}\right)\right|_{-R_c+x_o}^{R_c+x_o}$$

Steering & Brake Torque vs. Scrub Radius





Resultant mechanical behavior of "fail-silent" non-functioning steering motor

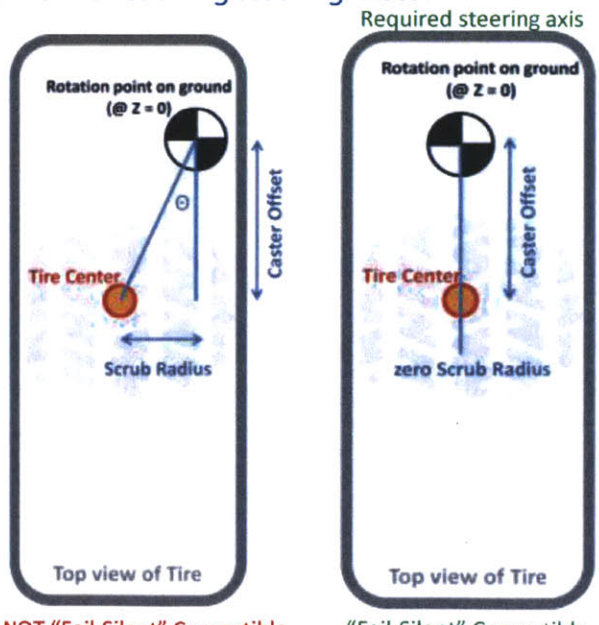
Tan Θ = Scrub / Caster

Θ (fail-silent wheel angle) < 5°

Max Scrub radius = (Tan Θ) / Caster

Caster = 40 mm

Max scrub radius = 3.5 mm



Steering Torque and Power Estimations (01/26/11)

The following steering torque and power estimates are based on 1:1 gear reduction for 5mm incremental differences in scrub offsets, 5RPM changes in rotational steering speed and a given 50/50 weight distribution front and rear for a 700kg gross vehicle weight (GVW). These estimates will differ with further changes in gear reduction, scrub offset, steering speed, weight distribution and GVW.

Scrub Offset (mm) @ 5 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	89	98	111	127	148	172	201
Max Steer Power: w/ Rear Braking (W)	89	92	99	111	125	144	167
Max Steer Power: No Braking (W)	89	91	97	107	120	138	160

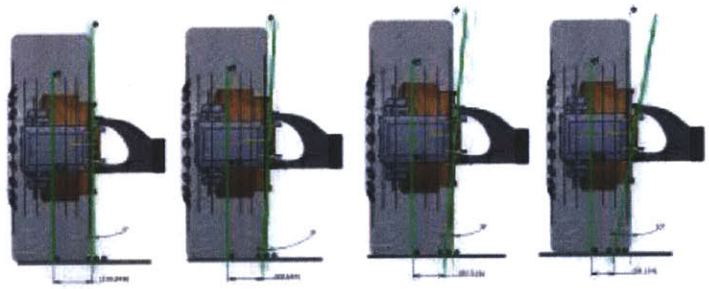
Scrub Offset (mm) @ 10 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	179	196	221	254	295	344	401
Max Steer Power: w/ Rear Braking (W)	179	184	198	220	250	288	329
Max Steer Power: No Braking (W)	179	182	194	213	241	276	319

Scrub Offset (mm) @ 15 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	267	293	331	381	443	517	602
Max Steer Power: w/ Rear Braking (W)	267	276	298	331	375	432	500
Max Steer Power: No Braking (W)	267	273	290	320	361	414	478

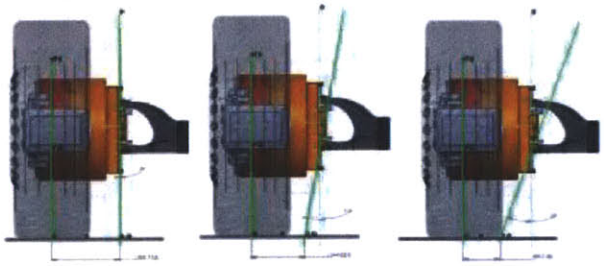
Scrub Offset (mm) @ 20 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	356	391	442	509	591	689	803
Max Steer Power: w/ Rear Braking (W)	356	368	397	441	501	576	667
Max Steer Power: No Braking (W)	356	364	387	426	481	552	638

Scrub Offset (mm) @ 25 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	445	489	552	636	739	861	1003
Max Steer Power: w/ Rear Braking (W)	445	460	496	550	626	720	834
Max Steer Power: No Braking (W)	445	454	484	533	601	690	797

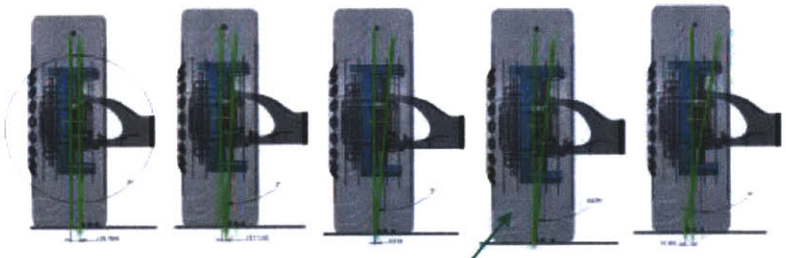
Scrub Offset (mm) @ 30 RPM, 50/50 FRWD	0mm	5mm	10mm	15mm	20mm	25mm	30mm
Max Steer Torque: w/ Front Braking (Nm)	170	187	211	243	282	329	383
Max Steer Torque: w/ Rear Braking (Nm)	170	176	189	210	239	275	319
Max Steer Torque: No Braking (Nm)	170	174	185	204	230	263	305
Max Steer Power: w/ Front Braking (W)	534	586	663	763	886	1033	1204
Max Steer Power: w/ Rear Braking (W)	534	553	595	661	751	864	1001
Max Steer Power: No Braking (W)	534	545	581	639	722	827	957



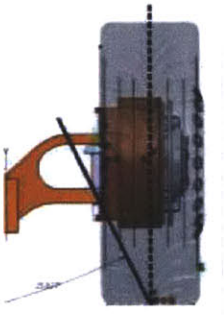
"pancake" hub-motor (100mm width, 175mm rim) – large scrub radius, 80-100 mm (10+degree inclination too high for omnidirectional vehicle)
None compatible with "fail-silent" robot wheel control system



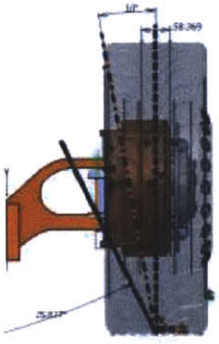
"pancake" hub-motor with planetary gearbox (85mm) – unreasonable scrub radius and inclination
None compatible with "fail-silent" robot wheel control system



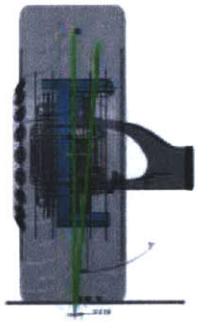
"sausage" cylindrical-motor - small (25 mm) to zero scrub radius (5.6-degree kingpin inclination)
compatible with "fail-silent" robot wheel control system



Zero scrub radius, but inclination too large



Maximum inclination requires a ~60 mm (58.369mm) motor width

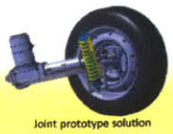


Zero scrub radius with 5° inclination

7.F ROBOT WHEEL ANALYSIS

A	B	C	D Robot Wheel Review	E September 23, 2010	F	H 2011 Review

Hiriko Core Features:
1. Wheel Robots - In-Wheel electric motor module with embedded suspension, electronic braking, and independent electronic steering system.
2. Front Egress - Frontal entry system that integrates front windshield, driver controls, and accommodates easy ingress/egress for passengers.
3. Folding Chassis - An actuated folding mechanism connects the front passenger cabin with rear storage module.
4. Drive-by-Wire - Vehicle control system built upon FlexRay and CANbus technologies.

				 Supplier "HUB" proposal (summer 2010)	 Initial MIT proposal (summer 2010)	 Proposed resolution (fall 2010)	 Joint prototype solution (spring 2011)
3	design/packaging	powertrain axle	battery space	Battery space is compromised from potential rack-&-pinion, and even more from hydraulic brake sub-component system (pumps, lines, electro-mechanical actuators)	The core of the front and rear powertrain is dedicated to the volume of the battery packs. Each pack consumes a volume space of 500mm x 600mm x 165mm.	First we must ensure that the components of an electrically actuated hydraulic brake system can be housed in a different region than laterally in-between the wheels (not in powertrain module region). Brake pumps and actuators may have to be situated on main chassis (left or right cavity). However, in the case of the steering mechanism(s), a solution must be found incorporating either a geared servo motor or a pivoting linear actuator (behaving as a split rack-&-pinion) on each robot wheel. A single rack-&-pinion bisects the battery compartment and compromises the modularity of the vehicle. The only available place for a rack-&-pinion would be behind the powertrain module (400mm behind the wheel center axle) with rocker arms mounted to the module to translate the motion to the wheels; this will increase the length of the car, an an undesireble consequence, which compromises the Hiriko car concept.	Leading/trailing arm maintains ample space for battery compartment since swing arm occupies longitudinal volume. Encrouches less into battery module volume
4			battery slide	The ability to slide batteries out from the front and rear powertrain module will be lost if a "HUB"-proposed rack-&-pinion steering component is added. This creates difficulty for servicing and battery leasing program.	Keeping the components as modular as possible, the battery core is built on a drawer system that enable easier access from the front and the rear of the vehicle. This becomes crucial for rapid servicing through the Hiriko battery leasing model.	(see above, G3)	no conflict with battery slide (see above, H3)
5		sub-components	part count	potentially relatively higher part count from multiple subsystems	opportunity to reduce because of the elimination of subsystems (many of which require integrated fluid assemblies).	Goal must be to focus the majority of the vehicle's complexity into the robot wheel in order to significantly reduce the components in the vehicle's body.	Relatively fewer moving pats than previous proposals. However each component is fairly custom and complex
6			integration	Overall more integrated -- compromises modularity for businesses of assembly and servicing models (see modularity section below)	Highly decoupled mechanics and modules for product flexibility and assembly & servicing models. Requires highly reliable control system and mechanically induced safe defaults states	Must find balance of which systems must maintain modularity versus which ones may remain more integrated. Designs should strive to keep steering decoupled and modular since it must be tightly designed with the suspension; however, the initial brake system may remain centrally integrated since such a component may be eventually substituted for a fully electromechanical system	Complete module is well compartmentalized. Simplicity of module eliminates the need for tuning of the steering components. Complete module requires two assembly locations - (1) swing arm pivot and (2) coil-over suspension attachment.
7		sub-components (continued)	technology	Suspension, steering, and brake proposals reinforce old technologies (hydraulic brakes, rack & pinion). Drive motor promotes potential future in axial flux asynchronous technology being used more in the automotive industry.	The use of electromechanical brakes may be more efficient since no hydraulic fluid needs to be pressurized by a pump to permit brake assist and ABS functionality. In addition to the functional benefits, developing newer technologies may provide the potential for patents and licensed technologies on suspension, braking, and steering systems.	Focus must be dedicated on the key enabler of the robot wheel - the suspension and steering integration	All drive functions are self contained in Robot Wheel unit. As mentioned above (H6), module only requires two points of assembly.
8			volume	loss of space in vehicle body and powertrain axle from other components/modules (need full assembly model from "HUB" to analyze volume trade off)	Tightly localizes all robot wheel components within the wheel. Does not depend on external sub-components or assemblies located in the vehicle body.	Continue to push for tighter packaging in/near the wheel and show any and all dependent sub-systems. Also focusing on eliminating or minimizing the number of mechanical (sub)systems that must be local will provide the vehicle with greater design flexibility (for example - a rack-&-pinion is fairly constrained as far as its location, however a brake system's components may be placed practically anywhere in the vehicle)	The leading/trailing arm assembly reduces the amount of volume consumed width-wise. Integrators must be mindful of the scale of the steering actuator attached to the swing arm since its movement can begin to consume a significant amount of volume if required steering motor power inceases - resulting in a larger motor and/or gear reduction.
9		wheel arm	wishbone volume	Double wishbone suspension system uses more space	straight axel connection provides more space for other components or wiring	Must leave free space for connectivity, sensors, and/or ECUs	Leading/trailing arm occupies relatively less space than double wishbone (E) but more than stright axle connection (F)
10			connectivity	Cables will flex at two points across wishbones and pivot/flex for steering	Cable must flex once at suspension and steering block	Recommend designing suspension and steering unit simultaneously with connections	Single flex point at arm connection
11			suspension travel	Wishbones are only 165mm and 175mm in length (typical car = 300mm). Suspension creates a tight arc movement - when moving vertically the wheel travels laterally up to 80mm; this would create a great under braking instability. Longer wishbones to minimize this effect and behave closer to a typical car will result in more space lost from the passenger cabin, batteries and powertrain module packaging.	Uses a vertical rail system inside the rim with damper and spring separated. Does not use coil-over because assembly is already limited in suspension height by rim. Overall suspension travel is mostly dictated by the rim diameter. 150mm total travel may be increased to 200mm by either (1) using a 17" rim or (2) using a 16" rim and repositioning the drive motor perpendicularly to rim face	Solution TBD	

12	development/manufacturing	technology	unique	Competing in the saturated automobile low cost market is a losing proposition. A small start up "OEM" like Hiriko cannot survive in normal automobile market providing an electric vehicle without drastically unique features. It will just get beaten		Must compete offering unique features and benefits urban EVs and utilizing Mobility-on-Demand business models.	New "Basque Robot Wheel, BRW" venture is underway
13			Difficulty to duplicate	"HUB" corner unit solution does not integrate new technologies, tackle high levels of complexity, and generate new IP in the engineering. This makes their solution too easy to duplicate, easy to beat in price, and lose relevancy very quickly.	Suspension, steering, and brake units provide domains for Hiriko Cars to lock in custom technologies	Focus on development of unique and compact suspension/steering assembly	Majority of component are proprietary technologies developed through Hiriko project collaboration and by prior supplier research.
14		local costs	suspension	Integrates traditional wishbone suspension architecture with coil-over. ...Can minimize development costs	MIT suspension mechanism uses single DOF slider solution which simplifies the geometry for integrated steering. Requires development / more engineering	Consider solutions that still use one degree of freedom to simplify suspension	Single degree of freedom
15			brake	Off-the-shelf component reduces development costs. Necessary compact packaging may require a custom brake disc and/or caliper; nevertheless, traditional and known. Suffers from regenerative braking "blending issue." There is a resultant lag in transitioning between the hydraulic brake and drive motor brake when engaging regenerative braking. Highly inefficient energy recovery.	Electric (VE) brake caliper will be more expensive than a sole traditional caliper. Nevertheless, the only subsystem it requires (as does any electrically actuated brake or steering unit) is a backup 42-volt battery. In addition VE brake solution can be simplified for Hiriko application – only requires one actuator. Achieves regular purpose braking, parking brake, ABS, and wear adjustment. Also allows for the introduction of regenerative braking. Majority of brake components requires similar manufacturing processes.	Design for electrically actuated hydraulic brake system and make packaging accommodations for eventual electromechanical brake.	Uses back-drive capabilities of hub motor for primary braking. Drum brake is also integrated into hub motor assembly for redundant fail-safe mechanical solution.
16			steering	Drive-by-wire steering system will require significant development cost regardless of independent or rack-&-pinion (commercial rack-&-pinion is not compatible and would require additionally developed sub-systems to actuate).		Pursue drive-by-wire steering system that provides most flexibility for omni-directional movement and fits packaging requirements	Maintains omni-directionality. Independent steering units permit boh O-turn & 4-wheel turning.
17		global costs	complexity trade-off	less complex, requires more subsystems	more local complexity for simpler chassis	The objective of the robot wheel is to concentrate the complexity in order to drastically reduce the complexity and part count of the rest of the vehicle. This will require more upfront investment, but will result in pay-offs in the long run.	Less complex than both previous options with less moving parts, single degree of movement, and no tuning required. However, leading/trailing arm component is fairly complex to manufacture as it is responsible for integrating all drive sub-systems.
18			Vehicle level part count	Vehicle level part count can only be drastically reduced if most (almost all) function is handled locally in a corner wheel module. Hydraulic brake systems, rack-&-pinion systems, and motor cooling systems only result in highly integrated marginally flexible assemblies that require many subcomponents.			
19			sub-systems	"wet" and/or complex sub-subsystems requiring liquid cooling and hydraulic fluids.	All core drive mechanisms are housed within the robot-wheel without subsystems	goal must be to minimize "wet" subsystems eliminating micro-maintenance	All dry sub-systems
20		Integration		horizontal - off-the-shelf components (open for competition)	vertical - custom core components (maintains control of the module)	(TBD by Hiriko Cars group)	Hybrid of custom and commercial components. More critical parts, hub-motor and swing arm, are custom developments from hiriko suppliers.
21	function/capabilities	steering freedom	O-turn	not enabled	O-turn achieved by turning all four wheels ~60 degrees (final degree is dependent on wheelbase-track ratio). Total sweep of wheel (with a 20-degree angled arm) to a ± 40-degree sweep, 80-degrees total	O-turn is necessary for tight perpendicular parking, a unique feature that has never been implemented in a production vehicle. This new feature provides not only functional benefits, but distinguishes Hiriko from any car (EV or otherwise) in the market. This also allows fleet owners and operators to increase fleet capacity or better utilize valuable urban parking space. The O-Turn allows off-street parking benefit of almost 8:1 for EV fleets.	enabled
22			O-turn safety	not enabled	O-turn achieved by turning all four wheels ~60 degrees (final degree is dependent on wheelbase-track ratio)	O-turn may result in a much safer driving experience since the driver almost never has to use reverse - can always maintain better vision of the direction he or she is moving	enabled
23			new Parking lot model	not enabled	O-turn achieved by turning all four wheels ~60 degrees (final degree is dependent on wheelbase-track ratio)	Maximum omni-directionality enables new parking lot model for Mobility-on-Demand. This will make it not only easy to park at a Mobility-on-Demand station by solving the vehicular circulation problems, it helps to achieve 3:1 parking ratios for on-street public parking spaces. Furthermore, all research and development goals related to autonomous vehicle movement or parking are complicated by the elimination of the O-turn feature because the vehicles cannot be strung together or packed as densely without full omni-directionality.	enabled (see 3.4.1 Collective Space Savings)
24			skid steering	Skid steering will not work with this vehicle since the track and wheelbase are comparable (skid steer requires the wheelbase to be less than the track width and lower friction between surfaces - also cannot be executed precisely).	no skid steering proposed	Since skid steering cannot be executed with precision, requires a drastically different wheelbase-track proportion, requires lower coefficient of friction, and causes significant wear on the tires - skid steering is not an option for executing O-turns with Hiriko. (Indy donuts)	no skid steering enabled (not necessary)
25		Suspension Dynamics	degrees-of-freedom (DOF)	Two degrees of freedom keeps wheels more perpendicular to ground when banking around a turn; however, each wheel travels laterally up to 80mm	Single degree of freedom - simpler to integrate local steering actuator	Two degrees-of-freedom (DOF) is not necessary for such a slow speed city vehicle (second degree typically only provide 1-3 degrees, which the tire flex can and will compensate for anyway) (Citroen 2CV and VW Beatle)	Single degree of freedom. Reduces complications switching modules - only two points of connection and no tuning necessary.
26			suspension travel	200mm (100 bump and 100 rebound)	150mm (100 bump and 50 rebound) ...travel may be increased to 200mm by either (1) using a 17" rim or (2) using a 16" rim and repositioning the drive motor perpendicularly to rim face.	The desired suspension displacement/travel is 100mm free bump travel (with 20mm bounce bumper engagement beginning at 80mm) and 100mm rebound or "droop." Final suspension mechanism will need to maintain 200mm of total travel.	Sufficient supension travel (180mm)
27			Dynamics / Handling	(to be analyzed - second degree of freedom with short wishbone arms causes excessive lateral displacement)	(to be analyzed - single degree of freedom does not maintain perpendicular relationship when banking on turn)	(TBD) see above on DOF section, F25.	To be analyzed - utilizes similar suspension systems found in older Voltswagon (Beatle) and Citroen (2CV) vehicles.

