Possible Futures for Fully Automated Vehicles: Using Scenario Planning and System Dynamics to Grapple with Uncertainty

by

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Submitted to the System Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

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Abstract

It is widely expected that fully automated vehicles (also commonly referred to as "driverless" or "self-driving" cars) will significantly change transportation systems in the United States and around the world. By reducing or eliminating many of the costs and disincentives of travel by automobile, these vehicles may have the potential to radically alter many of the inherent dynamics that have governed transportation systems since the advent of the automobile. To date, however, there has been very little structured analysis of these potential changes. Most of the existing literature addresses the technical challenges facing vehicle automation technology or considers immediate effects on the transportation system, usually analyzing single effects in isolation. Very little attention appears to have been paid to multiple simultaneous interactions that may occur across the transportation system and potential feedback effects that may arise among elements of the system.

This thesis examines how the transportation system might react to the widespread introduction of fully automated vehicles (AVs), specifically considering how these reactions will affect total usage of automobiles, as measured by vehicle miles traveled (VMT). For the purpose of this thesis, the system boundary is broadly drawn—potential system responses are considered within the transportation system itself (consisting of existing users, vehicles, and infrastructure) and the "macro-system" (which includes broader economic, regulatory, social, and political dimensions). To address the wide range of uncertainties involved, scenario-planning techniques are used to develop and explore three scenarios that span a range of important variables. Within each scenario, system dynamics methodology is used to explore potential system reactions to the scenario assumptions and to consider the ultimate implications for VMT.

The main insight from this analysis is that unstable responses (rapid movement to the extremes) appear more likely than steady transitions to "moderate" states. When the scenarios assume behavior can change substantially, the structure of the system suggests either that strong and growing forces will cause automobiles to become even more dominant over other modes than they are today (and VMT will rise dramatically), or public transit will become increasingly more appealing and assume a growing role (and VMT will drop substantially). The challenge of predicting the underlying behavioral changes is substantial: Who can say with any certainty how people will use a technology that provides point-to-point, self-directed, self-scheduled travel, with no requirement for attention or effort by a human occupant, potentially at higher speeds, in greater comfort, and with safer operation than today's automobiles? There are simply not enough existing data and no precedent for such analysis. Given the potential for unstable outcomes, depending on the desired outcome, it may be critical for policy-makers to consider the initial conditions of AV deployment, as these may have a substantial impact on the transportation system over the long term.

Thesis Supervisor: Patrick Hale
Executive Director, System Design and Management Program

Acknowledgements

This thesis represents a fascinating and challenging journey that I will surely remember over the years for its twists and turns, its moments of inspiration and frustration, occasional dead-ends, and the ever-present thrill of discovery. Like most journeys of discovery, I arrive at the end in a far different place than I ever could have expected. I would like to take a moment to recognize and thank all of those who participated in this journey, offering help and inspiration along the way.

First, to Pat Hale, Mikel Murga, and Wolfgang Gruel, I offer my sincerest thanks for your unselfish assistance, mentorship, your persistent and challenging questions and fruitful ideas, and for the technical (and occasionally spiritual) guidance that carried me through this very long process. To the researchers in the Media Lab's Changing Places Group—especially Ryan Chin, Waleed Gowharji, and Kent Larson—I offer my sincerest appreciation for stirring up the embers and lighting the fire under this idea in the City Science course in the Fall of 2014. To the staff and my fellow students in the System Design and Management Program, I will always be grateful for your humor and your appreciation of this topic, which led to some healthy (and insightful) debates in the E-40 student lounge, which I will remember fondly.

Then, some recognition must go to the broader community here at MIT, to the faculty of the Engineering Systems Division and the Sloan School of Management for your unfailing belief in the value of systems thinking and your open-mindedness in applying new tools to tackle old problems. And to the students and faculty in the Department of Civil Engineering and the Department of Urban Studies and Planning a great warm round of thanks for taking me in as one of your own, in spite of my status as a visitor from the "other side" of campus. This goes especially for Fred Salvucci, who inspired me to get involved in the transportation field, and who, along with Mikel Murga, taught one of the most challenging and eye-opening courses I have ever taken ("Urban Transportation Planning"). If there ever was a field deserving of the attention of the brightest minds and the best "systems thinkers," it is the field of transportation. I only hope that I can contribute in some modest way, and I am humbled to share this field with such bright and devoted people.

