AXIOMATIC REDESIGN

USING AXIOMATIC DESIGN TO IMPROVE VEHICLE PERFORMANCE
OF THE STEERING AND SUSPENSION SYSTEMS

by

BETO PELIKS

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEFREE OF

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ABSTRACT

Every year, automobile manufacturers strive to improve upon their existing designs. Every year, they make small adjustments and try to optimize their designs. Unfortunately, this 'optimization' is often a compromise between multiple components—and thus the individual components are not working as well as they could be.

Axiomatic Design is a methodology which attempts to avoid these relations between components. By fragmenting the assembly into smaller subcomponents, we can identify and sever these couplings. I used axiomatic design to help redesign a coupled automobile steering/suspension system.

Thesis Supervisor: Nam P. Suh
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INTRODUCTION

Recently, Ford proposed the following problem to the axiomatic design group at MIT:

If you let go of the steering wheel while driving on straight road, instead of continuing in the same desired path, the vehicle can swerve into other lanes.

However, because this problem only occurs on unsmooth roads (the car drives fine under controlled laboratory tests), it follows that there must be some coupling between the suspension and steering systems. This hypothesis is reinforced by the common stereotypes of German cars having great steering but a hard suspension, while American cars typically have poor steering systems but soft suspension systems. Thus, one cannot optimize the two systems independently—instead, one must compromise.

Following a preliminary investigation by H. Deo (2003), I have identified the major coupled elements in the existing design as the 'steering', 'camber' and 'suspension'. Briefly, I will describe these critical elements, followed by their implementation in existing automobile systems. I will then discuss my research into a new design. The paper is in chronological order and represents the design stage from start to finish:

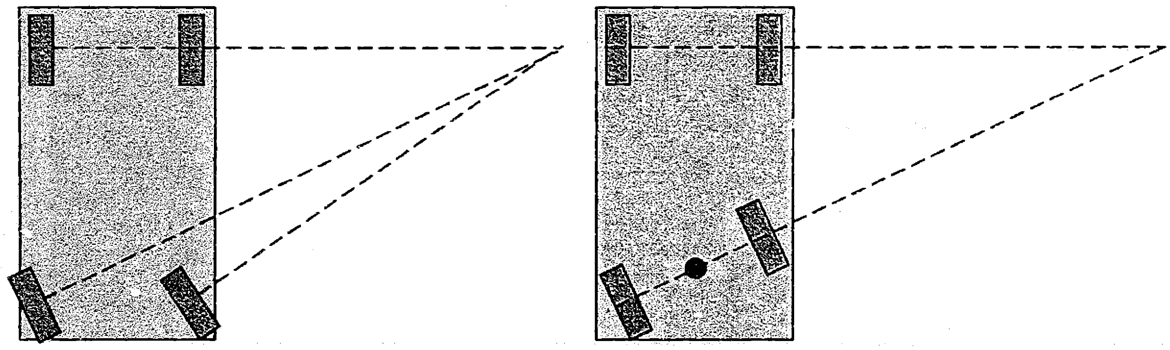
- Identifying the problem
- Conducting an FR/DP axiomatic design analysis of a new design
- Designing potential mechanisms
- Identifying the optimal design, then conducting a more detailed analysis
- Building a scaled prototype of the new design

DEFINITIONS

Steering System:

As the name suggests, the 'steering system' controls the turning of the automobile. There are several mechanisms which fall under the steering system; the critical ones which I will explore are the following.

Turning Wheels: The most obvious way to turn a vehicle is by adjusting the angle between the front and rear wheels. However, to make a controlled turn, the angles must be very precise—the arcs which the wheels follow must be perfectly concentric. Two significant designs have been used in the automobile industry, Ackermann and Tiller steering (Tiller steering is obsolete in modern vehicles). In Ackermann steering, each of the two front wheels pivot independently, with some control mechanism to ensure that they proportionally turn the correct amount. In Tiller steering, the entire front axle pivots. Unfortunately, this has many undesired consequences, including less stability on turns and poor shock handling (because the front axle bends under the load).



(a) Ackermann steering (b) tiller

Figure 1

Power Steering: Very few vehicles are now manufactured without power steering. In addition to adding comfort to the driver (it is easier to turn the wheel), power steering can improve vehicle stability and dynamics by reducing the impact of uneven roads. Indeed, power steering can negate nearly all disturbances from the road.

Scrub Radius/Caster: Both techniques (scrub radius and caster angle) are used to achieve the same goal. Scrub radius is the horizontal distance between the center of the wheel (the contact patch) and the steering axis. This distance can help to improve wheel stability. Perhaps the most obvious example of this technique is in shopping carts. By pivoting the wheel about a point before the contact patch, the wheel can 'self-adjust' and fluctuations on the path will thus have a smaller impact. Caster is similar to scrub radius, only instead of shifting the steering axis, it is instead angled.. An obvious implementation of caster is in bicycles: where the front wheel becomes more stable by angling the steering axis. The reason for this added stability is similar to that in the shopping cart: the point about which the wheel turns is actually in front of the contact patch.

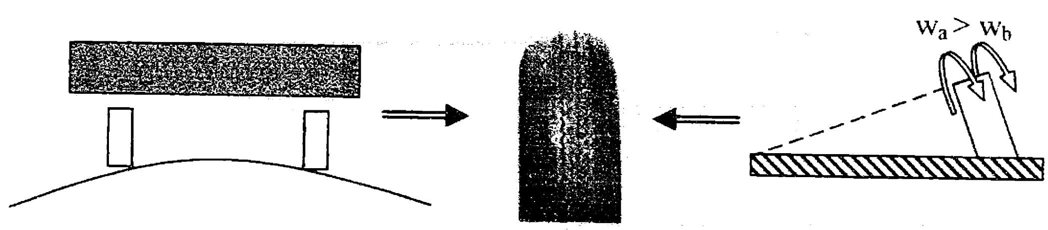
a) Scrub Radius b) Caster Angle

Figure 2

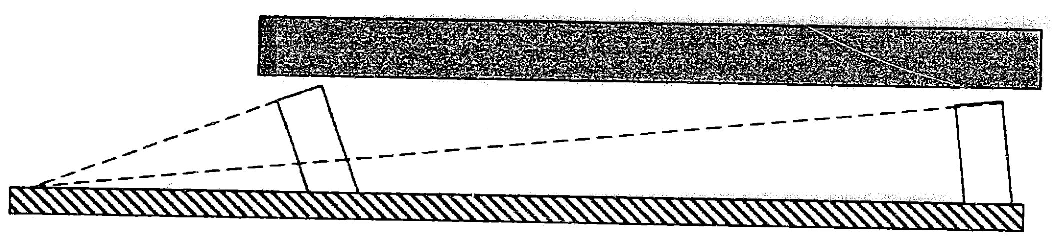
Camber:

For a number of reasons, the wheels must also tilt vertically:

- Many roads have positive crowns to force rainwater onto the gutters on the sides. Although this angle may be quite small, it can be enough to affect vehicle performance and tire wear. If the tire is not perpendicular to the road then, the following can occur:
    - **Differential tire wear**: Only part of the tire may wear down which leads to faster tire-wear and worse tire performance. (figure 2a)
    - **Differential compression**. If the tire compresses more in one area than another, it will act like a slice of a cone. The tire will then try to pivot about the point of the imaginary cone, which will create tire wear because (a) the outer part will want to spin faster than the inner part, even though they are both spinning at the same speed; and (b) the tires will try toe-in (or toe-out depending on the crown of the road), even though the steering is forcing them to follow a pre-determined path.(figure 2c)
- A change in camber can improve cornering at high speeds. Thus the differential compression (which was a problem above) can actually be a great benefit for turning. (figure 2d)



a) differential tire wear b) effect c) differential compression



d) camber can help in cornering

Figure 3

Suspension:

A vehicle suspension performs two important tasks. First, it ensures that all wheels contact the road most of the time (ideally, all the time). If a wheel loses contact with the road, then the driver can lose control of the vehicle (for instance, if one of the front wheels loses contact with the road, then the vehicle can no longer make a controlled turn). Second, the suspension creates a more comfortable ride. An ideal suspension would act as a low-pass filter: isolating the passenger cab from the high frequency road oscillations while allowing the passenger cab to follow the general contour of the road.