28	function/capabilities (continued)	Drive Torque	acceleration	(need to review axial flux motor data/properties)	(need to review cylindrical motor data/properties)	Although this will be a relatively slower speed vehicle, we must ensure the Hiriko have enough "low-end" torque to maintain a swift/zippy ride, reassuring the driver that it is not a weak vehicle (Hiriko's power perception is important and the ability of a vehicle to quickly accelerate is often necessary for urban driving). Our studies show that due to power restrictions, vehicle will only have good acceleration up to 20 km/h. After this the vehicle feels sluggish (slow to accelerate). Need to discuss options for incremental power boosts (>15kW for <1minute ?).	Meets drive specifications established for 15kW max micro-vehicles (see 3.3.2 Evolution of Robot Wheel).
29			capabilities for larger / heavier	potential to integrate planetary gear to adjust torque characteristics	potential to change gear ratio to adjust torque characteristics	Must ensure Hiriko does not only satisfy minimum necessary torque, since calculations are only for the 450kg (~1000lbs) lightest version of the vehicle. Robot Wheel should be strong enough or customizable/scalable to provide power for heavier vehicles or vehicle platforms that only use 2 robot wheels.	Drive torque can be increased with either liquid coolant or larger hub motor. Wheel size would need to be increased to do so.
30		Redundancy	independent compensation	rack-&-pinion couple wheels in pairs	4 wheel independent by-wire system inherently has built in redundancy – three other wheels can compensate in a case of missed signal or malfunction	Must come to agreement on fail safety measures and establish a safety group.	To be examined (see F30)
31			democratic dominance	may be able to implement 2 to 3 actuator rack-&-pinion to enable override or switching function as backup	Redundancy (and robot wheel independence) enables simpler and less-expensive "fail-silent" control system (as opposed to "fail-tolerant" system that requires double ECUs).		To be examined (see F31)
32		Autonomous compatibility		drive-by-wire component actuation proposed?	full independent local drive-by-wire systems proposed	Autonomous compatibility – full electrically controlled and actuated system offers significantly higher compatibility to driver assisted and autonomous driving, a valuable future feature that will help distinguish this car from the competition.	Full independent local by-wire compatibility
33	Modularity	Assembly	plug & play	Wishbone suspension requires independent component assembly and compression for coil-over, rack-&-pinion requires tuning/adjustment, hydraulic brake requires bleeding ...in addition to power & data lines	requires mechanical connection and data & power lines	The modular suspension corner approach will enable a shorter assembly line thereby reducing cost. Plug & play assembly enables small simple assembly shops/lines. This will expedite not only the manufacture and assembly of the vehicle, but also expedite servicing for fleet owners and operators that value high vehicle utilization and ease of service (a core market for Hiriko). Final specification should strive to maintain one-shot simple mechanical connection, data & power lines, and quick release hydraulic brake line	Two connection points - as simple as MIT initial proposal
34			attachment points	Current "HUB" corner-unit proposal requires at least 6 assembly actions (3 mechanical + 1 brake fluid line + 1 steering arm + 1 power & signal line).	MIT proposal requires as little as 2 actions (1 mechanical + 1 power & signal line).	Final module should require 3 actions (1 mechanical + 1 power & data line + 1 hydraulic line)	Requires 3 actions (2 mechanical + 1 power & signal line).
35		Compatibility	proprietary?	Assembling common components (double wishbone, coil-over, hydraulic brake disc assembly, and rack-&-pinion) leaves market open and vulnerable to imitation	Proprietary module (closed technology) – keeping the module and interface as unique and proprietary as possible will allow the Robot Wheel module provider to control the production, supply, servicing, and upgrading of the unit (similar to apple's 30-pin connector).	B.R.W must define what core components need to become/remain unique to give Hiriko a long term advantage and a domain to upgrade and improve the robot wheel	Core enabling components are proprietary
36			technology control			Controlling technology and compatible interfaces also ensures advantage in a business of customization. Users or fleet operators can then upgrade and customize with "Hiriko" certified hardware.	Hub motor is developed and controlled by core module supplier
37		Servicing	maintenance	Under less than ideal servicing conditions, the use of the hydraulic brake system will require the opening and subsequent bleeding of the hydraulic brake circuit. This is a time and cost consuming operation.	Plug & play ability allows fleet owner to rapidly remove old unit, snap on the new unit [and ship the old unit back to Hiriko services].	Keeping the robot wheel as modular as possible enables a new servicing/maintenance model where corner units can be rapidly switched when necessary keeping vehicles on the road and in service for the maximum amount of time.	Highly modular - plug & play enabled. Ideal for fleet sevicing and maintenance.
38			minimal downtime	(see above four points D37)	(see above four points E37)	Maintaining the availability of vehicles is especially crucial for the fleet and Mobility-on-Demand services, in which vehicles are used much more frequently and require minimal down-time. This can help justify higher initial investment costs and lower maintenance costs for fleet operators.	Ideal for fleet service because of few mechanical connections for complete drive system.
39			service shops	The potentially high part count only reinforces current auto shop servicing models.	An all-in-one unit encourages business to service full module	New business of module servicing shops, not parts shops. A reduced part count and specialized modular vehicle design approach can funnel the servicing of the specialized units back to Hiriko-Cars, contributing to a financially viable vertically integrated lifecycle of the product.	An all-in-one unit encourages business to service full module

7.G COMPARISON OF STEERING MECHANISMS PROPOSALS

April 7, 2011

Module of the car:

Robot wheel – Steering system

Problem detected:

Due to the SAPA steering system is very complex and expensive, it has been determined that is required to develop some different proposals to use as a backup solution for the steering mechanism that will be implemented in the M1.

Background:

Reference "Derivation of Hiriko Robot Wheel Specifications" document (Appendix section 7.C) in order to understand the torque requirements, concerning the dynamic study of the steering system in static conditions (parking – worst case scenario) from -20 deg to 52 deg.

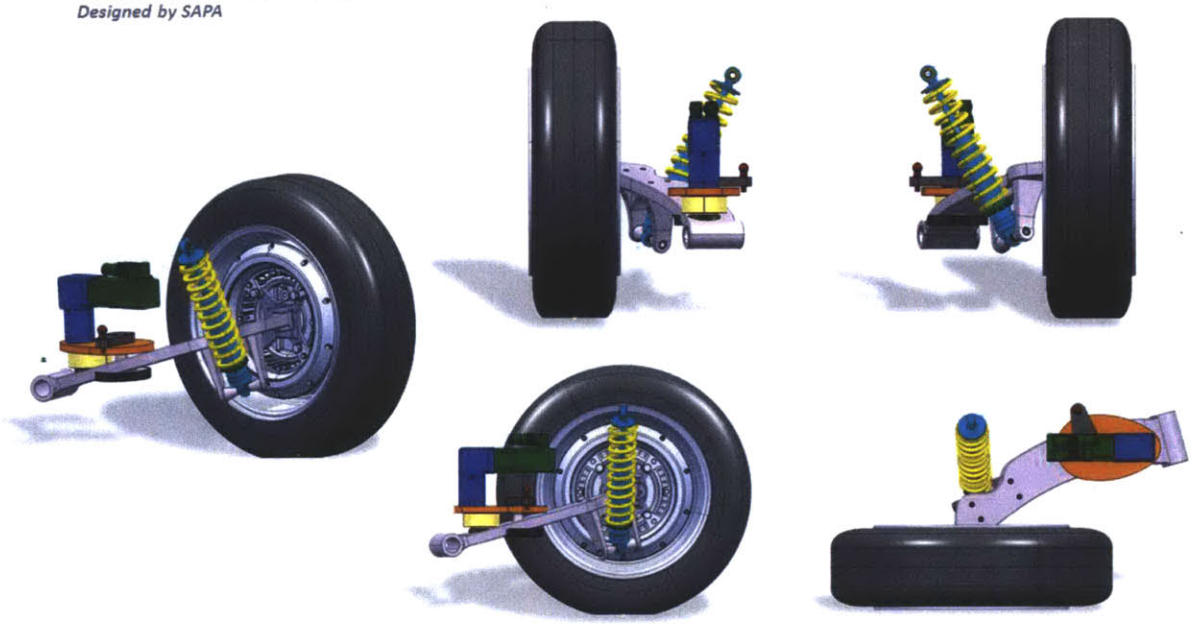
Requirements:

Gross Vehicle Weight:	680kg / 1000kg
Steering Geometry:	6deg Kingpin incl / 20mm Scrub Radius / 18mm Caster Trail
Steering Compliance:	From -20 deg to 52deg with 12MPa of brake applied. From -20 deg to 52deg without brake.

Comparison Chart:

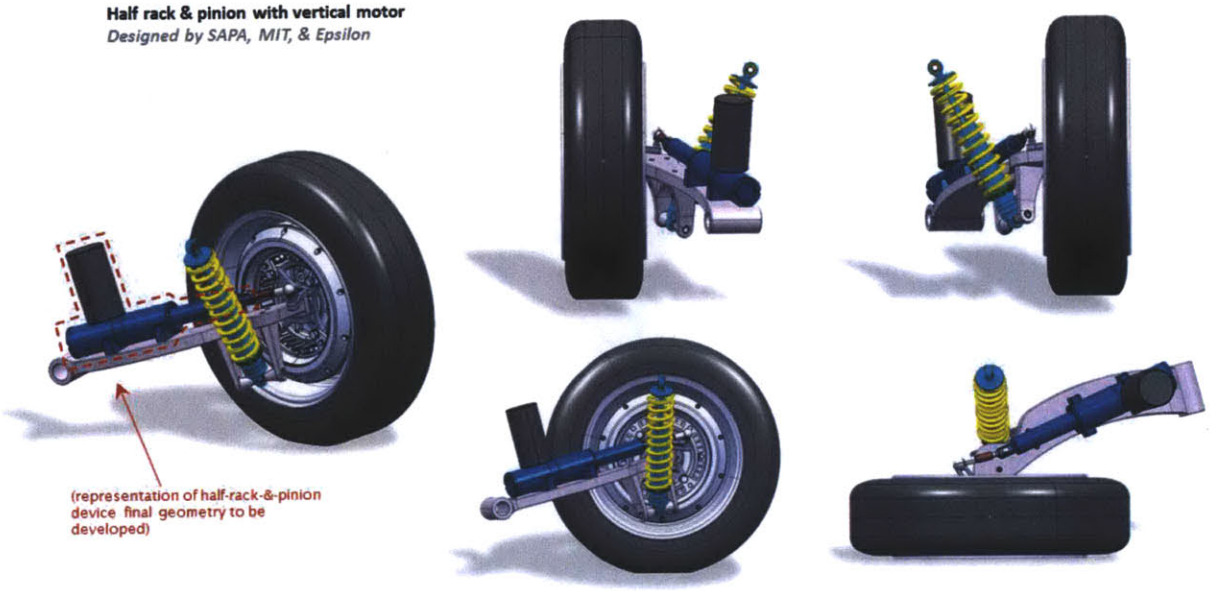
At the end of the document it is described a chart that compares the hard points in terms of power requirements, packaging volume, weight, cost, commercial availability, advantages and disadvantages of the different steering options.

Commercial component assembly of motor and reduction
Designed by SAPA



NAC harmonic drive & MagMotor assembly
Designed by Raul-David Poblano

Half rack & pinion with vertical motor
Designed by SAPA, MIT, & Epsilon



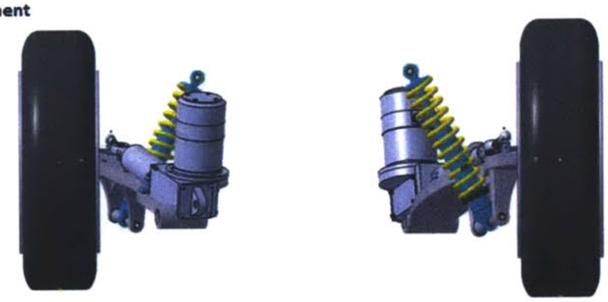
Linear actuator assembly
Designed by William Lark

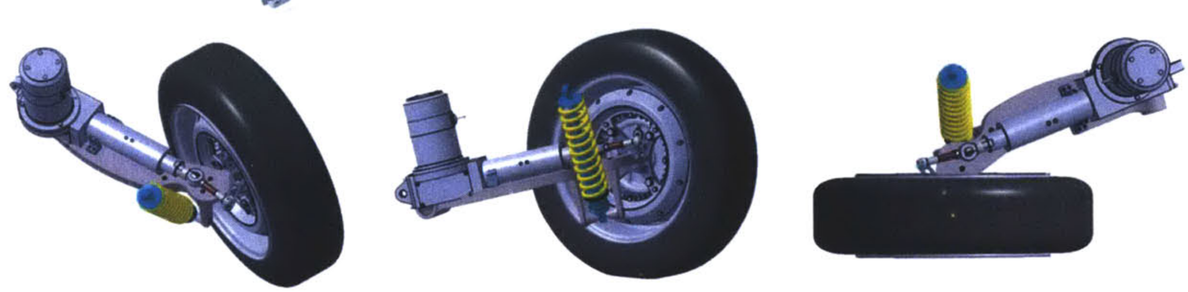
Steering Mechanisms Conclusions	SAPA assembly Solution	NAC Harmonic Drive & MagMotor Solution	Half Rack & Pinion Solution	Linear Actuator Solution
Steering Torque required @ Steering Axle	376Nm (W/Brake) – 680kg Vehicle Mass 361Nm (No Brake) – 680kg Vehicle Mass 423Nm (W/Brake) – 1000kg Vehicle Mass 419Nm(No Brake)– 1000kg Vehicle Mass	376Nm (W/Brake) – 680kg Vehicle Mass 361Nm (No Brake) – 680kg Vehicle Mass 423Nm (W/Brake) – 1000kg Vehicle Mass 419Nm(No Brake)– 1000kg Vehicle Mass	376Nm (W/Brake) – 680kg Vehicle Mass 361Nm (No Brake) – 680kg Vehicle Mass 423Nm (W/Brake) – 1000kg Vehicle Mass 419Nm(No Brake)– 1000kg Vehicle Mass	376Nm (W/Brake) – 680kg Vehicle Mass 361Nm (No Brake) – 680kg Vehicle Mass 423Nm (W/Brake) – 1000kg Vehicle Mass 419Nm(No Brake)– 1000kg Vehicle Mass
Power Requirements	N/A	BFA42-200: 1200 W BFA34-500: 970 W	N/A	N/A (24 Vdc, 36 Vdc)
Packaging Volume	± 9.45 m3	± 3.41 m3	± 7 m3	± 6.177 m3
Weight	N/A	±10 Kg	< 10 kg	±7 Kg
Cost	High	High/Med	Med	Med/Low
Commercial Availability	Available - Delivery date to determine	Available - Delivery date to determine	Available - Delivery date to determine	Available - Delivery date to determine
Advantages	- Small dimensions of the electric motor - High output torque with small electric motor - Design @ 85%	- Packaging volume - Of the self components - Different options for the implementation in the arm.	-Low cost steering half-rack -Faster speed for constant force -Complementary packaging -Small number of components	-Protection class IP66 -Packaging volume -Small number of components -Integrated feedback potentiometer -Integrated holding brake
Disadvantages	- Complex implementation in the arm. - High production cost.	- Cost** **currently design engineered for 25 RPM system – speed may be reduced to significantly reduce cost	- Relatively higher cost for motor and reduction in comparison half-rack	- Ideal values vs. current values: 5404 N & 41 mm/s Vs 6672 N & 15.3 mm/s Speed (actuator power or geometry improvements may be required)

SKF Linear actuator – integration of commercial component

Designed by William Lark

- Over 5500 N (1236 lbf) push and pull load
- Over 40 mm/s speed (1.6 in/s)
- 88 mm stroke
- 230–300 volts AC 3-phase
- IP65





7.H HIRIKO DRIVER INTERFACE OPTIONS

1/26/2011

In order to narrow down the scope of potential drive-by-wire interfaces for the Hiriko demonstrator/show-car, the following document outlines two basic approaches - (1) **joystick** and (2) **yoke/wheel**. While each have their benefits and drawbacks, the focus of these proposals highlight the core hardware and functions for each scenario.

(1) Joystick potential benefits

- Off-the-shelf "ready" robust and reliable hardware: Readily available in the market, used in construction vehicles and disabled assistance cars.
- Simple and self-contained: Does not require additional hardware or actuation.
- Existing markets: Already homologated in handicapped/disabled vehicles and common to young generations.
- Complements front entry/exit: Having the joystick solely positioned in the middle console reinforces the spacious minimal cabin, and keeps front open.

Joystick potential drawbacks

- Significant interface adjustment: Not commonly used by most drivers and must be easy to adjust to within seconds.
- Market acceptance: Drivers must feel comfortable and be willing to accept new interface (current testing underway to validate).