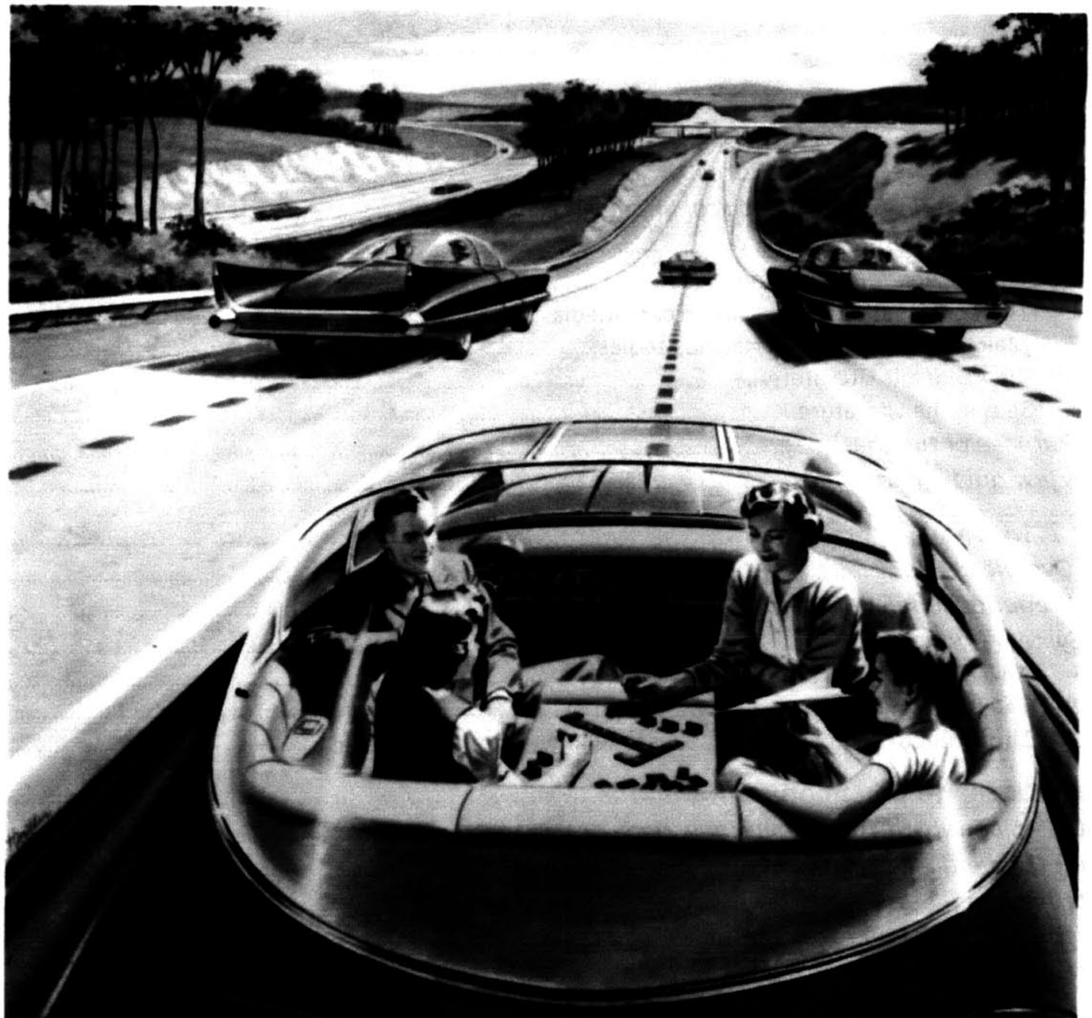
And, to those nearest and dearest to me, I offer my eternal gratitude and love: to my wife, whose seemingly infinite patience, optimism, and warmth have been the bedrock for me under sometimes shifting ground and turbulent waters; to my family and friends in New York, Washington DC, and the Boston area who have also been amazingly supportive and enthusiastic about my work over the past year; and to my two-year-old Basque shepherd dog, Oki, who has provided more moral and emotional support than he will ever know.

The parent or inventor of an art is not always the best judge of the utility or inutility of his own inventions ...