EXISTING SYSTEM

Deo (2002) has performed an analysis of existing automobiles and came to the conclusion that current designs "exhibit a high level of coupling, [including] coupling in the suspension and steering systems." [2] He continues by noting that the approach taken by industry to solve this problem has been one of minimization and compromises rather than complete solutions. One approach "has been optimization of suspension link lengths to reduce the change in wheel alignment parameters." [2] The other, more widely used solution has been to "optimize the spring stiffness [of the suspension] to get a compromise solution for comfort and directional stability." [2]

From his analysis, we clearly see coupling between FR151 and FR152. In other words, in the existing system, it is impossible to maintain tire-road contact without effecting the wheel alignment.

FR151: Maintain wheel alignment
DP151: Suspension kinematics
FR152: Maintain tire-road contact
DP152 Suspension travel
FR153: Adjust desired torque
DP153: Wheel angle

$$\begin{Bmatrix} FR...1 \\ FR...2 \\ FR...3 \end{Bmatrix} = \begin{Bmatrix} X & X & O \\ X & X & O \\ X & X & X \end{Bmatrix}$$

[2]

Under my own analysis, I have determined the critical elements in this coupling to be those of steering, camber and suspension.

Camber: The camber angle is directly coupled with the suspension system—an extension or compression in the suspension will alter the camber angle. This is not a side-effect, but instead caused purposefully by the linkage attaching the wheel to the frame. It is thus a *passive* system, which is controlled by the suspension. An incorrect camber can not only decrease tire tread lifetime, but also reduce traction and deteriorate steering (and ultimately vehicle stability)

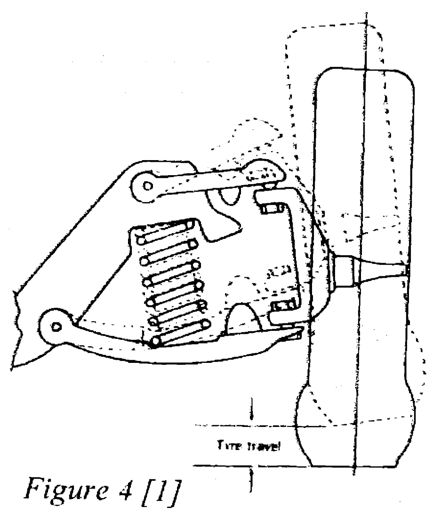


Figure 4 [1]

Steering/Suspension: The steering system is composed of a series of bars linked together, which connect the steering wheel to the tires. However, because the tires move with respect to the frame, there is some 'play' in the linkage. While this steering system works decently (it is present in nearly all modern vehicles) and is quite accurate, the precision (i.e.-tolerance) is not as high as it could be. This low precision is seen particularly when an uneven road surface causes the tires to move vertically—thus amplifying the weakness of the steering system.

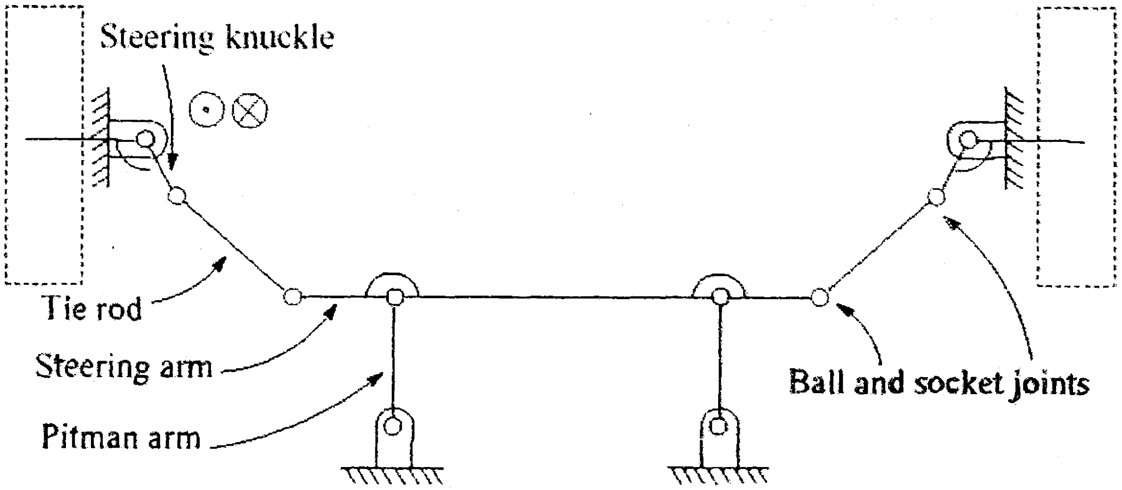


Figure 5 [2]

FR/DP ANALYSIS

As one can guess, the automobile design is extremely complicated, but established and relatively well-understood. Following is a new design for the automobile achieved using axiomatic design. However, due to time pressures and my inexperience with axiomatic design and automobiles, it is not a complete analysis—I do not detail all components in the automobile. Instead, because there are so many areas which can be improved, I decided to limit myself to one specific section. I decomposed the elements until the DP's were relatively obvious or pre-existing (i.e.-differential), or to continue would be significantly outside the scope of the thesis and would require more time (and money) than available.

DECOMPOSITION

FR1: Provide fast, easy and reliable mechanical transport
DP1: Automobile

$$\{X\}$$

This first FR/DP set is simply the automobile in its entirety. There are several DP's which can satisfy this FR (i.e.—motorcycles, boats, airplanes), but—for obvious reasons—I chose the automobile.

FR11: Move vehicle at desired velocity
DP11: Engine control system

FR12: Turn vehicle
DP12: Steering wheel angle

FR13: Ensure a comfortable ride
DP13: Passenger cab

$$\begin{Bmatrix} FR...1 \\ FR...2 \\ FR...3 \end{Bmatrix} = \begin{Bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{Bmatrix}$$

Decomposing the automobile into its major functions, we see that it must provide motion, it must turn and it must be comfortable. As one will see after further decompositions of the FR/DP's, the major purpose of this thesis is to uncouple the matrix above—specifically to uncouple FR12 from FR13 (i.e.-uncouple steering from suspension). DP11 is essentially the engine and its control levers, DP12 includes all aspects associated with a vehicle turning, and DP13 essentially provides the 'buffer' between the road and the passenger(s)

FR111: Accelerate
DP111: Throttle

FR112: Decelerate
DP112: Brake mechanism

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & X \\ X & X \end{Bmatrix}$$

The two major vehicle motions are acceleration and deceleration. DP111 and DP112 are commonly called the 'gas pedal' and 'brake pedal', respectively. Surprisingly, we see that the two FR's are coupled in current automobile designs—there is no way of accurately controlling the vehicle motion. Instead, both DP's must be actuated repeatedly to achieve the desired result. Indeed, perhaps this may contribute to some of the car accidents (it provides a complex, inaccurate control interface)

A superior alternative would perhaps be one throttle mechanism which controlled the velocity of the vehicle. After all, vehicles have speedometers (not accelerometers) and there are only speed limits (not acceleration limits). However, I feel that it is unlikely that customers or car manufacturers would positively respond to a new control system.

FR1111: Accelerate forward
DP1111: Forward gear mechanism

FR1112: Accelerate reverse
DP1112: Reverse gear mechanism

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ O & X \end{Bmatrix}$$

Decomposing FR111, we see that there are two forms of acceleration, both of which are uncoupled. The mechanisms used above are those used in modern automobile transmissions. I did not decompose these FR's any further because they are outside the scope of this thesis—nonetheless, further analysis would present more couplings in the leafs of this matrix (such as the couplings in the engine).