**note - Single central joystick proposed as solution from previous "Joystick & Screen Location" study below (page 4).*

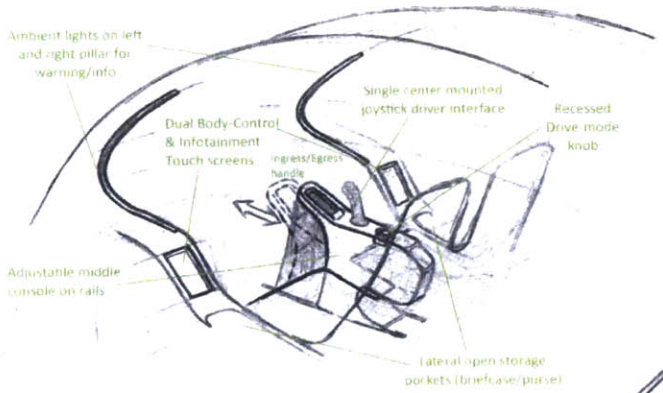
(2) Yoke/Wheel potential benefits

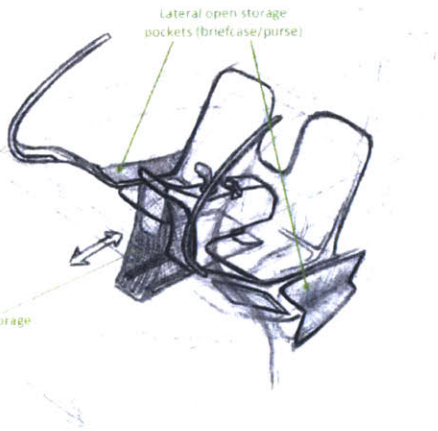
- Resembles common interface: Whether airplane yoke or wheel-like interface, all drivers are accustomed to similar controller.
- Dual hand control: Can be driven with left, right, or both hands at any time.
- Integrated body controls: The center of the yoke/wheel can also house a touch screen and/or buttons for vehicle body controls

Yoke/Wheel potential drawbacks

- Requires development: No off-the-shelf hardware. Developing such a "mission-critical" reliable component requires resources, experience and time.
- Requires articulating (moving) extended arm: Moving arm necessary to switch position of interface and park in middle console for entry/exit.
- Frontal barrier: Contradictory to frontal ingress/egress, and must be accommodating to driver displacement in front impact/crash scenario.

Driver interfa ce Option I Single central joystick with dual lateral touch screens





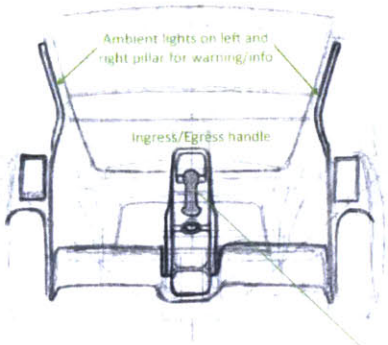
Note: no front display on door

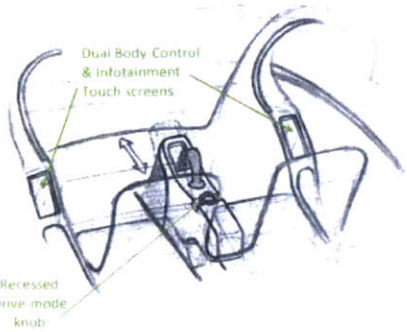
Intelligent ambient lighting placed in the interior A-pillars may supplement/replace the need for the front display on the door

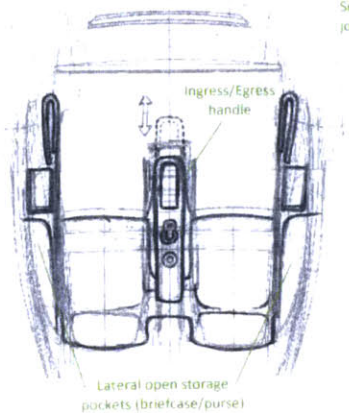
This keeps the front door simple, and the driver view open

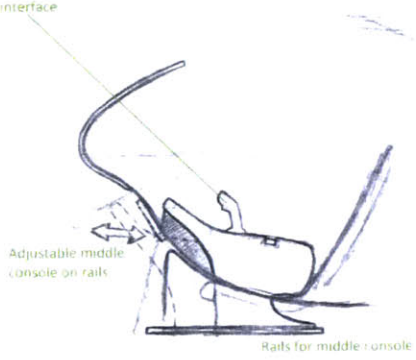
Other technologies can still remain optional if desired, such as OLED or projection

(Option I continued)



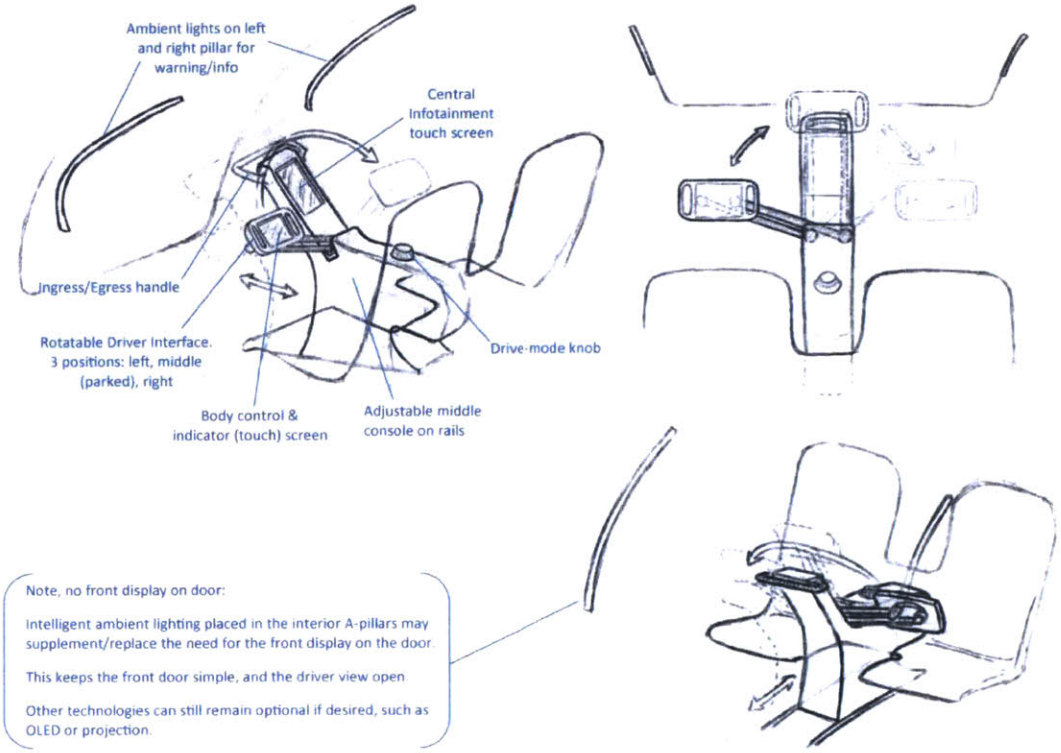






Sketches are just to illustrate components and function, not necessarily styling or design details

Driver interface Option II, Single yoke/wheel control mounted on rotating para llel bars



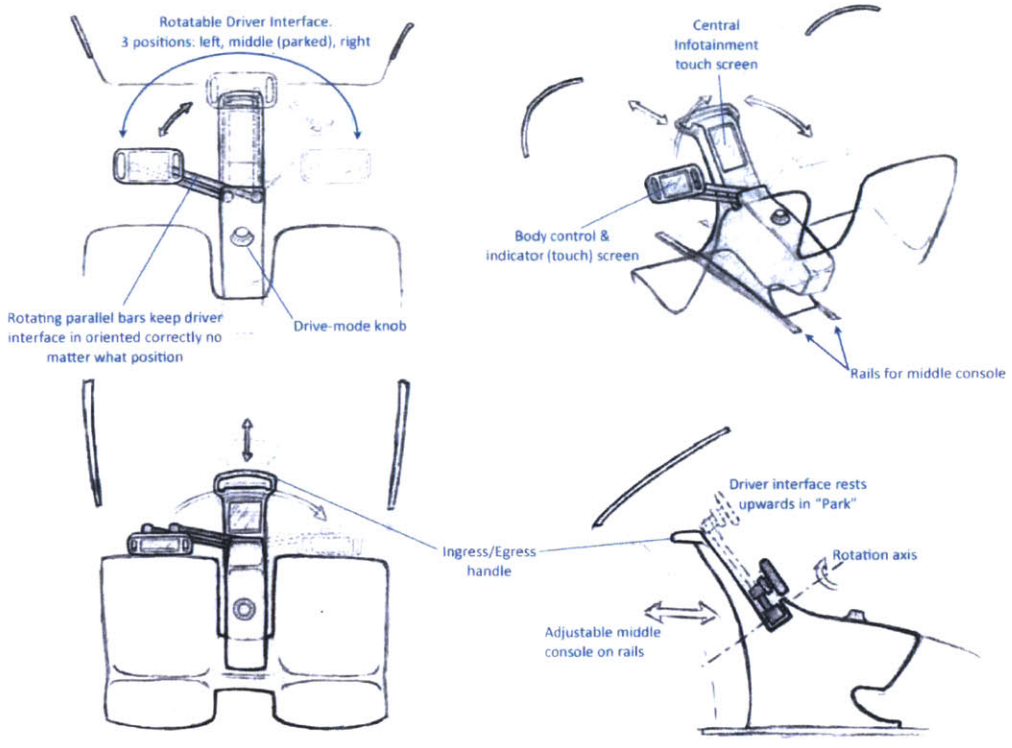
Note, no front display on door:

Intelligent ambient lighting placed in the interior A-pillars may supplement/replace the need for the front display on the door.

This keeps the front door simple, and the driver view open.

Other technologies can still remain optional if desired, such as OLED or projection.

(Option II continued)



Sketches are just to illustrate components and function, not necessarily styling or design details

Dual Four-bar linkage system for folding vehicle chassis

William Lark, Jr.
Nicholas Pennycooke

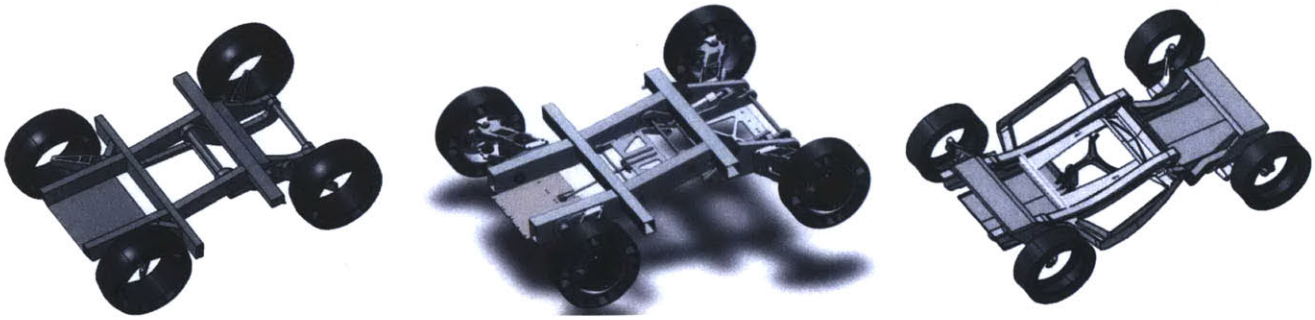
October 17, 2011

Summary

This document serves to describe the invention of a vehicle chassis that is capable of reducing its footprint by use of novel linkage and actuator geometries. The dual four-bar linkage mechanism is used on the MIT CityCar concept and provides one of the essential features of the vehicle - the ability to fold to reduce its wheelbase for overall footprint reduction. This core function is achieved by integrating two 4-bar linkages, activated by one or more linear actuators positioned in parallel. The dual 4-bar linkage and linear actuator(s) work in unison to fold the vehicle when parked while first providing the ability to maintain full maneuverability in its folded and unfolded state, secondly a fail-safe static system, and lastly a rigid but transformable chassis. This functionality is enabled by utilizing drive by wire in-wheel electric propulsion and steering systems, thus negating the need to conform to traditional vehicle architectures.

Specific to this invention:

1. Flexible Geometric relationship that allows for the smooth folding of the vehicle and dynamic adaption to various vehicle types and sizes. (Elements of the system developed have been transposed to allow a European "micro-vehicle" or "heavy quadricycle" class vehicle to fold).
2. Variable linkage proportions which can be fine-tuned to the specific vehicle's packaging constraints and design goals.
3. Binary state actuator integration allowing for fold/unfold initiation that occurs in a largely transparent way to the operator of the system.
4. Implications for how future electric vehicle chassis and powertrain architectures may be designed.

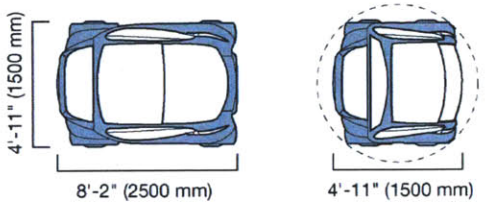


3D CAD Models showing design evolution

Background

The primary purpose of this invention is to enable significant reduction in the footprint of vehicles used in an urban environment. Although dramatic reduction of the vehicle's size may prove insignificant in low-density suburban and rural areas, it is of great benefit in densely populated urban areas where space for parking is scarce and land values are high. The significance is further magnified when considered in a shared use system, where the maximization of both land and vehicle utilization is critical. The cost to owners for utilizing parking and to cities for providing street parking is much higher than generally realized. However, the CityCar's footprint is significantly smaller than a typical car when it is folded, providing the potential for new business and user models.

CityCar utilizing dual 4-bar linkage to fold for primary function of wheelbase reduction



CityCar (unfolded) CityCar (folded)

Features:

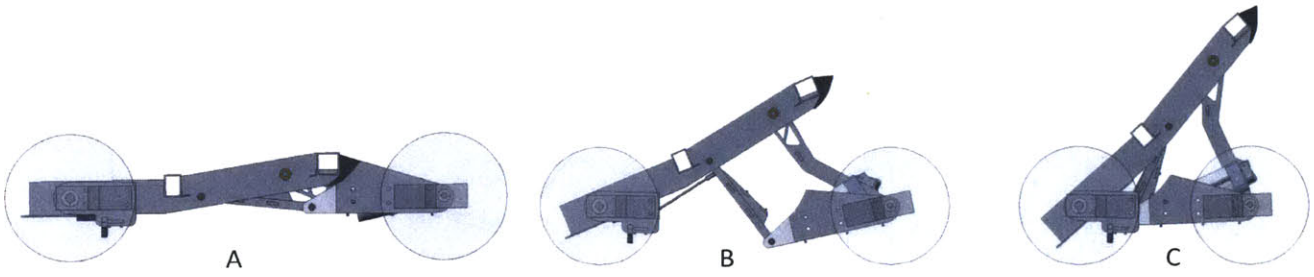
1. Reductions up to 40% of the total unfolded wheelbase (depending on linkage geometry).
2. Full drive maneuverability during any state of the fold (folded, unfolded, or any state in-between).
3. Goods in rear compartment, as well as batteries in front and rear modules, stay level to the ground because of relatively consistent angle position of rear compartment (maximum variation in tilt ~ 5 degrees).
4. Reduced energy consumption relative to other folding mechanisms since the majority of mass is not lifted
5. Eased front passenger entry and exit when folded
6. Maintains relatively low center of gravity (preserves stability when folded)
7. Mechanism is compatible for potential front and rear impact energy absorption.
8. Complete control of fold (speed and position) throughout intermediate states.
9. Chassis rigidity / structural integrity from 5th linkage (Linear actuators) in 4-bar-linkage system
10. Utilizing a non-back-drivable actuator mechanically stabilizes complete system which eliminates energy usage and prevents chassis collapse failure modes to keep vehicle locked in various positions (auto-lock 5th linkage)
11. Chassis behaves as rigid body in zero-power/power-failure situation

Technical Summary

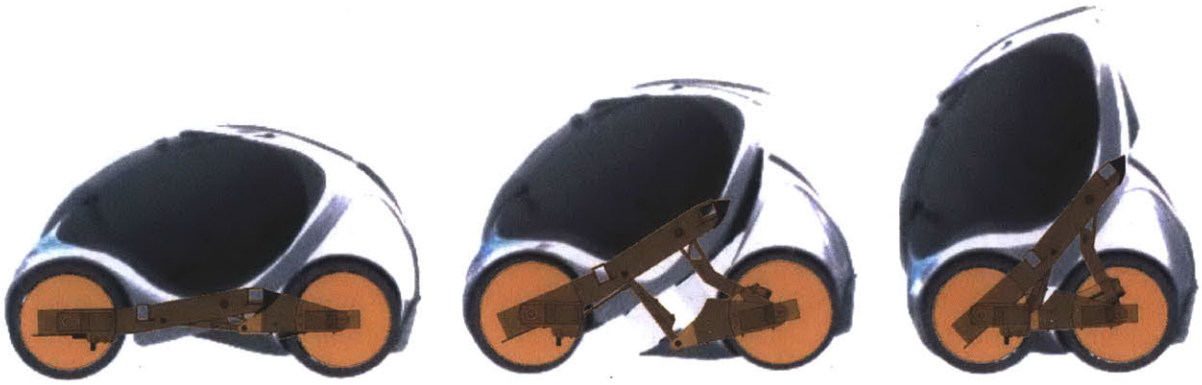
The invention integrates two 4-bar linkage systems that tilt the front passenger cabin forward while simultaneously contracting its rear storage cabin inward to significantly reduce the vehicle's wheelbase (up to 40%, depending on linkages and vehicle packaging constraints). The dual 4-bar linkage also functions to reduce the amount of mass that is lifted when folding the vehicle. The majority of heavy components (batteries, motor controllers, and other powertrain components) remain on the powertrain linkage cross members and are not elevated during the folding process. This significantly reduces the amount of energy consumed during each fold. The geometric relation and shared linkage between the front and rear 4-bar mechanisms not only work together to fold the vehicle, but also (1) tilt the passenger cabin about the front wheel axis which enables eased front ingress/egress.

The invention has been designed specifically to allow the vehicle to drive and steer normally in both the folded and unfolded position. The invention can be broken down into two sub-systems - the primary four-bar linkage in the rear and the secondary four-bar linkage in the front of the vehicle. The purpose of the rear four-bar linkage is to enable the above described reduction in wheelbase. This subsystem also acts as the main structural component, tying the front and rear chassis assembly together. The purpose of the front four-bar linkage is to first enable the vehicle to be driven in both folded and unfolded positions (as well as any point in between these two states) and second to keep the component mass low. Connected to the rear four-bar linkage, the front linkage system maintains the required angle relative to the ground needed to allow the steering mechanism to function properly. Geometries are chosen that require no further actuation to the front linkage mechanism in order to operate, as its motion is tied to that of the rear linkage.

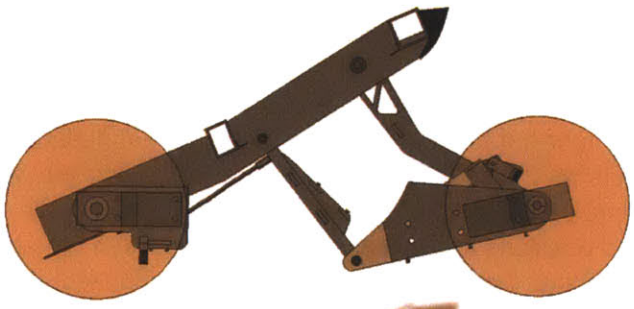
The overall assembly is electro-mechanically driven by an integrated push/pull linear actuator, which brings the front and rear wheels towards each other, entering the 'folded' state. Reversing the actuator pushes them back to their original wheelbase, returning to the 'unfolded' position. In addition to folding the vehicle, the actuator acts as a 5th linkage in the rear mechanism - providing added structural integrity and static rigidity. The non-back-drivable type of linear actuator incorporated firmly locks the assembly when power is not supplied to it, allowing the folding sequence to be halted at any point while maintaining the current angle of cabin tilt. A non-back-drivable actuator is not required for the system to achieve work, but does offer the above stated significant benefits. The system is also compatible with other non-electro-mechanical linear actuators, such as pneumatic pistons; however, the preferred assembly utilizes electric linear actuators because of the pure electric platform of the vehicle (in this case, the CityCar).