Plato
360 B.C.E.

And it will fall out as in a complication of diseases, that by applying a remedy to one sore, you will provoke another; and that which removes the one ill symptom produces others ...

Sir Thomas More
1516 A.D.



ELECTRICITY MAY BE THE DRIVER. One day your car may speed along an electric super-highway, its speed and steering automatically controlled by electronic devices embedded in the road. Highways will be made safe – by electricity! No traffic jams . . . no collisions . . . no driver fatigue.

Power Companies Build for Your New Electric Living

Your air conditioner, television and other appliances are just the beginning of a new electric age.

Your food will cook in seconds instead of hours. Electricity will close your windows at the first drop of rain. Lamps will cut on and off automatically to fit the lighting needs in your rooms. Television "screens" will hang on the walls. An electric heat pump will use outside air to cool your house in summer, heat it in winter.

You will need and have much more electricity than you have today. Right now America's more than 400 independent electric light and power companies are planning and building to have twice as much electricity for you by 1967. These companies can have this power ready when you need it because they don't have to wait for an act of Congress—or for a cent of tax money—to build the plants.

The same experience, imagination and enterprise that electrified the nation in a single lifetime are at work shaping your electric future. That's why in the years to come, as in the past, you will benefit *most* when you are served by independent companies like the ones bringing you this message—*America's Independent Electric Light and Power Companies**.

*Company names on request through this magazine

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Chapter 1. Background

1.1 Introduction

It is widely believed that the world is on the cusp of a new age of personal mobility. Vehicle automation technologies are expected to play a leading role, with fully automated vehicles—commonly referred to as "driverless cars," "self-driving cars," or "autonomous vehicles"—as one of the main symbols and drivers of this transformation. Fully automated vehicles (or "AVs") are defined by the National Highway Safety Administration as vehicles with "Level 4" automation, where "the vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip" (NHTSA 2013).[1] The expected benefits of this technology would indeed be transformative, with some suggesting a possible 99% reduction in traffic fatalities (Hayes 2011) and more than $60 billion in annual savings from reduced traffic congestion in the United States (Fagnant 2013). With such promises, much effort has been exerted analyzing the technical and institutional obstacles to deployment of AVs. However, little effort, and very little discussion, has been devoted to understanding the long-term, system-wide effects of this promising new technology.

1.2 The Context, in Historical Terms

Understanding the potential long-term effects of AVs is not just a matter of predicting market behavior, understanding the implications for planning agencies, or maximizing the utility of trips and minimizing their costs. Transportation has never been just about getting from here to there. It is about access to employment and critical services; it is about commerce, pollution, and energy consumption; it is about economic and community development, safety and risk, environmental justice, social stratification, and even racial segregation. Transportation touches every aspect of life, and the history of human habitation and living patterns has been largely defined by the many different costs of transportation, in terms of time, effort, risk, and money. Transportation has shaped cities throughout history, linking them inextricably to rivers, the sea, and overland trade routes. More recently, growing attention has been paid to the dynamic interplay of transportation and modern land-use and urban development patterns, with particular focus on the role of accessibility and transportation in the "agglomeration economies" that are fundamental to the livelihood of cities (Jenkins, et al, 2011).

To fully consider the effect of a new transportation technology, then, it may be worth considering the very nature of mobility itself, and the broad spectrum of modes it spans. At one end of that spectrum is that most fundamental source of human mobility: walking, which entails substantial costs in terms of time and fatigue and over certain distances and terrains will entail significant discomfort and risk. At the other end, taken to a logical extreme, would be instantaneous motion with no costs incurred on the traveler (i.e., "teleportation"). While the science-fiction dream of teleportation may seem silly and irrelevant, it may serve as a useful mental marker, as we consider how far humanity has progressed along this continuum. For example, the experience of falling asleep on an overnight

[1] NHTSA further stipulates "Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip." This

flight from JFK airport and waking up when the plane lands in San Francisco is surely closer to the experience of "teleportation" than how that journey would have been made just 150 years ago. In the 1850s, the best anyone could do was to travel by wooden sailing ship for 100-200 days in cramped quarters, 16,000 miles around Cape Horn at the southern tip of South America, and through the most dangerous stretch of ocean on the planet (the slower, and far more perilous, route was to plod across the plains, over the mountains, through the desert, in a horse-drawn wagon). In today's world of superhighways spanning the land under skies crisscrossed by the vapor trails of jetliners, it may be hard to imagine that not long ago, such slow-moving sailing ships were very much at the cutting edge of transportation technology.