FR121: Turn wheels
DP121: Steering mechanism

FR122: Minimize turning radius under high speed conditions
DP122: Camber adjustment mechanism

FR123: Rotate wheels different amount
DP123: Differential for rear wheels, free-bearing for front wheels

FR124: Maintain vehicle stability
DP124: Vehicle stability mechanism

$$\begin{Bmatrix} FR...1 \\ FR...2 \\ FR...3 \\ FR...4 \end{Bmatrix} = \begin{Bmatrix} X & O & O & O \\ O & X & O & X \\ X & O & X & O \\ O & O & O & X \end{Bmatrix}$$

Decomposing FR12 (turn vehicle) results in several leafs. To turn the vehicle, one must turn the wheels via the steering mechanism. This mechanism is later identified in the *Designs* section. DP122 allows the driver to make even tighter turns under high-speed conditions by adjusting the camber angle of the front wheels (see *Definitions* section for details). In addition, when turning, the wheels pass through concentric arcs of different radii (FR123). This is not an issue for the front wheels, because in this rear-wheel drive design, they are only attached to the frame by a bearing (they are not connected to the engine). However, to account for this difference in linear distance traveled by the rear wheels, a differential must be used. Finally, the vehicle must be stable when making turns. Automobiles often experience the highest forces and stresses when turning (because of the centripetal force). This is becoming even truer as vehicles become taller (i.e.-SUV's) and the speed limits increase.

FR1241: Control force distribution in vehicle
DP1241: Force control mechanism

FR1242: Minimize vehicle slip/skid
DP1242: Traction with road

FR1243: Steering system responds only to driver
DP1243: Power steering

$$\begin{Bmatrix} FR...1 \\ FR...2 \\ FR...3 \end{Bmatrix} = \begin{Bmatrix} X & O & O \\ X & X & O \\ O & O & X \end{Bmatrix}$$

Decomposing FR124 (maintain vehicle stability), we see several different forms of stability required to make a safe turn. First, one must control the force distribution in the vehicle (FR1241). When the vehicle turns, there is a significant weight transfer, as shown in *Figure 5*. The following equation provides a more analytical expression of the weight transfer while turning:

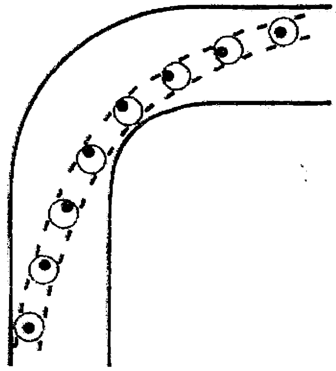


Figure 5 [1]

$$WT = \frac{(CF \times W \times CGH)}{TW}$$

WT=lateral weight transfer (lbs);
CF=centrifugal force (g's);
W=car weight (lbs);
CGH=Center of Gravity height (in);
TW=track width (in)

[1]

Equation 1 [1]

Thus, for a typical vehicle making an ordinary turn (W=2000lbs, TW=53in; CGH=24in; CF=.8g), the WT is 725lbs. This means that the weight distribution along the width of the car goes from 1000:1000 (left : right) to 275:1725. Consequently, this shift in mass 1) increases the chance of rolling; 2) affects the vehicle suspension; and 3) tilts the passenger cab, thus decreasing the comfort. To counteract this, a mechanism is required to counter the forces created by the turn. I have determined three such mechanisms which could satisfy DP1241, but—because they are out of the scope of this thesis—did not pursue them any further. Briefly, they are:

- Active Suspension: This system is used in several high-end cars, and can counter vehicle rolling quite well. By using computers and sensors, the vehicle can react and adapt to changes in force distributions. For instance, in the 2003 Mercedes-Benz SL500, the driver can activate the Active Body Control (ABC) system which can reduce rolling by as much as 95%. [7]
- Mass Distribution mechanism: The way the Hancock in Boston is able to endure such high winds is a clever mass-distribution system. On the two of the sky-scraper's floors are tuned mass dampers (TMDs)—which are essentially large masses attached through a spring/damper system. When the wind pushes the building, the masses shift, such that the center of mass of the sky-scraper does not move. A similar system could be used in an automobile where a relatively large mass could be shifted (either actively or passively) to counter forces incurred during turns. [8]
- Gyroscopic mechanism: Just as the spinning wheels of a bicycle serve to maintain the vehicles balance, so too could gyroscope be used to prevent the passenger cab from rolling. Obvious concerns with this mechanism include side-effects of the gyroscope (i.e.-how would it have to be manipulated or oriented to allow quick turns?) and dangers of having a 'flywheel' spinning with high energy in a vehicle.

Another form of vehicle stability is manifested in FR1242 (minimize vehicle slip/skid). As noted above, turning a vehicle can have a significant effect on mass distribution. Thus, the 'inside' tires (the front and rear tires which are closes to the center of the turn), will experience a reduction in traction caused by a reduction in the normal force transmitted through them. A further decomposition below will explain this FR in greater detail.

Finally, the vehicle must respond only to the driver (FR1243). High forces can be transmitted from the road/tires to the steering wheel during turns. A sudden force impulse (such as if a tire hits a bump in the road) in the steering wheel could dislodge the driver's grip of the steering wheel—which would make the driver lose control of the vehicle. To ensure that the driver has firm control of the steering wheel, I have chosen to minimize the force transmitted the steering wheel by implement a power steering system. Power steering is present in nearly all automobiles and enhances the power and control of the driver with respect to the steering system.

FR12421: Maximize coefficient of friction between tire and road
DP12421: Good tires

FR12422: Maximize force normal to road
DP12422: Good vehicle aerodynamics

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & X \\ O & X \end{Bmatrix}$$

The force of friction is a function of the coefficient of friction and the normal force. Modern automobiles incorporate both of these variables to achieve optimal traction. FR12421 (maximize coefficient of friction between tire and road) can be achieved by using good tires. Innovative new tire designs not only incorporate specially engineered materials, but also complicated tread patterns to maximize rubber-pavement contact. However, further decomposition of this FR is beyond the scope of this thesis.

FR12422 (maximize force normal to road) can be achieved by implementing vehicle aerodynamics which 'push' the vehicle to the ground, thus creating an artificially high normal force. This concept is used in race cars, where the extraordinarily high speeds and tight turns require especially high traction. As with FR12421, though, further decomposition of this FR is beyond the scope of this thesis.

FR131: Minimize effort (both physical and mental) required to control vehicle
DP131: Intuitive, centralize interface

FR132: Maximize passenger cab comfort
DP132: Ergonomic, customizable passenger cab

FR133: Minimize vertical acceleration of passenger cab
DP133: Vertical comfort system

$$\begin{Bmatrix} FR...1 \\ FR...2 \\ FR...3 \end{Bmatrix} = \begin{Bmatrix} X & O & O \\ O & X & O \\ O & O & X \end{Bmatrix}$$

Comfort is perhaps the largest selling feature of automobiles today. Of course consumers want vehicles with powerful engines, high fuel efficiency and good steering, but comfort and style are often the luxuries which consumers care most about. Comfort is a rather generic term, though, which can be decomposed into the above FR's.

FR131 notes that a centralized and intuitive interface minimizes effort required by the driver. Although further decomposition is beyond the scope of this thesis, one example of such a DP is in some of the 2003 Infiniti models, where the center vehicle control panel (which usually houses the stereo system, air conditioning, etc) is in fact slanted toward the driver. Thus, unlike other cars, the control panel can be easily viewed and accessed by the driver. [9] Another example might be to control the gas/break pedal positions and force required to actuate them.

FR132 (maximize passenger cab comfort) is a very broad functional requirement. It includes everything from the seat shape, position and orientation to temperature control system. Developments in this area could include multiple audio systems (so passengers could listen to different audio than the driver) or more customizable seats (i.e.—backseats are renowned for being uncomfortable). Further decomposition of this FR is beyond the scope of the thesis.

The final functional requirement for comfort is to minimize the vertical acceleration of the passenger cab (FR133). The vertical comfort system is further explained below.

FR1331: Minimize vertical displacement of passenger cab while vehicle is static
DP1331: Suspension lock system

FR1332: Maximize passenger cab comfort while vehicle is moving
DP1332: Dynamic comfort system

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ O & X \end{Bmatrix}$$

The two FR's above simply decompose FR133 (minimize vertical acceleration of passenger cab) into two basic categories: when the car is stopped and when it is moving.

FR13311: When car is off, do not permit vertical motion of passenger cab
DP13311: Suspension lock mechanism

FR13312: When car is turned on (still static) do not permit vertical motion of passenger cab
DP13312: Suspension adjustment mechanism

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ X & X \end{Bmatrix}$$

When the vehicle is turned off, DP13311 (suspension lock mechanism) locks the vehicle suspension so that the vertical position of the passenger cab is essentially fixed. This allows the easier entry and exit for passengers as well as easier loading and unloading of cargo. Perhaps a superior alternative to DP13311 would be a height adjustment lever which could raise and lower the vehicle a certain distance to provide easier access (this concept is currently used in some public buses, where the entire bus lowers several inches to provide easier entry and egress from the bus for the elderly or handicapped).