3D CAD Model exhibiting initial designs of chassis in (A) unfolded, (B) mid-fold, and (C) fully folded positions

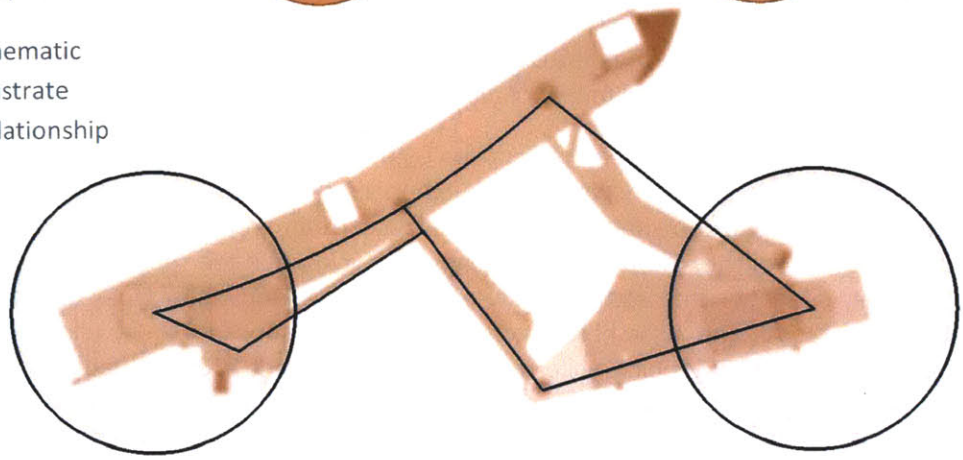


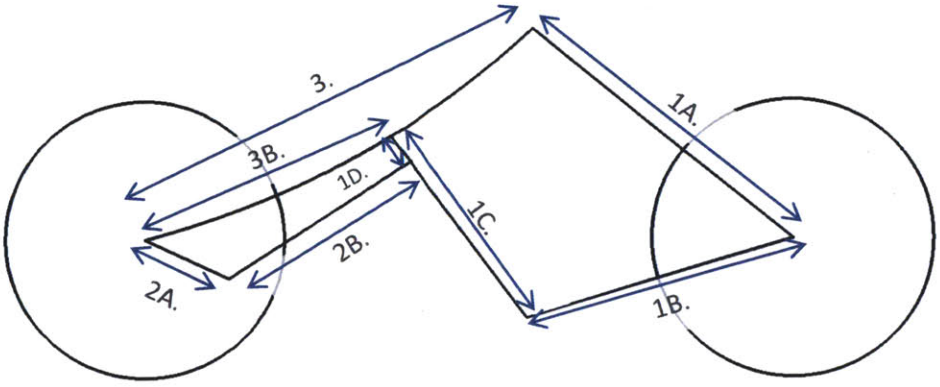
Asymmetric front and rear powertrain linkages – earlier design

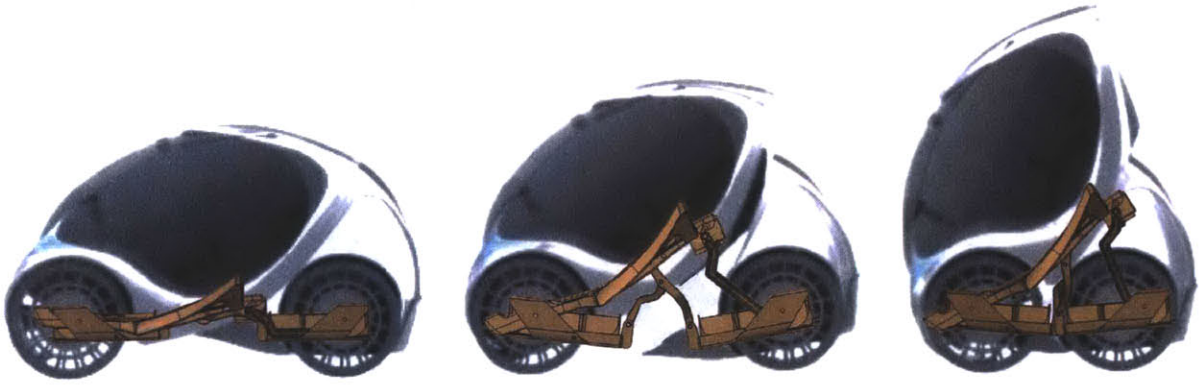


Dual Four-Bar Linkage Folding System shown in relation to CityCar EV.

Simplified kinematic outline to illustrate geometric relationship



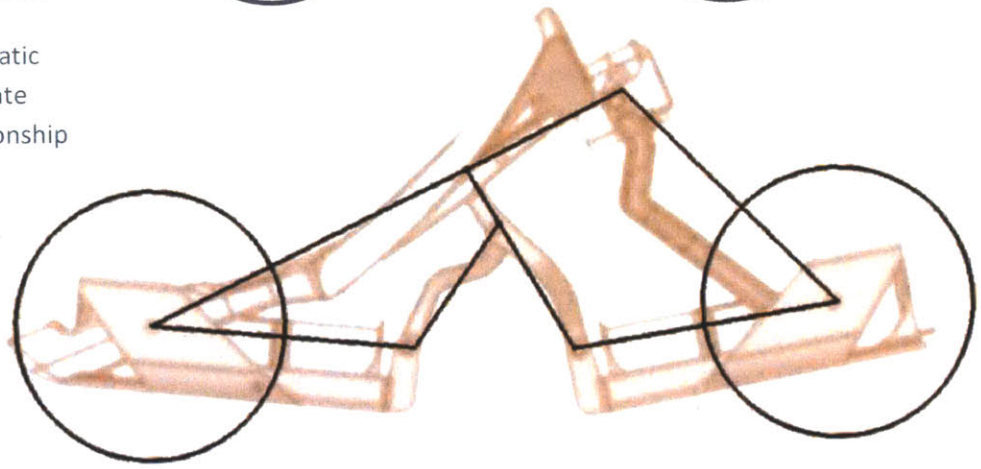


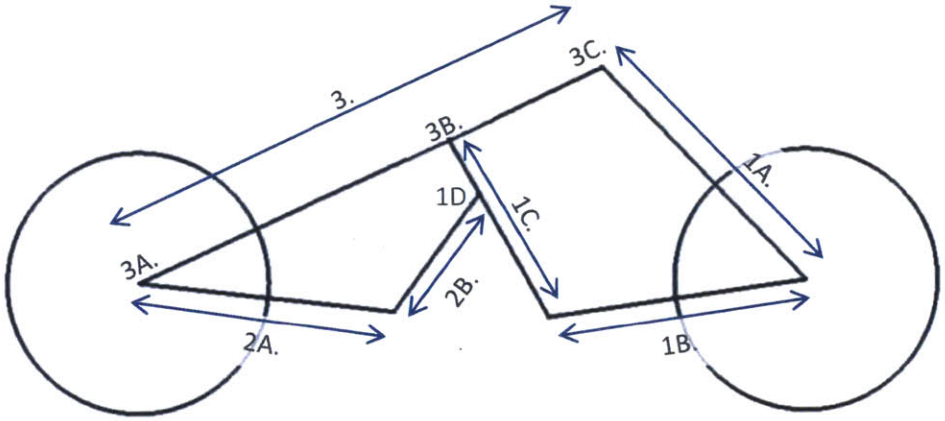


Symmetric front and rear powertrain linkages – recent design

Dual Four-Bar Linkage Folding System shown in relation to CityCar EV

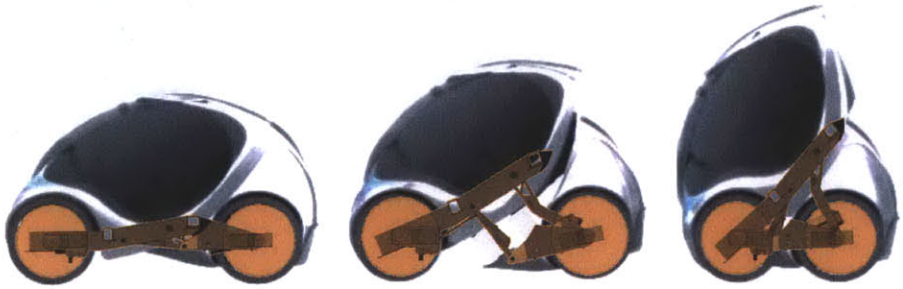
Simplified kinematic outline to illustrate geometric relationship





Description of subassemblies and parts

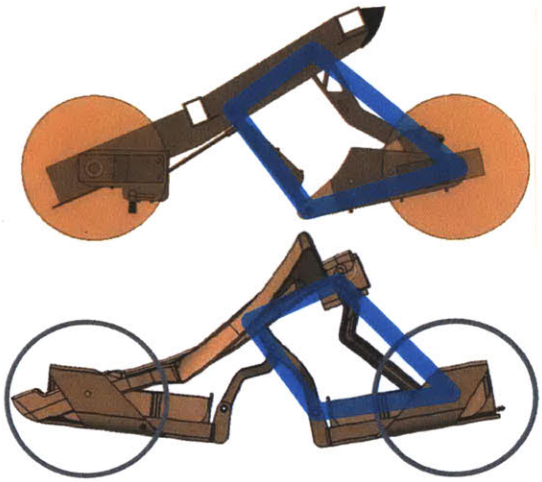
The invention consists of three main bodies assembled with linear actuators to create a synchronized folding system that tilts the vehicle about the front axis, pulls in the rear axis to reduce the wheelbase, and keeps both the front and rear powertrain level in orientation.



Asymmetric front and rear powertrain linkages – earlier design

Symmetric front and rear powertrain linkages – recent design

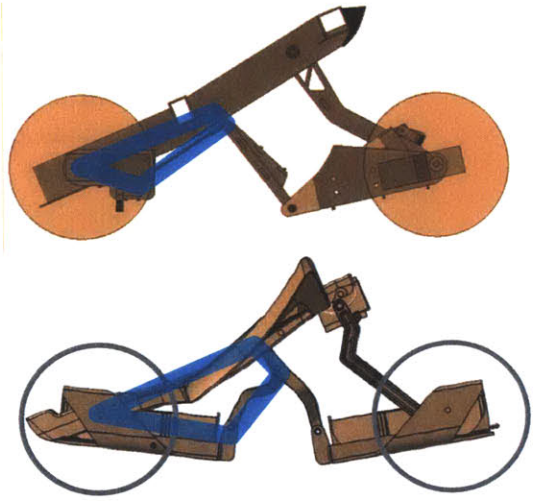
- **1.** The **primary 4-bar linkage** is located at the rear of the vehicle. It connects fully to the ladder chassis and its main purpose is to lift and tilt the vehicle forward to reduce its footprint. This rear assembly is actually comprised of three linkages with its fourth being the ladder chassis. See Figure X for corresponding part labels The following linkages serve unique purposes:



    - (1A) The **lifting linkage** is a major structural member that supports the majority of the vehicle's rear load when folded and distributes this load directly to the rear powertrain linkage (1B), which subsequently provides mounting points for the vehicle's robot wheels.
    - (1B) The **rear powertrain linkage** supports (at least half of) the components responsible for powering and driving the vehicle: the battery module, motor controllers, and robot wheels (suspension, drive motors, steering system, and brakes). Therefore the base must be contrasted robust enough to handle both lateral and torsional forces and vertical loads directly from the weight of the components. The axis of the connection point between 1A and 1B is centered on the rear wheel axis, so as to minimize excessive torque requirements when folding, and subsequently rolling the wheels forward.

- (1C) The **adjusting linkage** provides significantly less axial load support as most of it is provided by the lifting linkage that connects the vehicle chassis directly to the rear axle. However the adjusting linkage does significantly assist with torsional loads, orientation of the powertrain linkage assembly relative to its vertical axis (keeping it straight, preventing twisting about the z-axis), and leveling the powertrain assembly in both its folded and unfolded state. The adjusting linkage serves dual purposes as a section of it also serves a one of the linkages for the secondary 4-bar assembly (1D), so that as the rear primary 4-bar linkage begins to fold the front secondary 4-bar linkage assembly is simultaneously activated. The length of 1C therefore controls rear module 'dip' or change of angle mid-fold, as well as front module motion based on connection point to 2B.

- **2.** The **secondary 4-bar linkage** is located at the front of the vehicle and its main purpose is to rotate the front powertrain relative to the ladder chassis, keeping it level to the ground. Although this section of the overall assembly does not serve to reduce the vehicle's wheelbase, by keeping its powertrain level to the ground it permits the vehicle to maintain all driving capabilities while folded (even O-turn, translation, and 4-wheel steer, in the case of the CityCar). Two of the four front linkages are embodied by (1) the ladder chassis and (2) a section of the adjusting linkage from the rear assembly. The remaining two linkages coordinate to orient and support the font powertrain linkage:

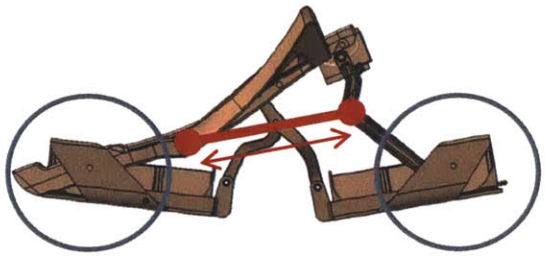


  - (2A) The **front powertrain linkage** behaves practically identical to the rear powertrain linkage supporting crucial drive components. However this linkage is connected directly to the ladder chassis along the front axle, keeping it more stable and accurately oriented relative to the chassis. In particular models of the dual 4-bar linkage folding chassis the front powertrain can be identical as the rear powertrain to increase modularity, improve economies of scale and reduced cost. This is however not a requirement for the system to work.
  - (2B) The **synchronizing linkage** behaves similar to and is connected to the adjusting linkage. Because the front powertrain linkage is connected directly to the chassis, the synchronizing linkage does not require as much lateral and torsional support. This linkage can in some cases (as done in the previously shown prototype) incorporate a length adjustment feature to allow tuning between the front and rear powertrain once the total invention is assembled.

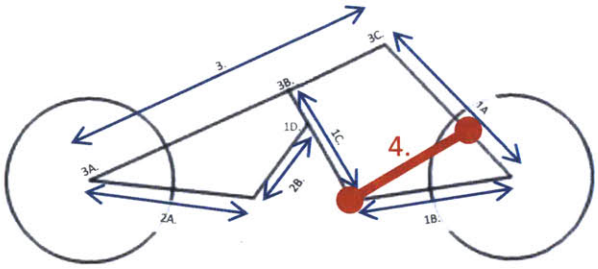
- **3.** The **ladder chassis** is comprised of two parallel long-running members with lateral cross-members that provide the main structure for the vehicle body, seat harnesses, and in reference to the folding system, the pivot connections for each of the 4-bar linkages. From front to back, there are three main axes about which the primary and secondary 4-bar linkages pivot:

  - (3A) The **front axle pivot** is aligned within the center of the front wheels and provides the connection to the front powertrain linkage. This is done to achieve similar torque reducing effects as done between 1B and 1C. Along the axis, the left and right pivot connections remain separated allowing space in-between to accommodate the battery module. These front axle pivot connections must be relatively strong to transmit and distribute the loads from the wheels to the chassis.
  - (3B) The **adjusting linkage pivot** may remain relatively smaller than the other two since it is transmits lower axial loads.
  - (3C) The **lifting linkage pivot** provides the connection to the lifting linkage and must be relatively strong to handle the transmitted forces from the rear powertrain assembly. This pivot should be designed at least as strong (if not stronger) than the front axle pivot since it must handle significant lateral, torsional and axial loads over a longer moment of the lifting linkage.

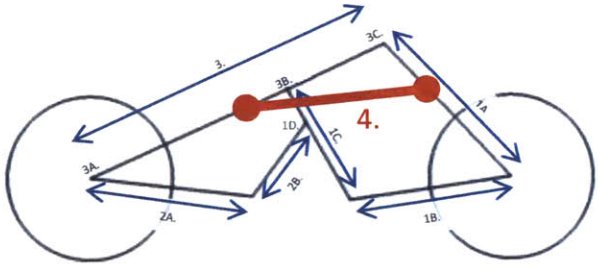
- 4. **Linear actuators** are incorporated into the primary 4-bar linkage at the rear of the vehicle to lift and lower the rear of the vehicle. There are various orientations in which the actuators can be placed. The placement is usually dependent on two factors – the stroke length of the available commercial actuators, and packaging constraints within the design of the particular vehicle. Depending on the power system(s) available on the particular vehicle, various commercial linear actuator types are compatible for use (electro-mechanical, pneumatic, or hydraulic). In the case of the CityCar and subsequent prototypes, electro-mechanical Acme screw type linear actuators proved best for a number of reasons. First, requiring only electrical power to extend and withdraw the actuator rod is opportunely compatible to the core powertrain of an electric vehicle. Other pneumatic and hydraulic type actuators require peripheral



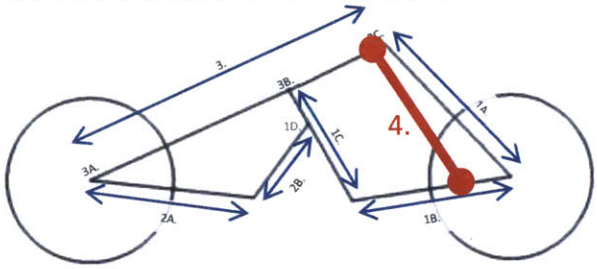
subsystems such as pumps and/or compressors. Second, there are packaging benefits of the electro-mechanical linear actuators, as all required components are built in to the cylindrical unit. Thirdly, the actuator does not need discreet position reporting (potentiometer, encoders, etc.) other than end-condition limit switches, as the current design calls for a binary fold/unfold system. This aids in simplifying the control of the invention. Lastly, the non-back-drivability of the acme screw type linear actuator adds an important level of stability and safety to the folding system. The actuator behaves as a 5th link in the 4-bar linkage system and locks the assembly rigid, limited only by the holding force before failure, rated by the specific actuator used. Therefore the system only moves when the linear actuator receives power to expand or retract, consequently folding or unfolding the chassis. Linear actuators to fold and unfold the chassis can be placed in multiple orientations as shown.