Then, when the vehicle is turned on (but still static), the suspension adjustment mechanism (DP13312) alters the suspension characteristics to match the new load. Thus, the suspension system is able to adapt to varied conditions. This mechanism could not only adjust to heavier loads, but also differential loads (such as a large mass placed only in the trunk). The details of this mechanism are beyond the scope of this thesis, but one such mechanism might be an air-suspension system, where one could adjust the spring characteristics by altering the pressure and the damping by either adjusting the size of the valve openings in the suspension system or by applying some external friction source.

FR13321: Isolate high frequency oscillations from road
DP13321: Low-pass suspension filter

FR13322: Minimize passenger discomfort from passenger cab rolling
DP13322: Passenger anti-roll comfort system

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ X & X \end{Bmatrix}$$

DP13321 is the suspension system of the vehicle. It acts as a low-pass suspension filter, allowing the large variations in road elevation (such as hills or ramps) while damping the smaller discontinuities (such as rocks in the road, speed bumps, etc.). It is decomposed further below.

Another element of the dynamic comfort system is the passenger cab anti-roll system. In addition to being unsafe—a sudden shift in car orientation can disorient the driver—it is also uncomfortable. This FR is also decomposed below.

FR133211: Isolate high magnitude road oscillations
DP133211: Suspension spring/damper characteristics

FR133212: Isolate low magnitude road oscillations
DP133212: Tire dynamics

C1: Wheel cannot hit vehicle frame (Set maximum suspension travel)

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & X \\ O & X \end{Bmatrix}$$

The suspension system is composed of two major elements, one which isolates high magnitude road oscillations (such as speed bumps) and the other which isolate low magnitude road oscillations (such as small pebbles).

The high magnitude road variations (FR1332211) are isolated by the suspension spring/damper system. By adjusting the characteristics of this system, one can develop a low-pass filter which will specifically focus on reducing the transmission of large oscillations from the road to the passenger cab. Further analysis of this suspension system is beyond the scope of this thesis.

Smaller road variations are dampened by the tires. Because they are relatively flexible and inflated with air, tires can compress/extend a few centimeters (at steady state, tires are already compressed, so relative to this position they can both compress and extend) This small variation—caused by tire material, inflation and tread—can isolate slight road discontinuities.

FR133221: Minimize passenger cab rolling
DP133221: Passenger cab anti-roll system

FR133222: Prevent passengers from sliding on seat
DP133222: Seat shape

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ X & X \end{Bmatrix}$$

To minimize the discomfort from vehicle rolling, one can essentially eliminate the problem or minimize the effect of the problem. FR133221 prevents most of the discomfort by minimizing the passenger cab rolling. It is further decomposed below.

FR133222, minimizes the remaining effects of turning which cannot be eliminated by DP133221. When making a sharp turn, the passengers are often pushed to the side and must use parts of the passenger cab to support themselves. These parts, are often not meant to support such use and are thus bad for the individual components (they are being used incorrectly) and uncomfortable for the passengers. To counteract this, a special seat shape which 'cups' the body could be implemented to support passengers in such a situation.

FR1332211: Minimize torque from vehicle rotation
DP1332211: Lower center of mass of passenger cab relative to vehicle width

FR1332212: Counteract vehicle rotation
DP1332212: Mass/force distribution mechanism

$$\begin{Bmatrix} FR...1 \\ FR...2 \end{Bmatrix} = \begin{Bmatrix} X & O \\ O & X \end{Bmatrix}$$

To minimize the rolling of the passenger cab caused by vehicle rotation, one can make both passive and active implementations.

First, as noted in *Equation 1*, the amount a vehicle rolls is dependent on the height of the center of mass. Thus, a lower center of mass relative to the vehicle width would diminish the torque generated by the centripetal force. Thus, one can either lower the center of mass of a vehicle or increase the distance between the left and right wheels.

Second, one can counteract the vehicle rotation with a mass/force distribution mechanism. Several mechanisms can achieve FR1332212.

First, one could implement the mechanisms used in FR1241 (see above). Thus, the passenger cab could be locked with the vehicle frame and respond the same way.

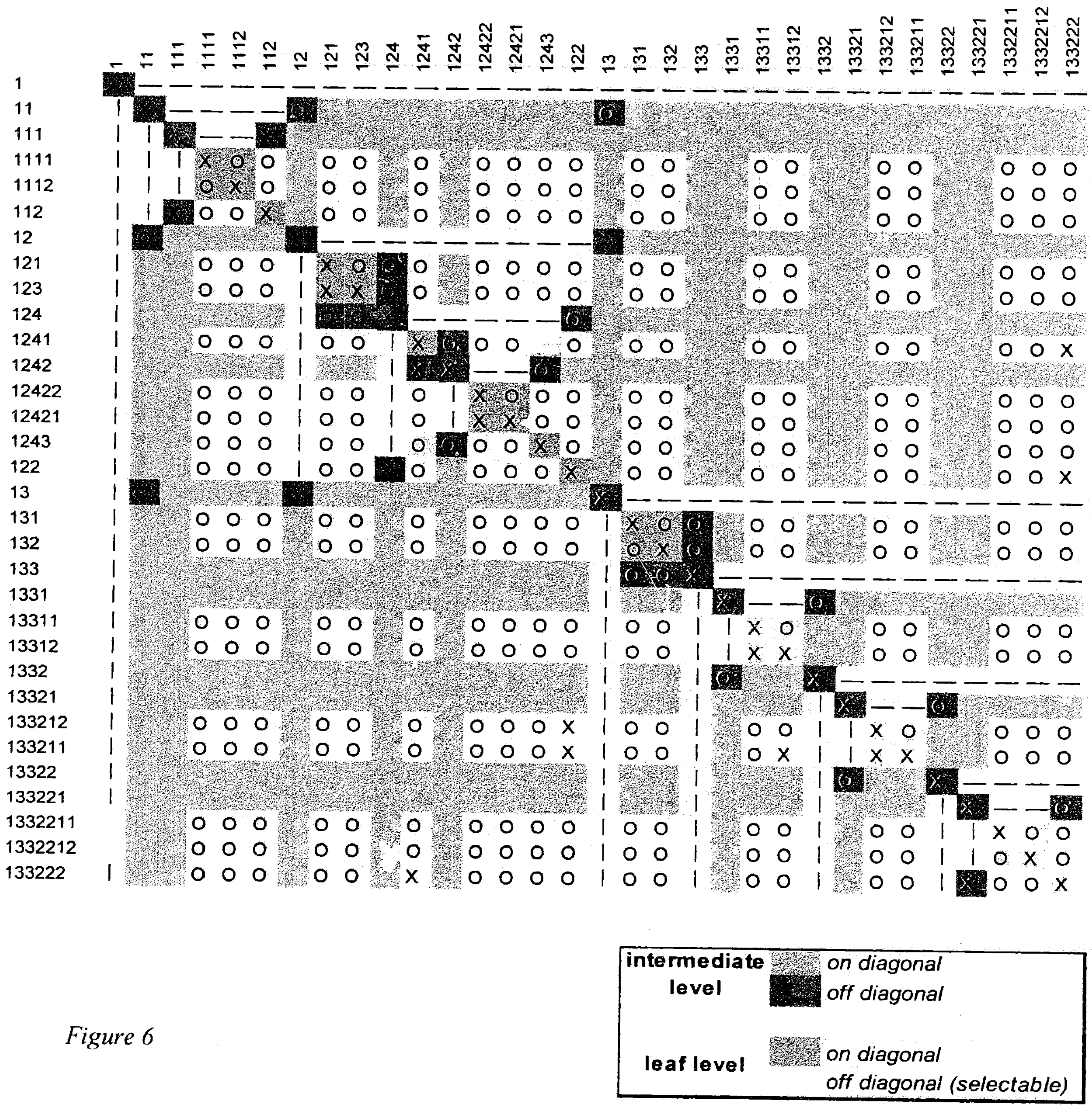
Second, one can isolate the passenger cab from the frame of the vehicle. Such a mechanism would allow the passenger cab to rotate free from the vehicle frame along a longitudinal axis of the car, thus introducing one degree of freedom. To maintain control of the rotation of the passenger cab one could either use an active system or a passive system—both of which would be actuated by and respond to the centripetal force generated by the vehicle turning.

FULL MATRIX

While the above decompositions are not coupled, to be a 'successful design', the entire design matrix must be uncoupled/decoupled. In other words, there cannot exist any couplings between lower order parameters. This is precisely where problems in the vehicle steering/suspension have occurred. Although on a higher order, the systems may appear to be independent, a more detailed analysis shows that the leafs of these systems are indeed coupled. Below is a full design matrix of my FR/DP analysis.

Notice some of the off-diagonal elements which are visible in the full design matrix, but cannot be seen in the above analysis. For instance, we see that there still is a coupling between the camber and the suspension (FR133211 and FR122). This arises because when the tire tilts, it must also raise and lower vertically. Thus, the tilting of the wheel affects the suspension. Note, however, that this is a decoupled set, because the suspension does not affect the camber.

From this full design matrix, we see that there are no couplings (aside from FR111/FR112, accelerate/decelerate, which has already been discussed above). Thus, this design intent appears to satisfy the principles of axiomatic design—as a decoupled system. Although this may seem well in theory, putting it into practice is a different story...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133
1331
13311
13312
1332
13321
133212
133211
13322
133221
1332211
1332212
133222
intermediate level
on diagonal
off diagonal
leaf level
on diagonal
off diagonal (selectable)

Figure 6

NEW DESIGNS

After a careful study of the above FR/DP analysis, I used it as a guide in my development of a new steering/suspension system which would allow the driver to turn the vehicle without activating the suspension system and vice-versa. However, even this was a rather broad criteria—turning creates a centripetal force which tilts the passenger cab and thus activates the suspension system. To counteract this, I attempted using some force-control mechanisms (DP1332212) which might in fact isolate the passenger cab from the rolling. However, due to time constraints, I chose to focus on a more detailed area—the actual interaction between the steering and suspension systems.

While creating the designs, I encountered several different actuator mechanisms. The two main actuators which I employed are: a) harmonic drive; and b) pneumatic cylinder. I will briefly discuss each of these actuators, then discuss the designs I created.

ACTUATORS

Harmonic Drive:

Harmonic drive was first developed in 1955 for aerospace applications but has since spread into numerous other fields. It is light weight and offers an extremely high gear ratio (as much as 1:320). [10] In addition, the design does minimizes backlash (< 30 seconds of arc) which, coupled with the high gear ratio, can achieve extremely high accuracy. [10] Moreover, because of the high gear ratio, the actuator can be both light and compact. A single unit (without the motor) can cost as much as US$1500. However, in mass production, this price would obviously drop significantly.

Pneumatic:

Hydraulics are currently utilized in several automotive elements, the primary example being suspension. Numerous high-end car manufacturers offer a customizable passenger cab height. In fact, height control can even be used to improve vehicle dynamics and safety. Thus, a pneumatic system could be driven by the same pressure unit used in the existing system (it would additionally require a control system and air cylinders). Again, the pneumatics can be both light and compact. [11]

Flexible Torsional Shaft:

Although clearly not an actuator on its own, the flexible torsional shaft can transfer energy from an actuator on the vehicle frame to a system on the suspension. Flexible torsional shafts are free to translate and bend, while still accurately controlling the torque transmitted. Thus, one can mount an actuator on the vehicle frame (where size and weight are not an issue) while still controlling a mechanism on the vehicle suspension. A single shaft can cost approximately $900, but in mass production, this cost would obviously drop significantly.

DESIGNS

The following designs have been designed using the above FR/DP analysis as a guide. Specifically, three elements in the old design which were coupled are now uncoupled: turning of wheels (i.e.-steering), tilting of wheels (i.e.-camber) and vertical displacement of wheels (i.e.-suspension). Following are a series of designs which allow independent control and motion of the three elements noted above. They are in chronological order and thus represent a progression of ideas.

Method 1

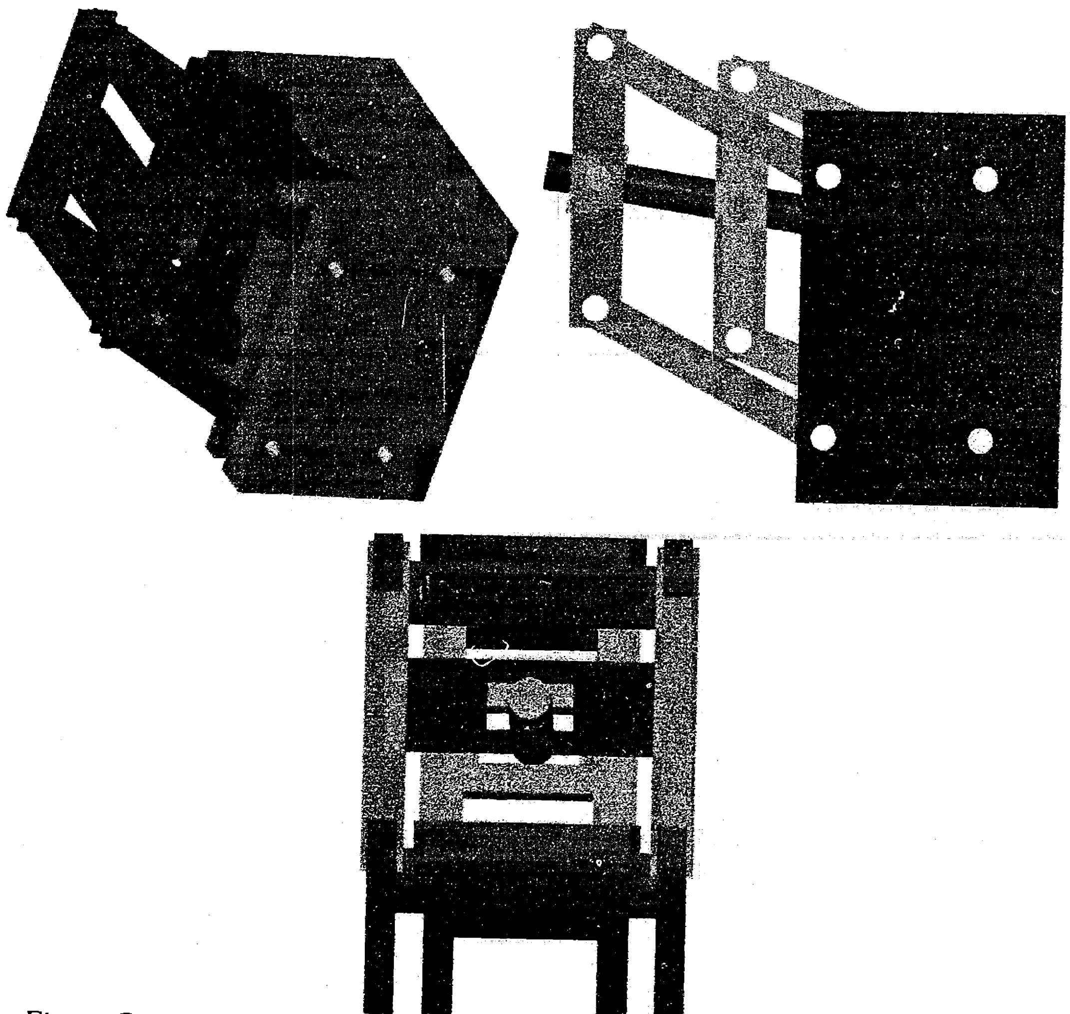


Figure 7

This design employs pneumatic drive systems to adjust the camber and steering angles, while using a linkage system similar to that in current automobiles for the suspension. Two nearly identical four-bar linkages (shown in blue) allow the entire system to move vertically. They are both hinged at the frame. The tire is attached to the green rod via a bearing and is thus free to rotate. Camber angle is controlled by adjusting the vertical distance between the inner and outer linkages. However, as only the distance between the two linkages is constrained, both are still free to move vertically as one unit. The tire rod (shown in green) is attached to the linkages via two horizontal steel connecting bars with bearings (shown in brown and gray). Note that the connecting bars are attached to the linkages via bearings, so they are free to pivot. A pneumatic piston is used to control this distance.