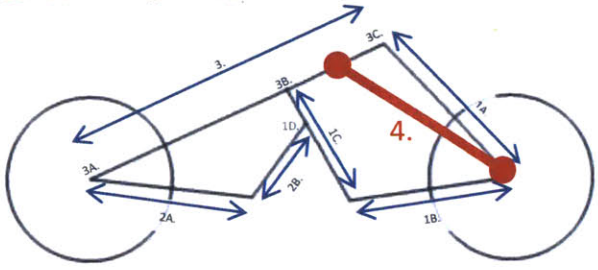
"Push/extend to fold" type linear actuator, attached between lifting linkage and powertrain/adjusting joint



"Pull/withdraw to fold" type linear actuator, attached between lifting linkage and chassis



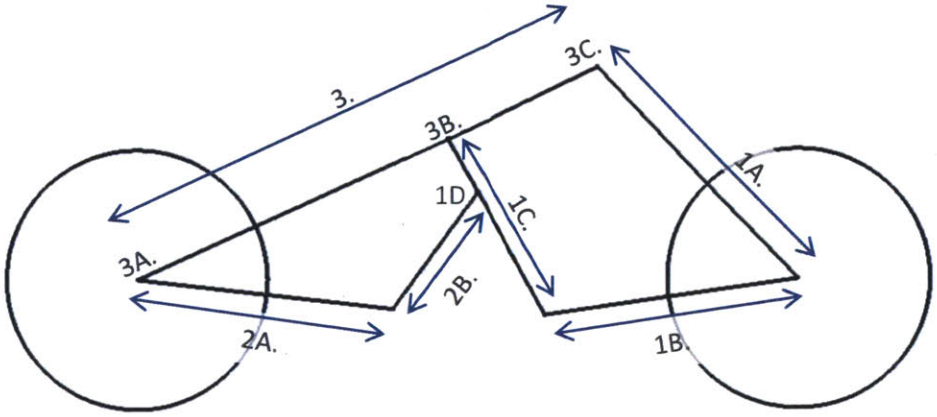
"Push/extend to fold" type linear actuator, attached between rear powertrain linkage and chassis joint 3C



"Pull/withdraw to fold" type linear actuator, attached between chassis and powertrain/lifting linkage joint

Developing the Dual 4-Bar Linkage Vehicle Folding System

The linkages are attached to each other in the following manner:



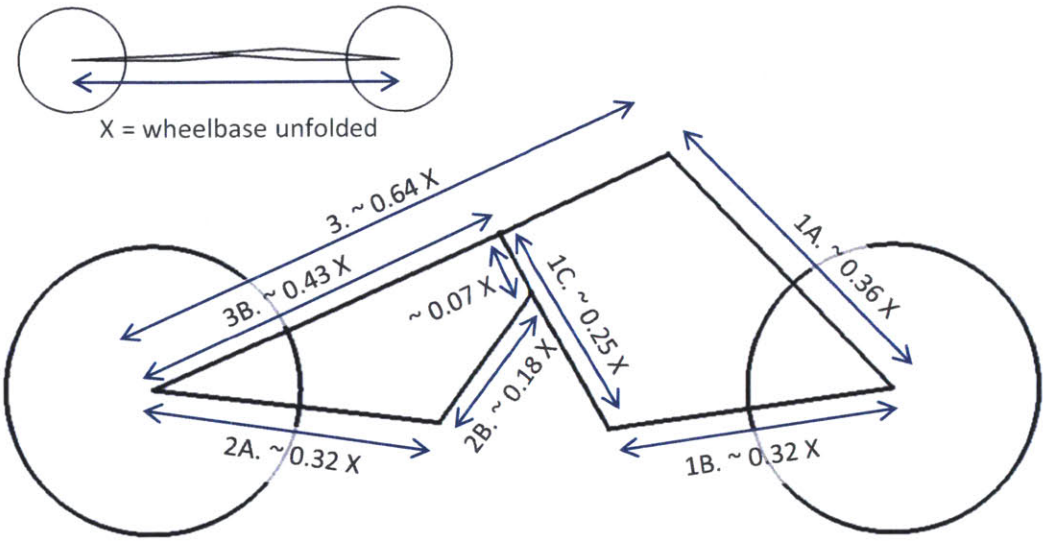
Primary 4-bar linkage
The lifting linkage, 1A, is attached to the ladder chassis at pivot 3C.
The adjusting linkage, 1C, is attached to the ladder chassis at pivot 3B.
The opposite ends of both the lifting linkage and adjusting linkage are joined together by the rear powertrain linkage 1B.

Secondary 4-bar linkage
The front powertrain linkage, 2A, is attached to the ladder chassis at pivot 3A.
The synchronizing linkage, 2B, joins the front powertrain linkage to the adjusting linkage at pivot 1D.

If non-back-drivable actuators are not used, it is recommended to incorporate locking mechanisms at the end states of folding and unfolding. Registering rest areas, such as bumpers between the mechanical elements, can be used to help distribute the various loads, assisting the assembly to behave as one body when in its driving position.

When developing the invention, multiple manufacturing processes are compatible. Initial prototypes have been developed by the following methods: (1) CNC laser-cut wood assemblies (2) machined and welded aluminum framing, (3) member and joint aluminum space frame, and (4) blended construction of aluminum and composites (carbon fiber). When feasible, other automotive manufacturing practices such as metal stamping, casting, or forging may also be used to develop the folding system.

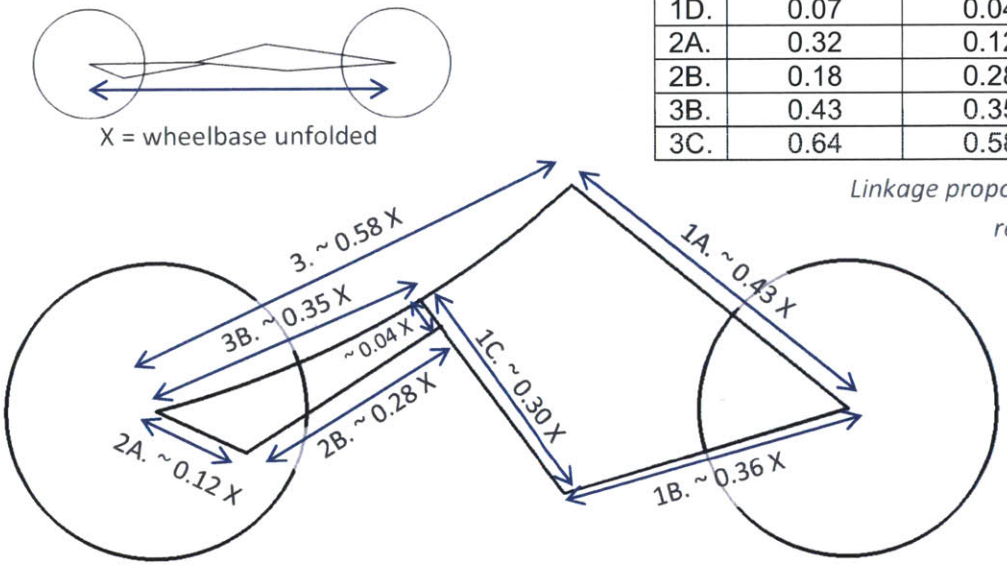
Although the invention can be fabricated in multiple manners, one of the key aspects of the dual four-bar linkage folding system is the relationship between the lengths of the linkages. For small vehicles with wheelbase lengths similar to the CityCar (1600-2100mm, such as the Smart ForTwo coupe and Toyota/Scion IQ), the following link proportions work well to reposition the chassis to a suitable inclination when folded.



Chassis at mid-fold (symmetric front & rear powertrain

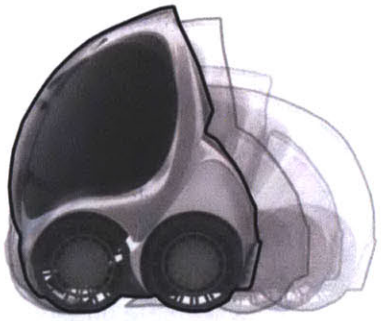
	Proportion of wheelbase length, x		Estimated proportion range
	Symmetric powertrains	Asymmetric powertrains	
1A.	0.36	0.43	0.35-0.45
1B.	0.32	0.36	0.30-0.38
1C.	0.25	0.30	0.23-0.32
1D.	0.07	0.04	0.03-0.08
2A.	0.32	0.12	0.10-0.38
2B.	0.18	0.28	0.16-0.30
3B.	0.43	0.35	0.33-0.45
3C.	0.64	0.58	0.54-0.68

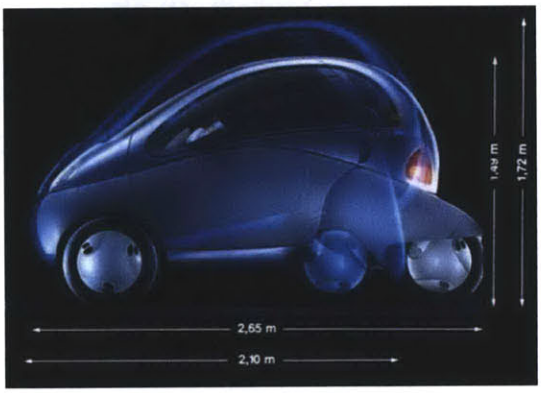
Linkage proportion ranges are researched recommendations, not limits.



Chassis at mid-fold (asymmetric front & rear powertrain linkages)

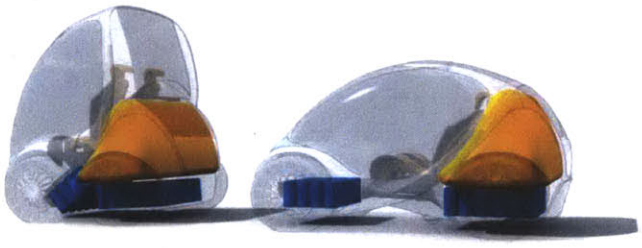
Advantages over Existing Methods





Previous single-pivot folding solutions on CityCar and Renault Zoom concepts

Previous folding chassis concepts for the CityCar have been developed at MIT, and other commercial concept concepts have addressed the issue of vehicle folding for reduced space while parking (*reference: Renault Zoom 1992*). However, most of these concepts exploit a single pivot arm to lift and tilt the body of the vehicle. This method, while perceived simple, is by nature very limited and poses greater technical difficulties in execution. In order to achieve the wheelbase reductions garnered by the proposed invention, a long single pivoting arm is needed, which will lift the majority of the vehicle's mass up significantly, and restrict chassis packaging and steering maneuverability. Currently no other patents have been found providing a similar solution to reducing the vehicle's wheelbase. The dual 4-bar linkage system instead decouples the rear cabin onto the rear 4-bar mechanism which conserves energy since it translates many of the heavy load components, all while maintaining the relative kingpin (wheel steering axis) position - giving the vehicle total maneuvering capabilities during any state of its fold. Also early empirical experiments of scaled models show that the distribution of weight between the front and rear cabin allows the folding mechanism to behave as an energy absorbing component for front and rear impacts/crashes. Although more thorough and extensive testing is required to prove commercial viability, preliminary testing shows that exploiting this type of folding chassis in a front or rear impact scenario may be able to reduce the rate of the deceleration in the passenger cabin. Particular linkages may also be strategically designed to compress or fail, acting as dynamic crumple zones, thus reducing crash force transmission to the passenger cabin.



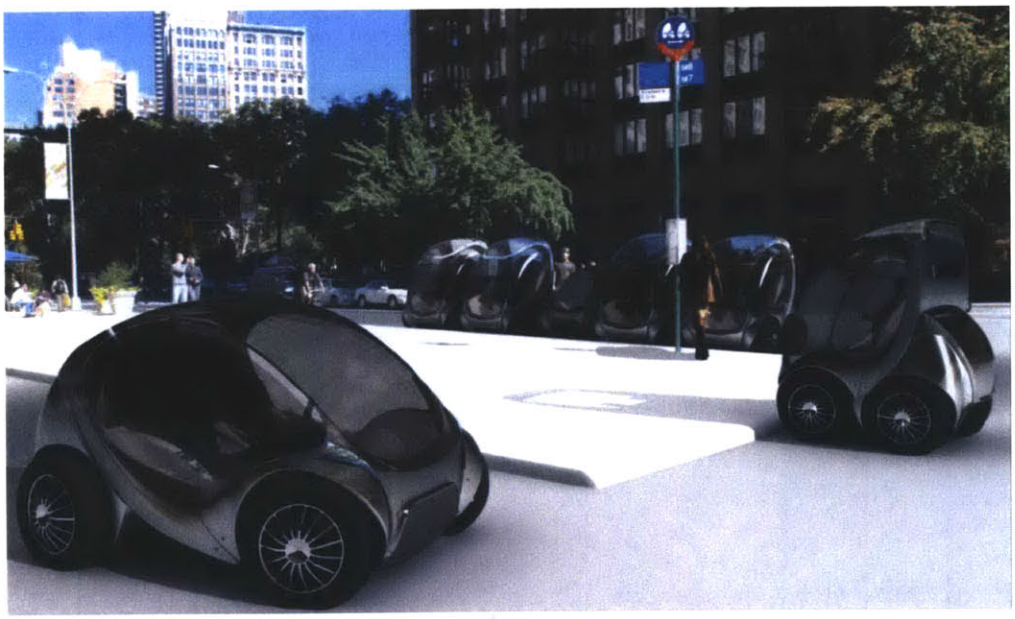
Maintaining low center of gravity with balanced batteries and storage compartment

Comparison of relative crumple zones on a regular small vehicle chassis versus that of the proposed invention

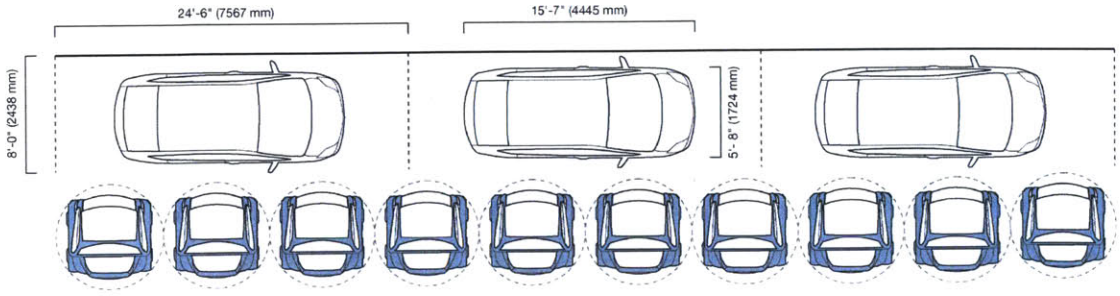
Commercial Applications

The invention is targeted towards urban mobility. Although there are applications in the automotive market for individual ownership, there are greater benefits in fleets for mobility services. Giving convoys of vehicles the ability to fold has larger ramifications when it comes to vehicle sharing, parking structure design and layout, as well as sidewalk design. The folding chassis can be designed in such as a way that three foldable vehicles are able to fit in the parking space usually allocated for one non-foldable vehicle. Parking density and thus possible fleet penetration in a mobility-on-demand service can be dramatically increased for those operating these vehicles in such a shared use scenario.

As for the automotive industry, the folding chassis may be a complementary option for emerging alternative energy vehicles, especially full electric. The main purposes of a vehicle chassis, whether it is body-on-frame or unibody construction, are to (1) behave as the main structural member for component mounting, (2) handle driving dynamics, and (3) manage crash safety. When scaled up to a full size automobile, the linkage design can be designed to perform all three of these functions.



CityCar using dual 4-bar linkage to fold for Mobility-on-Demand scenario in New York City

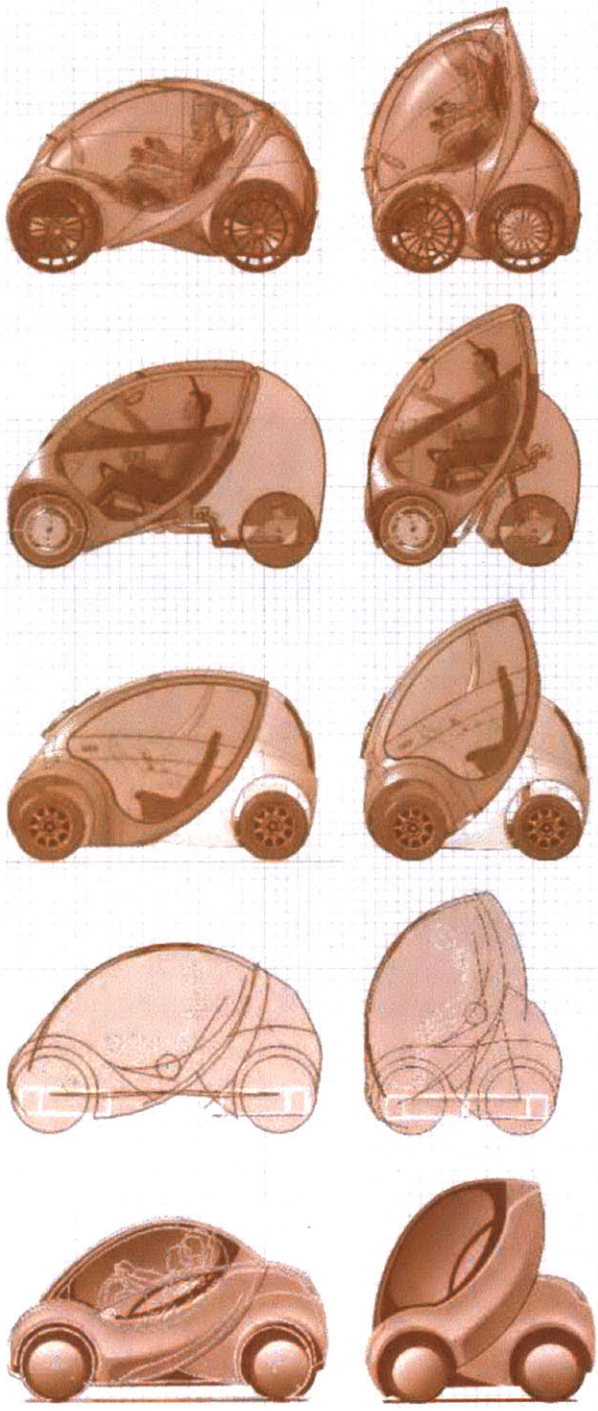


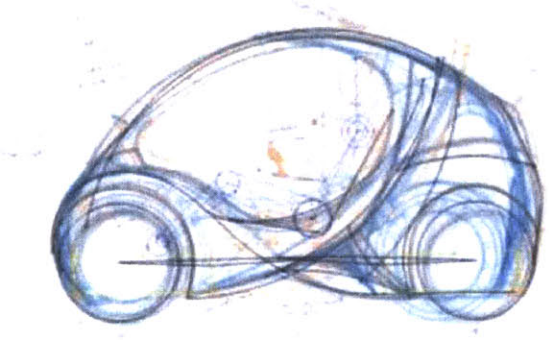
Folded CityCar vs. conventional 4-door sedan
Parking ratio = 3.3 : 1

7.J DESIGN EVOLUTION THROUGH INDUSTRIALIZATION PROCESS

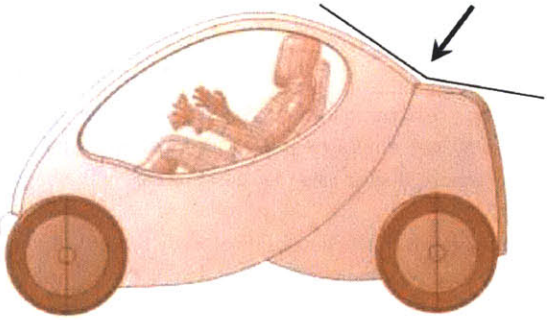
Hiriko Design Evolution 3/9/11

	length (mm)	height (mm)	length (mm)	height (mm)	inclined angle
June 2010 First CityCar Design Used in renderings and half-scale prototype	2537	1583	1851	2278	41°
October 2010 MIT adjusted design considering feedback from CIE	2600	1684	1839	1750	30°
January 2011 Epsilon developed design with assistance from MIT incorporating supplier technologies	2625	1615	1975	2315	32°
February 2011 Recommended profile adjustments from MIT to ETUD considering new design was underway	2480	1521	1766	2197	40°
March 2011 Initial ETUD design proposal. Introduction of rear kink because of 2.1 meter limit	2593	1562	1942	2044	32°