The steering angle is adjusted by displacing the tire rod in the smaller of the linkages (i.e.-in the gray connecting bar). The tire rod is pivoted in the first connecting bar such that any displacement in the other bar will result in a change in steering angle. Again, a pneumatic piston is used to adjust this distance.

The suspension can be attached in any number of places, including the following:

- A: Placement at one (or more) hinge(s) would control the vertical displacement of the wheel. For instance, one could employ a torsional spring coupled with a damper at any of the hinges shown above without affecting the unsprung mass.
- B: A more conventional placement of the suspension would be at one of the links. By pivoting the suspension on both the frame and the link (at the places shown above), the suspension system could control the wheel position.

Method 2

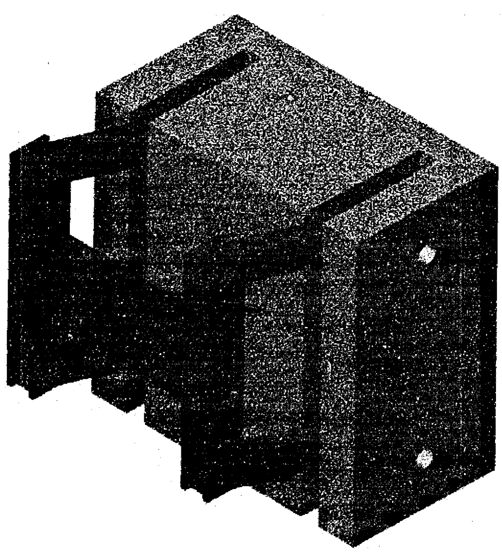


Figure 8

Unlike Method 1—which solely uses pneumatic pistons as actuators—this method solely uses harmonic drive. Again, a four-bar linkage is used to suspend the wheel from the frame. The linkages are hinged on the frame and the wheel is connected via a horizontal connecting bar.

The camber is adjusted by a harmonic drive unit which is attached to the vertical link member. It rotates the connecting bar via either a gear or a chain. The gear setup would also reside on the vertical link member and ultimately connect gears on the harmonic drive unit and the connecting bar. The chain would simply connect the harmonic drive to the gear on the connecting bar. Both systems ensure that the weight of the vehicle is not carried by the harmonic drive unit—but instead by the suspension system. To decide which method to implement, I used the information axiom outlined in the axiomatic design process. Essentially, the method with the lowest part count and highest repeatability is the optimal choice. Viewing the chain as a composite of many smaller links (rather than as one part), it clearly has the higher part count. Because there are more moving parts in the chain than in the gear setup, I feel that the gear method is the preferable choice. To confirm this analysis, I used a piu chart—another decision making tool with different criteria than that in axiomatic design. Again, I achieved the same answer.

	Cost	**Robustness**	**Ease of implementation**	**Ease of Maintenance**	**Lifetime**	**Total**
Gear	0	0	0	0	0	**0**
Chain	+	-	0	0	-	-

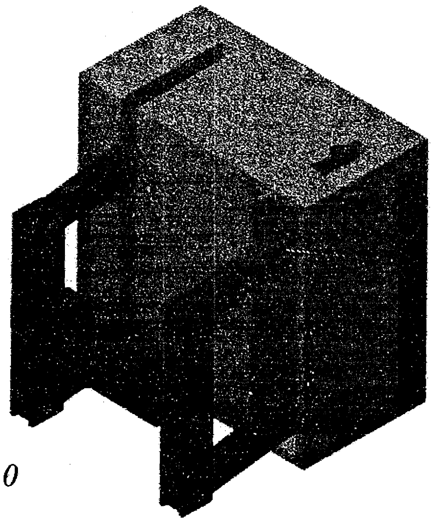
Figure 9

The steering is controlled by a harmonic drive unit which is mounted on the connecting bar. A bevel gear connects the harmonic drive unit to the tire rod. Because the harmonic drive unit is mounted directly on the connecting bar, it is independent of the camber angle and position of wheel.

Method 2b

An alternative to mounting the actuators on the suspension linkages is to attach them to the vehicle frame and connect them to gears on the suspension via a flexible torsional rod. Thus, the actuators could be as large and heavy as required without jeopardizing the success and integrity of the suspension system.

Method 3



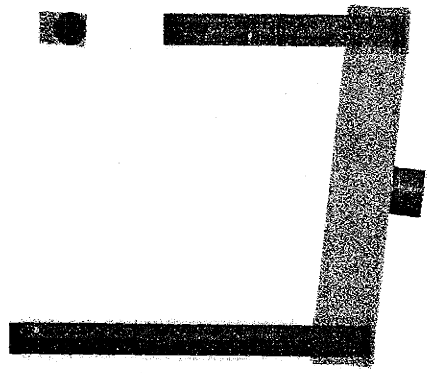


Figure 10

This method involves more moving parts than the previous method, but has a simpler and arguably more robust design. The suspension system is the same as in the previous methods, but the camber and steering mechanisms have been changed.

The camber angle is controlled by a harmonic drive unit mounted on the horizontal connecting bar. It is connected the tire rod directly via a gear system (see method 2 analysis for choice of gear versus chain). The mountings are similar to that of the steering mechanism used in method 2, only here—because the axis of the camber angle is parallel to the axis of the harmonic drive unit—a bevel gear is not required.

The steering is controlled by horizontally translating one of the suspension linkages with respect to the other. As shown in *Figure 10*, this adjustment angles the horizontal connecting bar and thus, the steering angle. Because the actuator required to shift the suspension linkage can be mounted on the vehicle frame, weight and size are not critical elements. Thus, one can implement any number of actuators, including pneumatics, harmonic drive or even a mechanical lever. The critical factor in this design, however, is friction. In addition to the pivoting linkages in the suspension, the connecting bar must pivot in the linkages and one of the suspension linkage sets must translate. Adding to the difficulties, there are tremendous loads on these pivots which require high load bearings.

Method 3b

Just as in Method 2b, the actuator responsible for controlling the camber angle could be mounted on the vehicle frame and connected to the tire rod via a flexible torsional shaft.

FURTHER ANALYSIS

UNSPRUNG MASS

The vehicle can be divided into two basic categories: sprung mass and unsprung mass. The sprung mass includes the vehicle frame and anything rigidly attached to it, such as the passenger cab, engine and half of the suspension system. The unsprung mass includes everything else, such as the wheels and half of the suspension system. The unsprung mass must follow the contour of the road, and thus, the lighter it is, the less energy it will transfer to sprung mass. Using existing suspension systems, a lighter unsprung mass will create a smoother ride because there is less energy to absorb.

Thus, although not listed as constraints in the FR/DP analysis, to work with current suspension systems, the method should be as light as possible. An analysis (detailed in the Appendix) shows that the weight changes considered in the above methods do not greatly impact the acceleration of the passenger cab, but nonetheless, a lighter unsprung mass will create a smoother ride and will also be more energy efficient. My analysis agrees with that performed by D. Hrovat, who notes that "in general, the reduction of unsprung mass does not offer significant ride improvement for passive suspensions." [5]

The first method obviously has the highest unsprung mass because it has four sets of suspension linkages and two actuators. Method 3b, on the other hand, has only two sets of suspension linkages and only one torsional rod.