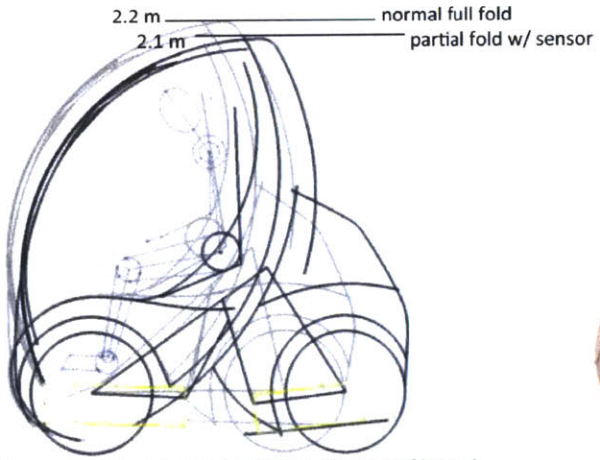




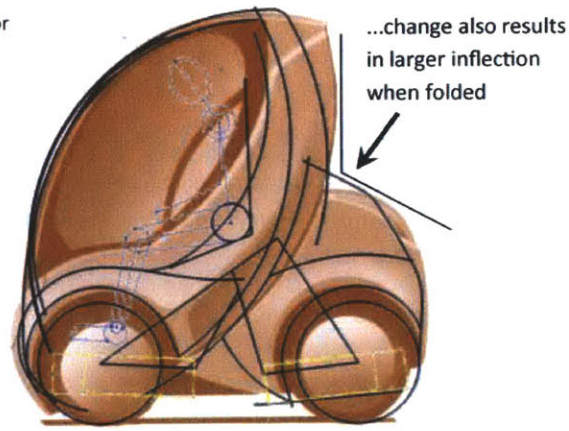
Overlap of previous designs and profile recommendation from MIT in February



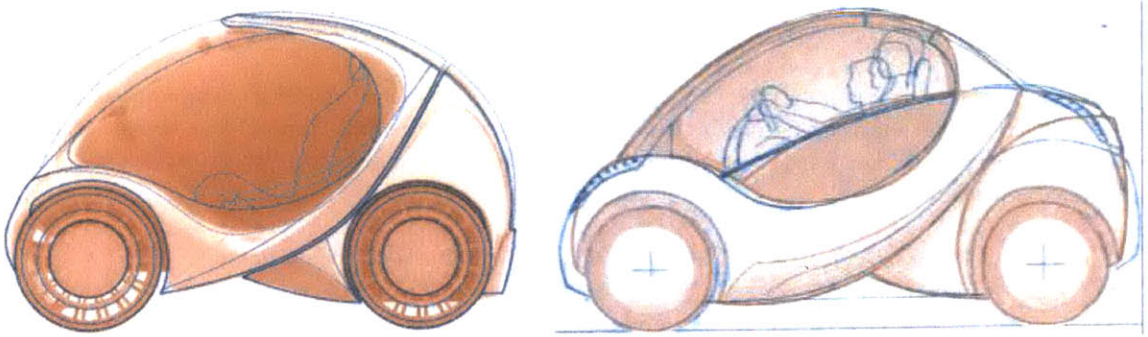
Preliminary architecture proposed by ETUD
First introduction of rear roof kink/crease because of 2.1 meter folded limit



However with proposed adjustments in profile and kinematics, vehicle can simply fold partially to remain under 2.1 meter limit (proximity sensor on roof stops fold when too close to ceiling).



When proposed design folds partially it can remain under 2.1 meters and is 2044mm in length, about the same as current folded length



Significant profile change from 2.1 meter height limit. Characteristic profile can be preserved utilizing intelligent technological solution instead of altering static geometry (roof proximity sensor already included in specifications).

7.K AUTOMOTIVE EXPERT DISCUSSIONS

Interviewee #1

Mobility in the future:

27:00 Finding creative solutions to handle personal requirements within the city I think -you know- the vehicle that was developed by MIT does a great job at that [with] the stacking, the charging, and contributing back to the grid... At some point there were more electric cars than gasoline cars in the beginning, but for various reasons the gasoline engine won out.

28:50 But in terms of working inside of a city center like the MIT car – the folding, the grid, being able to get into the car, being able to move to your individual spots – I think those things will happen as you know in Europe there already areas that you can't bring your car into the city center ...but it's still going to take a lot of time

Supplier-OEM relationship

33:10 Both have gone through extremely difficult times ... downsizing... reformulating... bankruptcy
Prior to that there was a trend which I think is still for the Foreseeable future I the way forward where that is where the suppliers work very closely with the OEMs in terms of developing total systems and subsystems which are delivered just in time to install into the vehicles ...so that the suppliers take on a much bigger responsibility in terms of the engineering and designing and working with the OEMs and supplying a totally assembled system or subsystem which goes into the vehicle as required. ...a lot of companies have done work on that in the last 10-15 years. Suppliers have on-site areas where they build their components or subsystems and they go straight onto the assembly line. And again it's the partnership, it's the commitment that going to be *so* important (Think about Ford which was totally vertically integrated to the point where the iron ore would go into the plant and a car would come out the other end) ...the vertical integration has continued to become more and more flattened out and horizontal and certainly the future I think is more horizontal integration where a number of players have a responsibility, commitment, and investment into the final product.

38:10 Cars have become so complex – the electronics and computing capacity ...When it comes to the product – I'm a strong believer in brands ...as long as it performs to a prescribed specification I'm not sure people care where it comes from ...most critical part of a car is integration ...he buying the brand the brand is responsible for the integration and reliability who cares where all that stuff comes from as long as it works to whatever specification the brand has determined.

42:50 [The important Factors are] 1. What is looks like, 2. how to integrate all the componentry 3. How to establish, nurture and promote the brand

1:10:00 Traditionally there's been certain parts or components that the OEM has almost always bought – you know like tires. And so you're probably going to see from those suppliers the new stuff – the new innovations case that's their thing – that's all they do, that's them. So their investing thinking about it working on what's next so you're probably going to see that kind of evolution you know certain kinds of products that they've always done – that's their thing.

1:22:30 I think suppliers have been over the years very involved in developing modular interiors that can be installed robotically and that they take certain architectures of the interior – in fact depending on the financial climate that OEMs and supplier will be working on in the future and how much more responsibility that the supplier takes I think that we'll see more innovation coming from the suppliers.

1:24:50 From and OEM's perspective you'd rather have fewer suppliers involved in larger contributions

1:25:27 when you look at a car today the manufacturer is mostly involved in putting the car together .. a lot of them stamp their sheet metal, forge a few parts ...almost everything on the inside of a car (listing parts) ..companies probably make engines and sheet metal and I think almost everything else comes in from a supplier Sheet metal engines, transmissions, powertrain stuff ...probably 80% of the rest of the car comes from outside

END

Interviewee #2

Future Mobility

10:10 Halfway to the 2050 mark (inflection point) Energy will be a major issue – hard to tell where those things are heading. Now from a transportation standpoint, if you're talking about urban areas, there going to be more constraints on cars and parking and road pricing. ...so twenty years out there are range of scenarios, one of those being people are going to be doing more car sharing, pay-per-use type thing; but one has to figure out what are the inflection points to do that."

Zip Car is one example, another is that I own a portion of a vehicle and share it with other Cost of Ownership = hardware + cost of mileage which will go up with cost of energy

...what's going to be the motivation to get people to change?

Modularity

If you modularize things you can speed up production ...for example the whole supplier responsible modules showing up at the plant – the whole instrument panel cockpit or the whole propulsion system for example ...the biggest issue is the legacy issues around them – supplier agreements labor unions ... and then how do you design the interfaces ...also how do you balance the profit sharing if the supplier is taking on more responsibility ...however the electrification aspect; some of the designs that you guys have done are actually compelling because it's like a whole clip - the propulsion, steering, the suspension are all one module that you just hang on the vehicle and those are interchangeable corners so that's good .. which is dramatically different than an internal combustion engine so there could be some savings from that standpoint.

27:20 ... It's my opinion and experience that the electrification of al lot of these traditional mechanical elements is actually in the longer run lower cost – initially it might be a bigger investment but if you get the volumes up – like the cell phone or consumer electronics industry ...the analogy is similar, not exact, but similar. ...They might be some players that say "I will own the space around wheel robots, or whatever it is," and they get the cost down and the industry to adapt it perhaps and then it becomes less of an impediment.

We've done things like integrated suppliers at the design phase, at the engineering phase, and at the build & assembly phase we've run those trials. And Volkswagen has also done similar tests. ...it's feasible. On a lower volume it might be a safer lower risk way to go. And that's why this initiative in the Basque region is pretty interesting to see how it plays out. ...because if it does work out at that level where the stakeholders are getting their value capture it a robust reliable system that they can deploy, then that removes some of the excuses that have been thrown out to why you shouldn't do it that way.

30:10 I would call it a test well of a business model. Can a federation of non-major automotive suppliers build a low volume vehicle and make money out of it? And you could argue that's something that happened in the Basque region. ...Now you could also say now look at this test well that's happening in the silicon valley with Tesla and Fisker. ...they're not a big major OEM, how could they engineer something for profit with all the risk they have in terms of technology? Those models are becoming more feasible and possible. You might see that kind of business model easily happen if a country like China wants to buy the option ...if they want to control this kind of solution down the road.

You may see them become even more feasible if you see a country like China who just wants to own it.

It follows the consumer electronics model ODM (original design manufacturer - like HTC)

Modularity in alternative vehicle platforms

47:02 You kind of have to start with flexibility and options – It's kind of like natural selection

(In reference to modularity providing variation in a budding alternative energy vehicle market) *Q: Is there value in keeping some level of flexibility and modularity in a new market?* A: I think you have to, it's like evolution right – there's variation, and then natural selection follows. If you don't, it's like the Model-T issue. Ford ran [the Model-T] wild because everyone was buying it, but after a while people were like that's not what I want because these alternatives are better. ...there was like an 18 month period to retool beyond the Model-T just to get back relevant in the market.

Narrowing the mission profile – Configure-to-order vehicles for fleets

Modularity and customization is all about how you manage those interfaces

There are always architectural constraints that reduce your ability to go wildly different

END

Interviewee #3

Future mobility

7:30 Much more customization. The days of just picking a car from these nine options – I think someone is going to decouple that and say here's 800 apps that you can have for your car, each one cost you $2/year. Which ones do you want? I think you're going to see much more off built systems for navigation and entertainment

Average person is still getting bigger ...people are generally getting bigger, so there's no reason to think you can get the cabin of the car smaller. Cabin same volume. A lot more aerodynamics of the car than we have now – drag coefficients well under 0.2. You have to do that to get the fuel economy down. 54 MPG before 2030.

22:45 I think you're going to see it customizable on the initial purchase, I don't think you're going to see it reconfigurable. Layer up-fits – increase battery capacity ...like a truck that can add a battery.

NEVs only in retirement communities in Florida, Arizona, and Palm Beach, California.

29:20 Aerodynamics losses from smaller cars will start to be outweighed by fuel costs - aerodynamics will outweigh fuel economy

No motivation to gamble when on top

31:50 They (OEMs) don't handle it (disruptive technologies) well. ...The guy that's going to do the best is the guy that's desperate. The guy on top isn't going to risk it. And it's good form. It's true, if you're the leading manufacturer ...what is the motivation to gamble when you're on top."

By-Wire systems

37:30 Steer by-wire w/o mechanical interface [you're not just going to see it just because] ...Now with by-wire systems, unless you're going to get into autonomous vehicle systems where the car can drive itself, now the motivation for by-wire becomes much greater. Why, why would you do it? Unless it's better or more reliable, why would you do it? (the motivation for hydraulics was the lack of corrosion on the system that came before it, cable braking). If you don't have a true motivation to change it, it's a fashion statement and no one in mainstream will do it.

40:21 I see rear-by-wire braking. Less fluid lines to run to the rear. More modular. And the primary front brakes still have hydraulic. I don't think you're going to see steer by-wire [ever]. I cannot see it by 2030. Incremental change with no benefit to the customer, so you're not going to do it.

I think you'll still see a steering wheel – repetitive positioning, support for airbag (smaller), ability to drive in various ways (even knees)

Supplier – OEM relations

50:14 Suppliers hate the OEMs – all of them. the OEMs are arrogant and overbearing. They assume that they know how to make everything and that you're and idiot – the supplier.

Profit margins are razor thin - Maybe $0.02 of profit in a $0.50 part "There's no water left to squeeze out of that rock"

"It's hostile at least and downright war at best"

People in the engineering within the OEM organization are very reluctant to commit to anything new.

The only way that you can have a fully integrated supplier is if the amount of money that the supplier get is a combination personal earning of his products and the vehicle profit. If he doesn't have a stick on both of those games, he's only going to play in the game he's got money in.

Constructive Criticism on the CityCar

1:02:00 I thought the Hiriko was pretty well done. I though the group didn't have a clue how impossible the task was. The main theme was maintained throughout the project. Big glass, 4-wheel steering, spins, folding.

The concept was faithfully done in the Basque region. I thought they really did a great job.

END

7.L MODULE MANUFACTURER SURVEY

Hiriko - Module Manufacturer Survey

1. Welcome

Hello / Hola / Kaixo,
Thank you for taking the time to complete this survey.
The following questions will be used solely for research purposes on the CityCar concept. (únicamente para mi investigación de CityCar)

Thank you / Gracias / Eskerrik asko,
-Will

William Lark, Jr.
MIT Media Lab

Please select the language in which you would like to complete survey (idioma):

- ◯ English
- ◯ Castellano (disculpen los errores de traducción)

Next (Próxima)

Hiriko - Module Manufacturer Survey

2. Hiriko Module

Which module of Hiriko do you primarily develop? (select all that apply)

- [ ] Robot Wheel
- [ ] Chassis
- [ ] Control System
- [ ] Surfaces (exterior & interior components)
- [ ] Driver Interface
- [ ] Power Source & Energy Management
- [ ] Other (please specify)

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

2. Módulo de Hiriko

¿Qué módulo de Hiriko principalmente desarrollas?

- [ ] Robot Wheel
- [ ] Chasis
- [ ] Sistema de control
- [ ] Las superficies (componentes exteriores y interiores)
- [ ] Controlador de Interfaz
- [ ] Energía
- [ ] Otros (especificar)

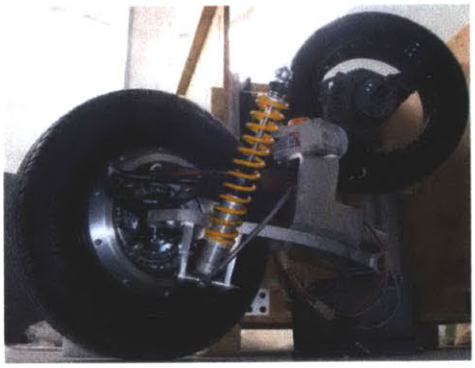
Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Robot Wheel

The modularization of the drive train in the RobotWheel provides the opportunity to customize its performance characteristics more easily than a traditional vehicle platform.

- ◯ Strongly agree
- ◯ Somewhat agree
- ◯ Neither agree nor disagree
- ◯ Somewhat disagree
- ◯ Strongly disagree



The RobotWheel can be utilized to rapidly develop vehicles other than Hiriko.

- ◯ Strongly agree
- ◯ Somewhat agree
- ◯ Neither agree nor disagree
- ◯ Somewhat disagree
- ◯ Strongly disagree

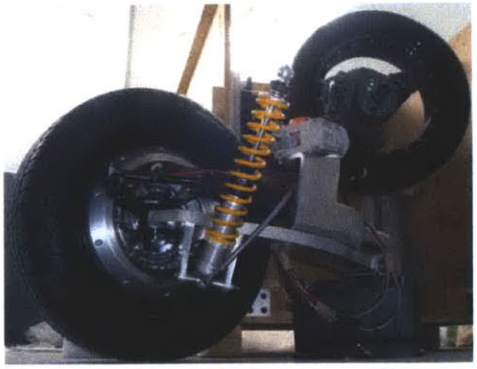
Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. RobotWheel

La modularización del "RobotWheel" ofrece la oportunidad de personalizar sus características de rendimiento más fácilmente que una plataforma de vehículo tradicional.

- ◯ Totalmente de acuerdo
- ◯ Algo de acuerdo
- ◯ Ni de acuerdo ni en desacuerdo
- ◯ En desacuerdo
- ◯ Totalmente en desacuerdo



La RobotWheel puede ser utilizada para desarrollar rápidamente vehículos aparte de Hiriko.

- ◯ Totalmente de acuerdo
- ◯ Algo de acuerdo
- ◯ Ni de acuerdo ni en desacuerdo
- ◯ En desacuerdo
- ◯ Totalmente en desacuerdo

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

Exit this survey

4. Hiriko Modularity (1 of 3)

Does the decoupled (modular) vehicle platform liberate design and manufacturing decisions?

- ◯ Completely liberated, my module can be redesigned fully independent of other systems.
- ◯ Greatly liberated, most of my module can be reconfigured independently, yet requires occasional check-in with other system teams.
- ◯ Fairly liberated, some of my module can be altered, but need to consult to other system teams first.
- ◯ Barely liberated, any alteration to my module requires redesign or adjustment from other team and surrounding components.
- ◯ No liberation, any module alteration requires redesign of all surrounding components and integration strategy must be revisited.

Are you likely to propose changes, improvements, or variation to your module, or wait until it is requested?

- ◯ I will definitely initiate variations within my module when I believe it offers business opportunities.
- ◯ I might initiate variations within my module if an opportunity arrives; I will recommend it to the Hiriko consortium.
- ◯ I am unlikely to initiate module variation; I may suggest it to the Hiriko consortium.
- ◯ I will only use variation within my module if requested by the Hiriko consortium.

Compared to your previous supplier roles developing other automobile components, does your role now within Hiriko permit you to be more empowered in module development?

- ◯ Yes, I have total control of my module.
- ◯ Much more than before, I have a strong influence on how and what gets developed.
- ◯ Somewhat empowered, I play a larger part in the decisions of my module.
- ◯ Little empowerment, the influence I have has improved marginally compared to before.
- ◯ No change, my role in Hiriko is identical to traditional supplier-manufacturer relationships.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

Exit this survey

4. Modularidad de Hiriko (1 de 3)

¿El desacoplado (modular) diseño de la plataforma del vehiculo liberar las decisiones de fabricación?

- ◯ Completamente liberado, mi módulo puede ser rediseñado totalmente independiente de otros sistemas.
- ◯ Muy liberada, la mayor parte de mi módulo puede ser reconfigurado de forma independiente, sin embargo, requiere de vez en cuando el check-in con los equipos del sistema.
- ◯ Bastante liberados, algunos de mi módulo puede ser alterado, pero es necesario consultar a los equipos de otros sistemas en primer lugar.
- ◯ Apenas liberado, cualquier alteración a mi módulo requiere rediseño o ajuste de otro equipo y los componentes circundantes.
- ◯ No liberada, cualquier alteración al módulo requiere el rediseño de todos los componentes de los alrededores y la estrategia de integración debe revisarse.

¿Es probable que propogan cambios, mejoramientos,o variación en el módulo, o esperar hasta que se solicitada?

- ◯ Definitivamente voy a iniciar las variaciones dentro de mi módulo cuando creemos que ofrece oportunidades.
- ◯ Yo podría iniciar las variaciones dentro de mi módulo, si la oportunidad llega, lo recomendaría al consorcio Hiriko.
- ◯ Es poco probable que iniciaría la variación del módulo, podría sugerir al consorcio Hiriko.
- ◯ Sólo se utilizará la variación dentro de mi módulo si es solicitado por el consorcio Hiriko.

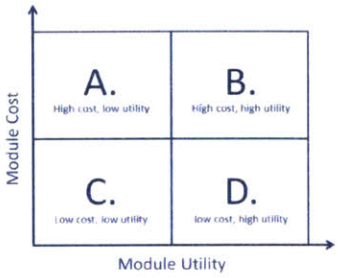
¿En comparación con sus responsabilidades de proveedores anteriores en el desarrollo de otros componentes del automóvil, su papel ahora dentro de Hiriko le permiten tener más poder en el desarrollo del módulo?

- ◯ Sí, tengo el control total de mi módulo.
- ◯ Mucho más que antes, tengo una fuerte influencia en cómo y qué se desarrolla.
- ◯ Poco poder, mantengo un papel más importante en las decisiones de mi módulo.
- ◯ Poco poder, la influencia ha mejorado marginalmente en comparación con antes.
- ◯ No hay cambio, mi papel en Hiriko es idéntica a las tradicionales relaciones de proveedor-fabricante.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

5. Hiriko Modularity (2 of 3)

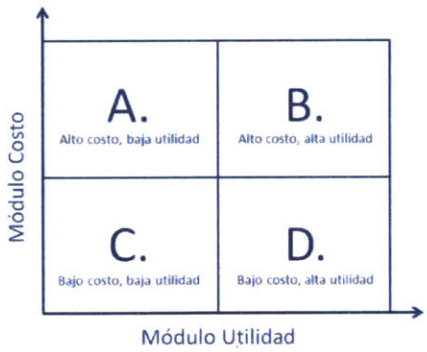


The "Cost-Utility Measurement" associates the relative functionality of a module at its comparative production cost. Relative to each other, where do you believe each module falls within this graph?

	A	B	C	D
Robot Wheels	○	○	○	○
Folding Chassis	○	○	○	○
Battery Module	○	○	○	○
Cabin/Body	○	○	○	○
By-Wire Controls	○	○	○	○
Rear Compartment	○	○	○	○

Hiriko - Module Manufacturer Survey

5. Modularidad de Hiriko (2 de 3)

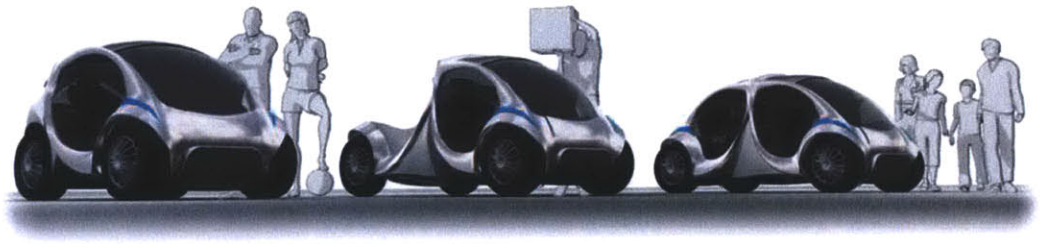


El "Coste-Utilidad de Medición" asocia la funcionalidad relativa de un módulo a su costo de producción. ¿En relación con los demás, dónde cree que cada módulo se inscribe en este gráfico?

	A	B	C	D
Robot-Wheels	○	○	○	○
Chasis Plegable	○	○	○	○
módulo de batería	○	○	○	○
Cabina (Body)	○	○	○	○
Sistema de control (by-wire)	○	○	○	○
Compartimiento trasero	○	○	○	○

The modules of the Hiriko platform allow us to create a variety of vehicles from most of the same components.

- ◯ Strongly agree, modules can easily be reconfigured for vehicle variety.
- ◯ Somewhat agree, the modules of Hiriko can be utilized for a feature variations.
- ◯ Neither agree, nor disagree – there is no change in product variety provided by the Hiriko modules.
- ◯ Somewhat disagree, the Hiriko modules complicate product variety.
- ◯ Strongly disagree; the Hiriko modules completely inhibit product variety.



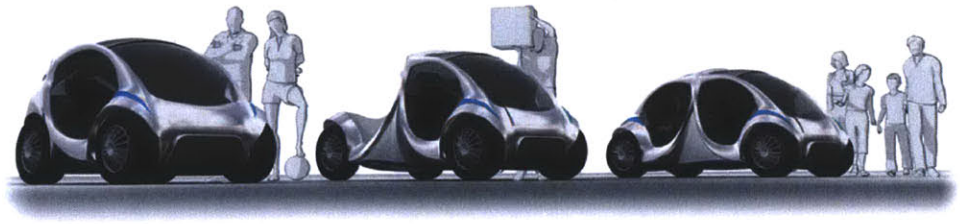
Hiriko's modularity will expedite future versions of this vehicle.

- ◯ Yes, because the systems are separate, I will be able to design the next modules or vehicles faster.
- ◯ Perhaps, with the separate systems the next designs may happen quicker.
- ◯ Unlikely, the development time may only be marginally faster.
- ◯ No, other versions will take just as long as before.

Prev (Anterior) Next (Próxima)

Los módulos de la plataforma Hiriko nos permiten crear una variedad de vehículos de la mayor parte de los mismos componentes.

- ◯ Totalmente de acuerdo, los módulos pueden ser fácilmente reconfigurado por la variedad de vehículos.
- ◯ Algo de acuerdo, los módulos de Hiriko pueden ser utilizado para algunas variaciones de características.
- ◯ Ni de acuerdo ni en desacuerdo - no hay ningún cambio en la variedad de productos proporcionada por los módulos de Hiriko.
- ◯ Algo en desacuerdo, los módulos de Hiriko complican la variedad de productos.
- ◯ Totalmente en desacuerdo, los módulos de Hiriko inhiben completamente la variedad de productos.



La empresa Hiriko ofrece nueva oportunidad para ampliar su negocio.

- ◯ Totalmente de acuerdo
- ◯ Algo de acuerdo
- ◯ Ni de acuerdo ni en desacuerdo
- ◯ En desacuerdo
- ◯ Totalmente en desacuerdo

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

6. Hiriko Modularity (3 of 3)

- Customization (developing unique modules or features for customers)
- Servicing (repairs and upgrades to particular module)
- After-market products (various components that the customers can purchase)
- Life-cycle management (reacquisition of modules for reuse, repurposing or recycling)

Hiriko's modular platform presents business opportunities to expand into the following services.

	Strongly agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Strongly disagree
customization	○	○	○	○	○
servicing	○	○	○	○	○
after-market products	○	○	○	○	○
life-cycle management	○	○	○	○	○

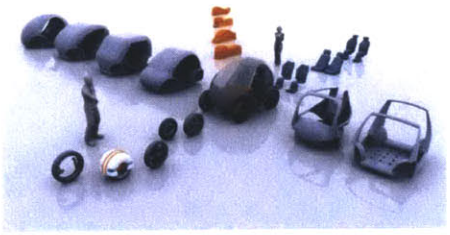
From the perspective of Hiriko, it is better to:

- ○ Coordinate with fewer suppliers, each contributing a large proportion.
- ○ Coordinate with many suppliers, each contributing a small proportion.
- ○ The number of suppliers and their proportion of contribution does not matter.

Hiriko - Module Manufacturer Survey

6. Modularidad de Hiriko (3 de 3)

- Personalización (el desarrollo de módulos o funciones exclusivas para los clients - MoD o usuarios finales)
- Prestación de servicios (reparaciones o actualizaciones a un módulo en específico)
- Los productos en el mercado secundario (productos diversos que los clientes pueden comprar en el comercio)
- Ciclo de Vida de la Gestión (la readquisición de los módulos para su reutilización o reciclado)



La plataforma modular de Hiriko presenta oportunidades para expandirse en los siguientes servicios.

	Totalmente de acuerdo	Algo de acuerdo	Ni de acuerdo ni en desacuerdo	En desacuerdo	Totalmente en desacuerdo
Personalización (customization)	○	○	○	○	○
Prestación de servicios	○	○	○	○	○
Los productos en el mercado secundario	○	○	○	○	○
Ciclo de Vida de la Gestión	○	○	○	○	○

Desde la perspectiva de Hiriko, que es mejor:

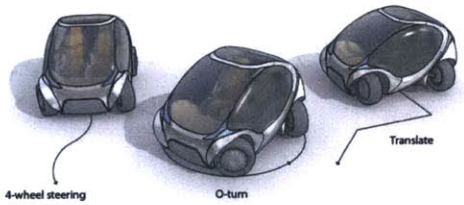
- ○ Coordinar con menos proveedores, cada uno aportando una gran proporción.
- ○ Coordinar con muchos proveedores, cada uno contribuyendo con una pequeña proporción.
- ○ El número de proveedores y su proporción de la contribución, no importa.

Hiriko - Module Manufacturer Survey — Exit this survey

7. CityCar

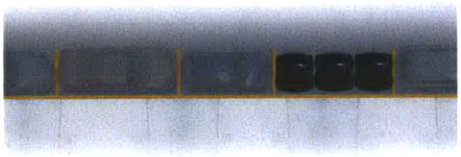
For the CityCar (Hiriko) vehicle, please rate the importance of the following maneuvers:

	Extremely important	Moderately important	Slightly important	Not important
O-turn	○	○	○	○
translation	○	○	○	○
4-wheel steering	○	○	○	○



Incorporating folding into the CityCar to reduce its footprint by 40% and enable a 3:1 street parking ratio can be worth the added engineering complexity.

- ○ Strongly agree
- ○ Somewhat agree
- ○ Neither agree nor disagree
- ○ Somewhat disagree
- ○ Strongly disagree



Incorporating folding into the CityCar to reduce its footprint while also easing entry and exit of passengers can be worth the added engineering complexity.

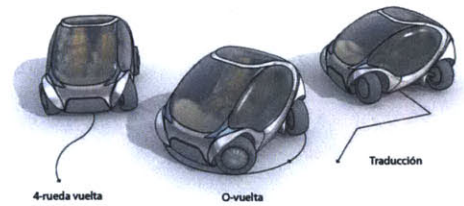
- ○ Strongly agree
- ○ Somewhat agree
- ○ Neither agree nor disagree
- ○ Somewhat disagree
- ○ Strongly disagree

Hiriko - Module Manufacturer Survey — Exit this survey

7. CityCar

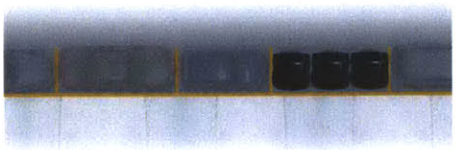
Para el CityCar (Hiriko) vehículo, por favor, evalúe la importancia de las capacidades:

	Muy importante	Moderadamente importante	Un poco importante	No es importante
O-vuelta (spin)	○	○	○	○
Traducción	○	○	○	○
4-rueda vuelta	○	○	○	○



La incorporación de plegado en el CityCar para reducir su huella en un 40% y habilitar unaproporción 3:1 aparcamiento en la calle vale la complejidad de ingeniería añadido.

- ○ Totalmente de acuerdo
- ○ Algo de acuerdo
- ○ Ni de acuerdo ni en desacuerdo
- ○ En desacuerdo
- ○ Totalmente en desacuerdo



La incorporación de plegado en el CityCar para reducir su huella a la vez que facilitar la entrada y salida de pasajeros vale la complejidad de ingeniería añadido.

- ○ Totalmente de acuerdo
- ○ Algo de acuerdo
- ○ Ni de acuerdo ni en desacuerdo
- ○ En desacuerdo
- ○ Totalmente en desacuerdo

Hiriko - Module Manufacturer Survey

Exit this survey

3. Control System

Does the Hiriko by-wire vehicle platform provide unique development opportunities compared to traditional automobile electronics platforms?

- ◯ Yes, we are able to research and develop unique electronic features that could provide future business advantages.
- ◯ Somewhat, we recognize potential opportunities for development.
- ◯ No change, the Hiriko platform does not provide unique prospects from traditional automobiles.
- ◯ Detrimental results; the Hiriko platform inhibits research and development opportunities.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

Exit this survey

3. Sistema de control

¿El Hiriko by-wire plataforma de vehículos ofrecen oportunidades únicas de desarrollo en comparación con las plataformas tradicionales de automóviles de electrónica?

- ◯ Sí, somos capaces de investigar y desarrollar las características únicas de electrónicos que podrían proporcionar ventajas empresariales futuras.
- ◯ Un poco, somos conscientes de las oportunidades potenciales para el desarrollo.
- ◯ No hay cambios, la plataforma Hiriko no ofrece perspectivas únicas de los automóviles tradicionales.
- ◯ Resultados negativos; la plataforma Hiriko inhibe las oportunidades de investigación y desarrollo.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Surfaces

Given the construction of the Hiriko body (plastic paneling attached to a space-frame chassis) alterations to the surfaces can be made fairly independent of other components.

- ◯ Strongly agree
- ◯ Somewhat agree
- ◯ Neither agree nor disagree
- ◯ Somewhat disagree
- ◯ Strongly disagree

How likely are you to make design variations, independent of changes in the chassis?

- ◯ Definitely, we plan to develop vehicle variations.
- ◯ Potentially, we could create some changes to the design, independent of the chassis.
- ◯ Unlikely, marginal changes are possible but improbable.
- ◯ Never, no changes will be made to the panels unless completely new vehicle platforms are made.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Las superficies

Dada la construcción del cuerpo Hiriko (paneles de plástico unido a un marco de espacio-chasis) alteraciones de las superficies puede hacerse bastante independiente de los otros componentes.

- ◯ Totalmente de acuerdo
- ◯ Algo de acuerdo
- ◯ Ni de acuerdo ni en desacuerdo
- ◯ En desacuerdo
- ◯ Totalmente en desacuerdo

¿Qué probabilidad hay de hacer variaciones en el diseño, independientemente de los cambios en el chasis?

- ◯ En definitiva, tenemos la intención de desarrollar variaciones de los vehículos.
- ◯ Potencialmente, podríamos crear algunos cambios en el diseño, independiente del chasis.
- ◯ Improbable, cambios marginales son posibles pero improbables.
- ◯ Nunca, no se harán cambios a los paneles a menos plataformas de vehículos completamente nuevos están hechos.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Driver Interface

Hiriko's modular by-wire system allows for unique customization of the driver interface.

- ◯ Strongly agree
- ◯ Somewhat agree
- ◯ Neither agree nor disagree
- ◯ Somewhat disagree
- ◯ Strongly disagree

How likely are you to develop a variety of driver interfaces that are compatible to Hiriko's electronic infrastructure?

- ◯ Very likely, settled on an electronic standard, we can make multiple driver interfaces that are all compatible.
- ◯ Somewhat likely, we may make a variation or two of unique driver interfaces.
- ◯ Unlikely, we expect to stay with the one driver interface developed.
- ◯ Never, we will not design another driver interface.

Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Controlador de Interfaz

El sistema modular de Hiriko de by-wire permite la personalización única de la interfaz del controlador.

- ◯ Totalmente de acuerdo
- ◯ Algo de acuerdo
- ◯ Ni de acuerdo ni en desacuerdo
- ◯ En desacuerdo
- ◯ Totalmente en desacuerdo

¿Qué posibilidades hay de desarrollar una variedad de interfaces de controladores que son compatibles con la infraestructura electrónica de Hiriko?

- ◯ Es muy probable, estableciendo en un electrónico estándar, podemos hacer varias interfaces de controladores que son todos compatibles.
- ◯ Algo probable, podemos hacer una variación de uno o dos de las interfaces de controladores únicos.
- ◯ Es poco probable, esperamos quedar con la interfaz del controlador que se desarrolló.
- ◯ Nunca, no vamos a diseñar otro interfaz del controlador.

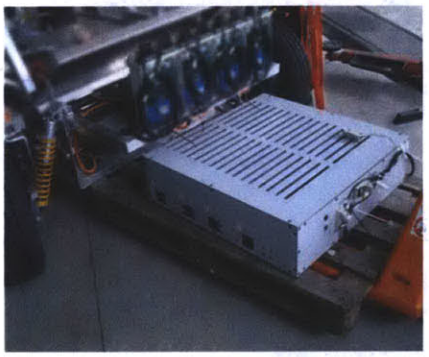
Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Power Management

How influential is Hiriko's modular platform in the possibility of using other energy modules?

- ◯ Strategic benefit, the battery compartment allows us to switch in other energy technologies when needed.
- ◯ Potential benefit, there is flexibility to adjust the power source technologies if required.
- ◯ Little benefit, the energy source is pretty restricted and not subject to modifications.
- ◯ No benefit, energy system is inflexible.



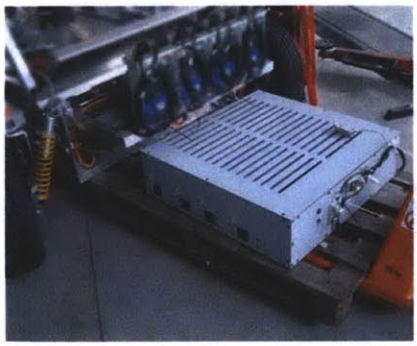
Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

3. Energía

¿Qué tan influyente es la plataforma modular de Hiriko en la posibilidad de utilizar otros módulos de energía?

- ◯ Beneficio estratégico, el compartimiento de la batería nos permite cambiar en otras tecnologías energéticas cuando sea necesario.
- ◯ El beneficio potencial, hay flexibilidad para ajustar las tecnologías de energía si es necesario.
- ◯ Poco beneficio, la fuente energía es bastante restringido y no está sujeto a modificaciones.
- ◯ No existe un beneficio, el sistema de energía es poco flexible.



Prev (Anterior) Next (Próxima)

Hiriko - Module Manufacturer Survey

8. CityCar (final question)

Please rate the value of the following CityCar (Hiriko) features:

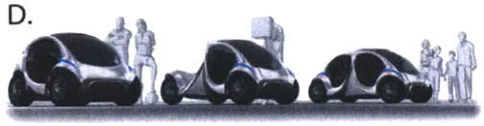
	Essential, core feature of business	Beneficial, provides valuable impact	Somewhat helpful, adds marginal value	Neutral, feature has no net impact	Unfavorable, somewhat problematic	Impractical, unfeasibly complex	Detrimental, destructive obstacles to business
A. Reduced footprint from folding chassis	○	○	○	○	○	○	○
B. Maneuverability from Robot Wheels	○	○	○	○	○	○	○
C. Eased entry & exit from front door	○	○	○	○	○	○	○
D. Customized utility from rear compartment	○	○	○	○	○	○	○

A.