FORCE ANALYSIS

STEERING

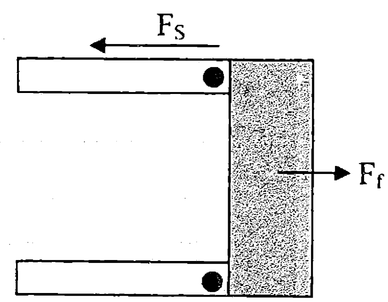
$F_f = \mu F_N = (0.7)(2200N) = 1540N$

$M_f = rF_f = (.05m)(1540N) = 77Nm$

$M_S = M_f = 77Nm$

$M_S = 77Nm = rF_S = (0.1m)F_S$

$\therefore F_S = 770N$



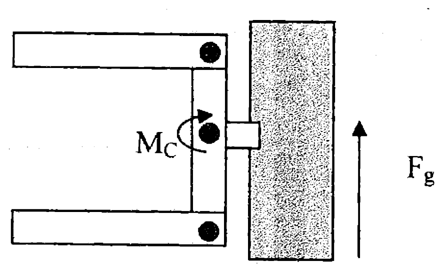
Top View of Steering/Suspension
Figure 11

CAMBER

$M_C = M_g$

$M_g = (F_g)r = (2200N)(.1m) = 220Nm$

$\therefore M_C = 220Nm$



Side View of Steering/Suspension
Figure 12

TIRE ROD DEFLECTION

$$\delta = \frac{FL^3}{3EI}$$

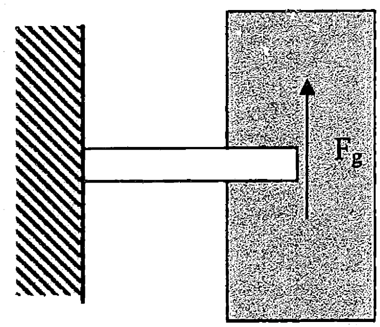
$$F = F_g = 2200N$$

$$L \approx 0.1m$$

$$E \approx 200GPa$$

$$I = \frac{\pi r^4}{4} \approx \frac{\pi(0.015m)^4}{4} = 4\text{E} - 8m^4$$

$$\delta = \frac{(2200N)(0.1m)^3}{3(200GPa)(4\text{E} - 8m^4)} = 9\text{E} - 5m$$



Side View of Steering/Suspension
Figure 13

MODEL

To demonstrate the feasibility of my analysis, I constructed a model out of aluminum. The purpose of the prototype was to demonstrate the principles highlighted above, and in should no way be construed as a final product (for instance, the prototype lacks bearings).

To construct the prototype, I first finalized my design and worked out the details of the design. This process included the force analysis above as well as modifying the design so as to minimize necessary machining. While building my model, however, I periodically discovered errors in the existing design. For instance, when manufacturing the connecting bar, I realized that using counter-bored holes would give me a higher tolerance range than counter-sunk holes when mounting the joining the two connecting bar pieces. This extra 'play' in the design minimized the effect of errors in the manufacturing process.

To minimize cost and labor, while still producing a meaningful prototype, I used aluminum. In addition, I used steel nuts and bolts to join the aluminum parts together. I machined the parts using a waterjet cutter, a mill and a lathe.

Figure 14 shows the model in its final form. The 'box' represents the vehicle frame while the wheel is connected to the end of the tire rod. Here the system is in it's default stage—all values are set to zero. The following figures, however, show how the system independently adjusts each of the three major elements: steering, suspension and camber.

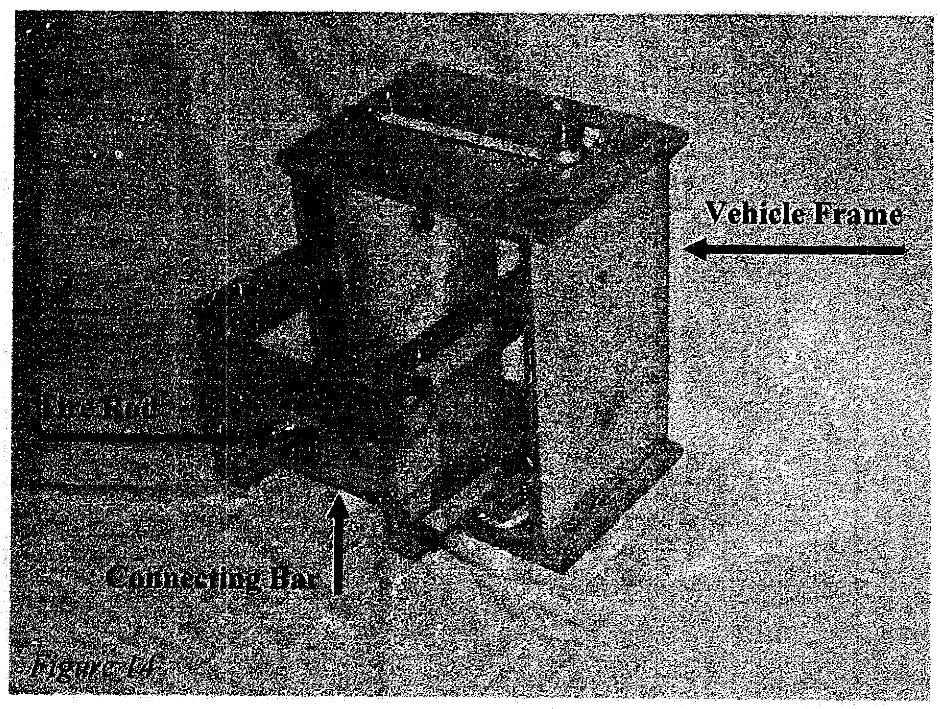


Figure 14

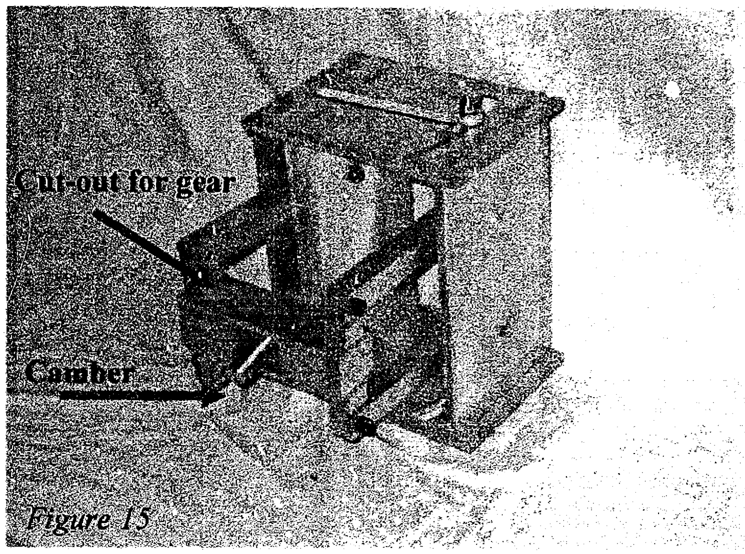


Figure 15

←
Camber Adjustment:

The camber is controlled by an actuator (not shown) which connects to the tire rod. There is a cut-out in the connecting bar, where a gear connecting the bar to the actuator might fit in.

→
Steering Adjustment:

Two 'arms' control the lateral motion of one of the suspension linkages. This could easily be controlled by mechanical, pneumatic or electrical actuation—size and weight do not matter because the steering is controlled on the vehicle frame.

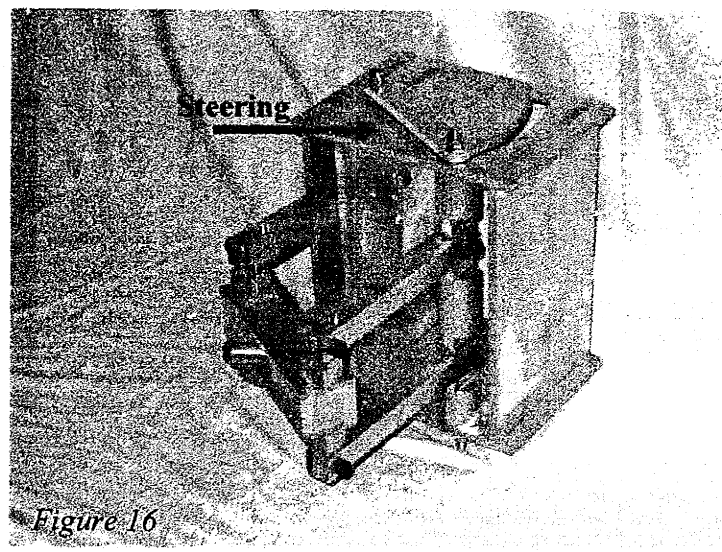


Figure 16

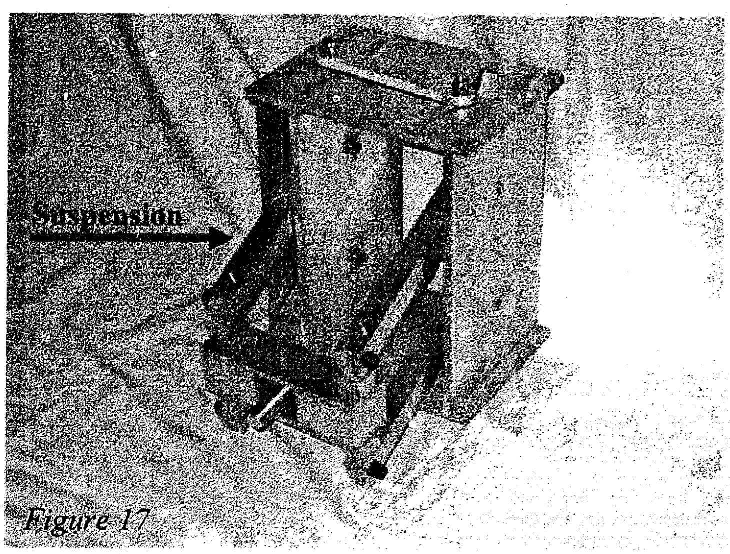


Figure 17

←
Suspension Adjustment:

The two four-bar linkages travel in the same paths, ensuring that the connecting bar is always horizontal (thus not affecting steering or camber). A suspension system could easily be mounted on any of the links.