B.

C.

D.



Final comments can be added below (optional)

Thank you for participating
Please click "Next" to submit the questionnaire
You input is much appreciated

-Will

Hiriko - Module Manufacturer Survey

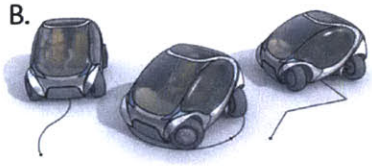
8. CityCar (pregunta final)

Por favor, califique el valor de los siguientes CityCar (Hiriko) características:

	Esencial, el núcleo de los negocios	Benéfico, proporciona valiosa impacto	Algo muy útil, agrega valor marginal	Neutral, no tiene ningún impacto neto	Desfavorable, algo problemático	Poco práctico, complejo	Desventajoso, obstáculos destructivos para las empresas
A. plegado para reducir su huella	○	○	○	○	○	○	○
B. RobotWheels para maniobrabilidad	○	○	○	○	○	○	○
C. la entrada y salida aliviado de la parte delantera	○	○	○	○	○	○	○
D. compartimiento trasero para gran variedad y personalización	○	○	○	○	○	○	○

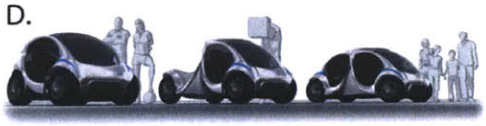
A.

B.



C.

D.



Comentarios adicionales (opcional)

Gracias por participar.
Por favor, haga clic en "Next" para finalizar el cuestionario

-Will

7.M SHARED MOBILITY SYSTEMS SURVEY

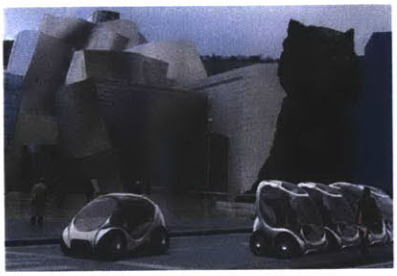
Hiriko in Shared Mobility Systems — Exit this survey

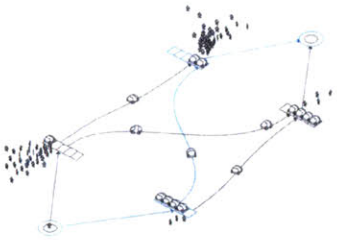
1. Welcome

Hello,
Thank you for taking the time to complete this survey. The following statements will be used solely for research purposes on the implementation of the Hiriko vehicle (CityCar) in the context of shared mobility services.

After each statement, please choose one of the following multiple choice options.
Comments may be added in the text boxes below if you choose to further elaborate.

The survey will take about 10 minutes to complete





Thank you,
-Will

William Lark, Jr
MIT Media Lab, PhD Candidate
www.wlark.com

By clicking NEXT, you understand and agree to the following terms and conditions

1) Your data will be kept private and confidential
2) You agree to share your information with the researcher
3) You can choose to opt out of this survey & any future related studies at any point

9%

Next

Hiriko in Shared Mobility Systems

2. Mobility Sector Experience

What role(s) have you had in the shared mobility sector? (select all that apply)

- [ ] System development
- [ ] System management
- [ ] Fleet operator
- [ ] Municipal services / government
- [ ] Utility Services
- [ ] Research
- [ ] Other (please specify)

18%

Prev Next

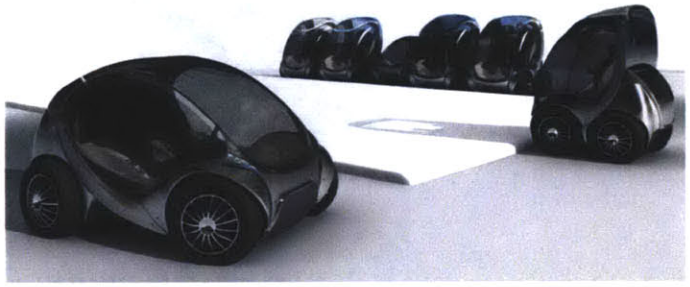
Hiriko in Shared Mobility Systems

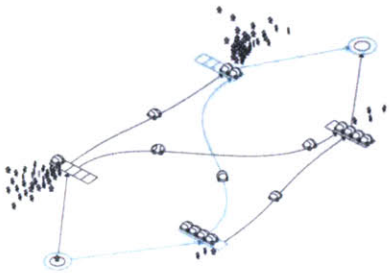
Exit this survey

3. Hiriko Summary

Hiriko is a foldable, electric, sharable, two-passenger vehicle for crowded cities. The compartmentalized modules enable vehicle features uniquely convenient for crowded cities, especially in Europe and Asia (over 3-to-1 parking ratios, vastly increased maneuverability, and eased entry & exit). The robot-wheels, cabin unit, power module, drive-by-wire module, and rear compartment combine to form a small urban vehicle with the adaptability to ease customization, servicing, and module reuse. Hiriko (CityCar) challenges vehicle standards through novel technologies in order to provide radical solutions for urban mobility.

Mobility-on-Demand (MoD) is a shared service in which various fleets of urban vehicles are utilized within cities for commuting and intermittent transit (similar to Car2Go, Velib, and Bixi). In this one-way mode, users are allowed to pick up electric vehicles from any charging station and drive to any other designated station (point-to-point rental). As a supplement to public transit, MoD strives to tackle the challenge of first-mile, last-mile trnsportation.





Urban commuters are continually seeking alternative solutions for transportation.

	Strongly Agree	Moderately Agree	Slightly Agree	Neither Agree nor Disagree	Slightly Disagree	Moderately Disagree	Strongly Disagree
In American Cities	○	○	○	○	○	○	○
In European Cities	○	○	○	○	○	○	○
In Asian Cities	○	○	○	○	○	○	○

Feel free to explain answer here (not required)

There are market opportunities for vehicles like the Hiriko in urban environments.

	Strongly Agree	Moderately Agree	Slightly Agree	Neither Agree nor Disagree	Slightly Disagree	Moderately Disagree	Strongly Disagree
In American Cities	○	○	○	○	○	○	○
In European Cities	○	○	○	○	○	○	○
In Asian Cities	○	○	○	○	○	○	○

Feel free to explain answer here (not required)

27%

Hiriko in Shared Mobility Systems

Exit this survey

4. Optimizing Shared Mobility Services

Shared mobility programs typically use identical vehicle models within their fleets (although ZipCar does employ a variety of automobile models). How important is it to have a variety of vehicle types in a shared mobility service?

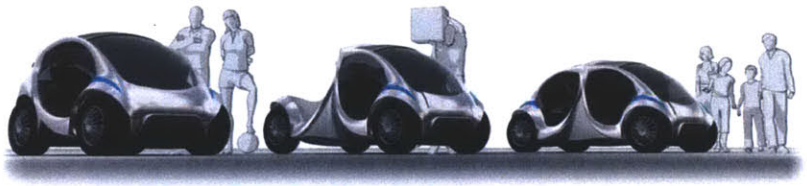
- ◯ Extremely Important
- ◯ Moderately Important
- ◯ Slightly Important
- ◯ Barely Important
- ◯ Completely Useless

Feel free to explain answer here (not required)

Would an operator of a shared mobility service value vehicle diversity within their fleet (given a standard compatibility to their system infrastructure)?

- ◯ Definitely, it's extremely important
- ◯ Yes, it's moderately important
- ◯ Perhaps, it's slightly important
- ◯ Unlikely, it's of little importance
- ◯ No, it's completely useless

Feel free to explain answer here (not required)



Exploiting Hiriko's modularity to have vehicles of various storage capacity, range, size, and performance can be an effective solution for shared mobility fleets.

- ○ Strongly Agree
- ○ Moderately Agree
- ○ Slightly Agree
- ○ Neither Agree nor Disagree
- ○ Slightly Disagree
- ○ Moderately Disagree
- ○ Strongly Disagree

Feel free to explain answer here (not required)

When selecting vehicles for a shared mobility program, it would be valuable to be able to customize the following features:

	Extremely Important	Moderately Important	Slightly Important	Barely Important	Completely Useless
Range	○	○	○	○	○
Storage capacity	○	○	○	○	○
Footprint (length & width)	○	○	○	○	○
Performance characteristics (horsepower or turning radius)	○	○	○	○	○

Feel free to explain answer here (not required)

Fleet operators of shared mobility services seek out vehicles with particular specifications that best fit their city characteristics and user demand.

- ○ Strongly Agree
- ○ Moderately Agree
- ○ Slightly Agree
- ○ Neither Agree nor Disagree
- ○ Slightly Disagree
- ○ Moderately Disagree
- ○ Strongly Disagree

Feel free to explain answer here (not required)

If you were managing a fleet of shared vehicles, the option to customize your vehicle features would be...

- ○ extremely valuable
- ○ moderately valuable
- ○ slightly valuable
- ○ of little value
- ○ of no value

Feel free to explain answer here (not required)

36%

Prev Next

Hiriko in Shared Mobility Systems

Exit this survey

5. Management of Mobility Services

Vehicles in shared mobility services are utilized more frequently throughout the day.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

If the average personal vehicle is used only an hour or two each day, about how much more do you believe vehicles in a shared mobility service are used?

- ◯ Less amount of time daily
- ◯ About the same
- ◯ About twice as much daily
- ◯ More than twice as much daily

Feel free to explain answer here (not required)

Servicing and maintaining the vehicles in shared mobility is significantly prohibitive to the system's profits.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Hiriko exploits a highly modular platform that allows major systems (drivetrain, energy module) to be decoupled, easily removed, and substituted. Reducing the maintenance of many subsystems by instead substituting and upgrading vehicle modules is a desirable approach for shared mobility fleets.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Fleet operators would consider employing more expensive vehicles if these vehicles saved them time in servicing and maintenance.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

The modular architecture of Hiriko is likely to reduce maintenance burdens to shared mobility fleet operators.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

45%

Prev Next

Hiriko in Shared Mobility Systems

Exit this survey

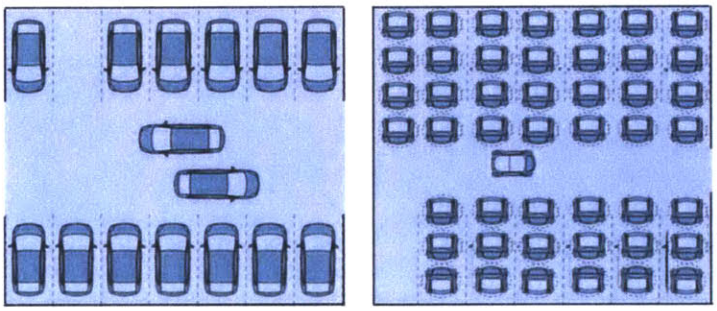
6. Adapting the Shared Mobility Service

How complex of a challenge is land acquisition when developing or expanding a shared mobility service?

- ◯ Most difficult challenge, often prohibitive
- ◯ Very challenging, requires significant resources
- ◯ Fairly challenging, feasible
- ◯ Slightly challenging, often achievable
- ◯ Simple, relatively trivial

Feel free to explain answer here (not required)

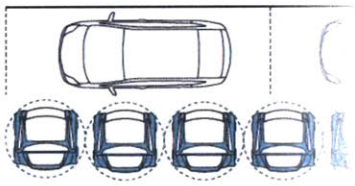
Utilizing a fleet of vehicles that have a small footprint or take little space while parked can ease the development and expansion of shared mobility systems.



- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Hiriko's folding capability (3-to-1 parking ratio) is uniquely valuable to shared mobility management.



- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

If you were to manage a new or expanding shared mobility fleet, you would seek to use vehicles very similar Hiriko.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Hiriko's platform permits eased switching of modules to adjust the vehicle's performance, range, storage, or other user features. As ridership grows, service coverage expands, and general system demands evolve, how valuable is the option to adapt the vehicles to these changes?

- ○ Extremely Important
- ○ Moderately Important
- ○ Slightly Important
- ○ Barely Important
- ○ Completely Useless

Feel free to explain answer here (not required)

In a shared mobility fleet, how frequently are the following modules likely to be changed?

	Multiple times within a year	About once a year	Every couple of years	Every several years	Rarely during vehicle lifespan	Never
Battery modules	○	○	○	○	○	○
RobotWheels	○	○	○	○	○	○
Rear storage / utility compartment	○	○	○	○	○	○
Driver interface	○	○	○	○	○	○
Information/Entertainment system	○	○	○	○	○	○
Cabin/chassis	○	○	○	○	○	○

Feel free to explain answer here (not required)

As the concept blueprint for Hiriko, the following questions concern features of the CityCar

55%

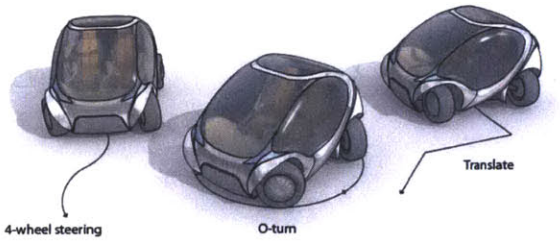
Prev Next

Hiriko in Shared Mobility Systems

Exit this survey

7. Increased Maneuverability

The CityCar utilizes four independent Robot Wheels that each turn up to 120-degrees. The large sweep in each wheel coordinate to provide the following maneuvers:
- O-turn: allowing the vehicle to spin on a dime continuously
- Translation: allows the vehicle to side-step perpendicularly
- 4-wheel steering: provides tight turning radius and enables slight translation while driving



Some CityCar movements enabled by its independently controlled wheel motors.

Given the maneuverability of the CityCar, incorporating a large degree of wheel sweep is worth the added engineering complexity alone.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Incorporating a large degree of wheel sweep is worth the added engineering complexity, when coupled with the modular architecture of the robot wheels; which enables rapid servicing and a generally unencumbered platform.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

For the CityCar vehicle, please rate the importance of the following maneuver capabilities:

	extremely important	moderately important	slightly important	not important
O-Turn	◯	◯	◯	◯
Translation	◯	◯	◯	◯
4-Wheel Steering	◯	◯	◯	◯

Feel free to explain answer here (not required)

End users factor in the importance of maneuverability (turning radius in a traditional automobile) when operating vehicles in small crowded areas.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

64%

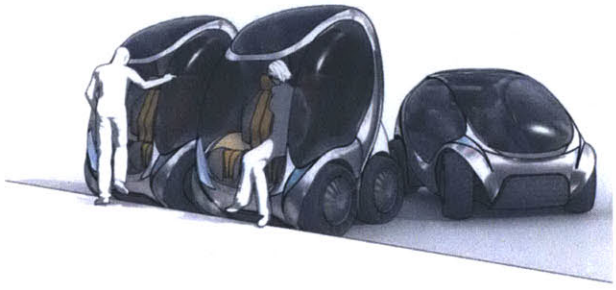
Prev Next

Hiriko in Shared Mobility Systems

Exit this survey

8. Front Entry and Exit

The CityCar utilizes a door in the front of the vehicle to ease entry and exit of its passengers onto the sidewalk once the vehicle is folded. In addition to the eased ingress/egress, the lack of side doors allows the vehicles to park tightly next to one another, maximizing parking surface area.



Permitting entry and exit from the front of the vehicle is a worthy benefit to challenging the traditional vehicle architecture (given support/demand from the end user).

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Permitting entry and exit from the front of the vehicle when coupled with the CityCar's folding and maneuverability for sidewalk access is worth added complexities.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

73%

Prev Next

9. Micro-Footprint through Folding Chassis

The CityCar utilizes a dual 4-bar linkage folding system to reduce its footprint by up to 40% when parking and maneuvering in tight low-speed situations. Passengers can remain in the vehicle during all states (unfolded, folded, and in-between).

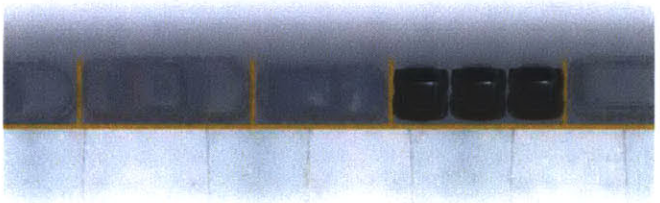
When unfolded and driving normally, the CityCar is slightly larger than the Smart Fortwo car. However when folded, it reduces its foot print to about 5' x 5' (five feet by five feet).

Incorporating folding into the CityCar to reduce its footprint by 40% and enable a 3:1 street parking ratio can be worth the added expenses in a shared mobility service.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Despite its added mechanical complexity, utilizing a folding chassis can be economically viable in a shared mobility system because of the potential savings in parking costs.



- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Vehicles with micro-footprints (less than 30 sq-ft) are very valuable in crowded urban environments

	Strongly Agree	Moderately Agree	Slightly Agree	Neither Agree nor Disagree	Slightly Disagree	Moderately Disagree	Strongly Disagree
In American cities	◯	◯	◯	◯	◯	◯	◯
In European cities	◯	◯	◯	◯	◯	◯	◯
In Asian cities	◯	◯	◯	◯	◯	◯	◯

Feel free to explain answer here (not required)

82%

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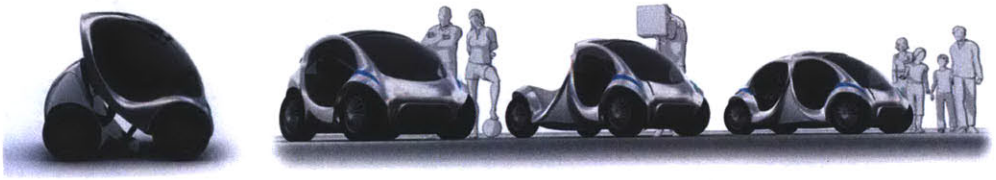
10. Decoupled Rear Compartment

The rear storage module of the CityCar is completely separated from the main cabin (similar to a pickup truck). It functions solely as a utility unit.



The decoupled rear compartment is a valuable module for fleet operators to customize.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Fleet operators will likely utilize the opportunity to customize the rear compartment for their own utility or service. (For example: delivery, maintenance/utility, cooled or heated compartment)

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

The rear compartment will likely be altered during the lifespan of the vehicle.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

Some levels of vehicle customization and personalization are desirable to system operators in a mobility-on-demand (shared mobility) service.

- ◯ Strongly Agree
- ◯ Moderately Agree
- ◯ Slightly Agree
- ◯ Neither Agree nor Disagree
- ◯ Slightly Disagree
- ◯ Moderately Disagree
- ◯ Strongly Disagree

Feel free to explain answer here (not required)

91%

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11. FINISHED

Thank you for participating.
Please click "Done" to submit the questionnaire.
You input is much appreciated.

-Will

Final comments can be added below (optional)

100%

Prev Done