CONCLUSION

In summary, this thesis introduced me to automotive and axiomatic design. I now have a greater appreciation for both. When I was first given the original problem, I had very little idea how to approach it. An automobile is full of complex, integrated designs which have constantly been optimized and fine-tuned for over a century—and I was asked to create a solution to a problem with this design in just a few short months. But where to begin? Before understanding axiomatic design, I probably would have analyzed the existing system, then attempted to optimize the characteristics of the individual mechanisms—such as spring length, damping coefficient, linkage size, and so on.

However, axiomatic design teaches one to start from the outside and to carefully approach the details of the designs. In other words, rather than focusing just on the steering and suspension systems, my analysis began with the entire vehicle and then slowly approached the problem from the outside-in. This approach a) allowed me to understand all elements of the problem and discover how the mechanisms integrated to create it; b) provided me with a deeper understanding of the individual mechanisms (in axiomatic design, I essentially created my own design for the car rather than optimizing existing designs); and c) guided my research and creativity.

The designs which I created appear to solve the problem by substituting the coupled design with a decoupled one. One can control the steering independently from all other vehicle functions. However, the suspension system is still slightly affected by adjustments to the camber.

FUTURE WORK

The current design is far from being implemented in an actual vehicle. First, more research and analysis could result in a cheaper, smaller, and lighter uncoupled design. In addition, due to time constraints, there are several elements which were not optimized. For instance, current vehicles orient the suspension in such a way that it can minimize the diving experienced when a car breaks abruptly. This could of course be resolved with an active suspension system.

Another possible improvement could be to minimize the lateral movement of the tire. Under my proposed design (as in existing designs), the tire travels in an arc, rather than a straight line. This can result in increased tire wear as well as decreased vehicle stability and traction. Deo (2002) has proposed a solution to this in his paper "Suspension referenced steering system: Independent steering of individual wheels"

Finally, there are other details which were not determined. For instance, while the current design is structurally sound, it is certainly not optimal. In addition, research must be made into the types of bearings and other materials used. Finally, as mentioned earlier, this paper focused on one specific topic—the interaction between steering, suspension and camber. However, I have not detailed the actual mechanisms used to control these systems (i.e.—what kind of suspension to use) or other mechanisms detailed in my FR/DP analysis.

APPENDIX

Unsprung Mass analysis

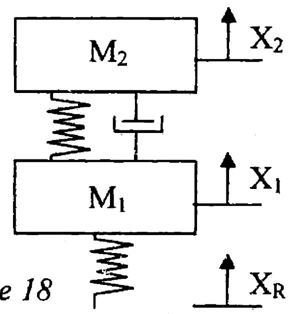


Figure 18

$$1a) M_1\ddot{x} = -K_1(x_1 - x_R) + K_2(x_2 - x_1) + b(\dot{x}_2 - \dot{x}_1)$$
$$2a) M_2\ddot{x} = K_2(x_2 - x_1) - b(\dot{x}_2 - \dot{x}_1)$$

$$1b) M_1s^2X_1(s) + K_1X_1(s) - K_2X_2(s) + K_2X_1(s) - bsX_2(s) + bsX_1(s) = K_1X_R(s)$$
$$2b) M_2s^2X_2(s) + K_2X_2(s) - K_2X_1(s) + bsX_2(s) - bsX_1(s) = 0$$

$$1c) X_1(s)\left[M_1s^2 - K_1 - K_2 - bs\right] + X_2(s)\left[K_2 + bs\right] = X_R(s)\left[-K_1\right]$$
$$2c) X_2(s)\left[M_2s^2 - K_2 + bs\right] = X_1(s)\left[bs - K_2\right]$$

Find $\frac{X_1}{X_R}$

$$X_2(s) = X_1(s)\left[\frac{bs - K_2}{M_2s^2 + bs - K_2}\right]$$

$$X_1(s)\left[M_1s^2 - K_1 - K_2 - bs\right] + X_1(s)\left[\frac{(bs - K_2)(bs + K_2)}{M_2s^2 + bs - K_2}\right] = X_R(s)\left[-K_1\right]$$

$$X_1(s)\left[\left(M_1s^2 - K_1 - K_2 - bs\right) + \left(\frac{b^2s^2 - K_2^2}{M_2s^2 + bs - K_2}\right)\right] = X_R(s)\left[-K_1\right]$$

$$\frac{X_1}{X_R} = \frac{-K_1}{M_1s^2 - K_1 - K_2 - bs + \dfrac{b^2s^2 - K_2^2}{M_2s^2 + bs - K_2}}$$

Find $\frac{x_2}{x_R}$

$$X_1(s) = X_2(s)\left[\frac{M_2 s^2 + bs - K_2}{bs - K_2}\right]$$

$$X_2(s)[K_2 + bs] + X_2(s)\left[\frac{M_2 s^2 + bs - K_2}{bs - K_2}\left(M_1 s^2 - K_1 - K_2 - bs\right)\right] = X_R(s)[-K_1]$$

$$X_2(s)\left[K_2 + bs + \frac{\left(M_2 s^2 + bs - K_2\right)\left(M_1 s^2 - K_1 - K_2 - bs\right)}{bs - K_2}\right] = X_R(s)[-K_1]$$

$$\frac{x_2}{x_R} = \frac{K_1(K_2 - bs)}{b^2 s^2 - K_1 K_2 + \left(M_2 s^2 + bs - K_2\right)\left(M_1 s^2 - bs - K_1 - K_2\right)}$$

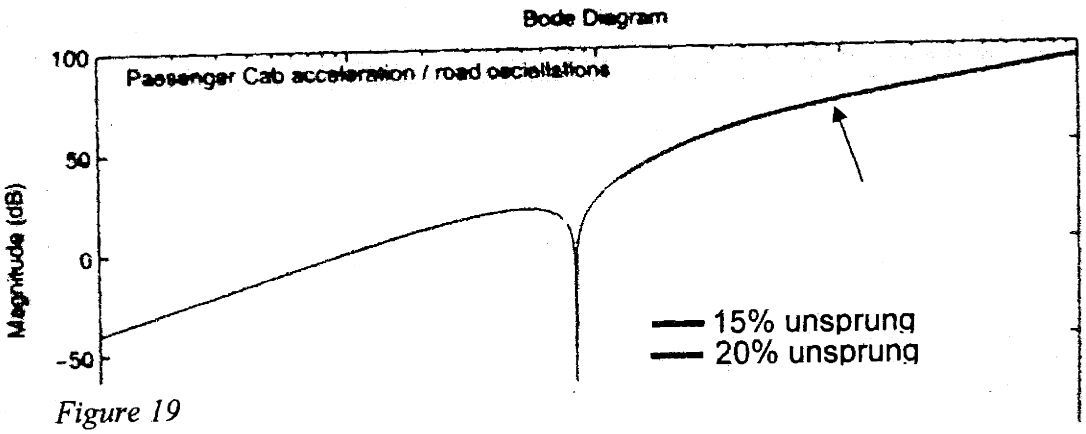


Figure 19

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