How big of a leap forward, then, will AVs be? Just as the advent of automobiles transformed the world by shifting the energy cost of travel from human and animal muscle to the internal combustion of fossil fuels, it may be reasonable to expect that the advent of AVs will have similarly transformative effects by replacing the full-time conscious efforts and attention of a human operator with an automated system that requires neither the attention nor the presence of a human being.

1.3 The Context, in Terms of Societal Impacts

The previous section considered transportation along a spectrum defined by the experience of the traveler. While this is useful for understanding progress in terms of the users of technology, it fails to account for the costs that the use of these technologies can impose on society and the world—the external costs, or negative externalities—which are not paid directly by the traveler.

In a literature review, Parry (2006) provides a fairly thorough list of negative externalities of automobile use. These include:

- *Local air pollution* and associated health effects
- *Global air pollution* and *greenhouse gas emissions*
- *Oil dependency* and related geopolitical and military costs
- *Noise*, which can have virtually constant negative effects on the quality of life for residents who live near highways and major roads
- *Sprawl*, including loss of natural habitats and open space
- *Accidents*, including property damage, injury, and death of non-automobile-users
- *Parking subsidies* (the costs to businesses of providing free parking) which are paid indirectly by everyone who patronizes those businesses, regardless of whether they drive or not

To this list, I would suggest the following additions:

- *Devaluation of real estate*, both through proximity to highways and parking lots and through mere occupation of high-value real estate (e.g., land that would be waterfront property along almost the entire east side of Manhattan is occupied by the FDR Drive today)
- *Loss of social capital.* Traveling by automobile eliminates many of the incidental social encounters that can play an important role in building the social capital of communities, and which would occur more often in non-motorized trips or on public transit.

- *Physical division of cities and neighborhoods, and elimination or reduction of access by non-motorized modes.* While these costs may be difficult to quantify, the effects are substantial, as evidenced by the Central Artery in Boston, which effectively isolated the North End from the rest of the city for over a 25 years (one very clear cost was the monetary cost of undoing this division by burying the highway, which accounted for a large part of the $14 billion, 20-year project known as the "Big Dig" (Stern 2003 and MassDOT 2015).
- *Air pollution and greenhouse gas emissions from electricity generation.* This is important to acknowledge, because too often it is suggested that switching to electric vehicles will solve all the problems of pollution from automobiles.
- *Transmission lines and other components of the electric power infrastructure,* which encroach on public spaces and damage the aesthetics of landscapes; these externalities will exist regardless of how clean or renewable the power source is, and will also be very relevant if there is a significant adoption of electric vehicles.
- *Externalities from renewable power sources.* Even renewable power generators, like wind turbines and solar panels have negative externalities, including visual encroachment and harm to wildlife, so even the exclusive use of renewable energy to power electric vehicles will have unwanted consequences.

1.4 Vision of the Future

Given the context into which AVs would emerge and given the scope of their potential capabilities, it's reasonable to consider that profound and far-reaching changes may be coming. A lot may be at stake with the introduction of AVs—both in terms of the opportunities for major improvements and the risks of harmful unintended consequences. However, as the remainder of this chapter will illustrate, there has not yet been a well-organized discussion about the long-term vision for AVs. This is understandable, since it is to be expected that the developers of the technology would be consumed with the immediate task of overcoming technical hurdles, researchers are hindered by a lack of data to conduct academically rigorous analysis, and many others may just be loath to speculate about a technology that is not yet fully realized and they may not comprehend. And yet, while it may seem irresponsible to engage in speculation at these early stages, it could be argued that there may be even bigger risks in not doing so. The bigger hazard may lie in a failure to take the opportunity early on to consider how the future might unfold, in a reluctance to articulate a vision for where this technology could take the world, and in adopting an overly hesitant ("wait and see") approach that might delay precautions and policy interventions until it's too late for them to put the technology and the larger system on a desired course.

1.5 Public and Academic Perspectives

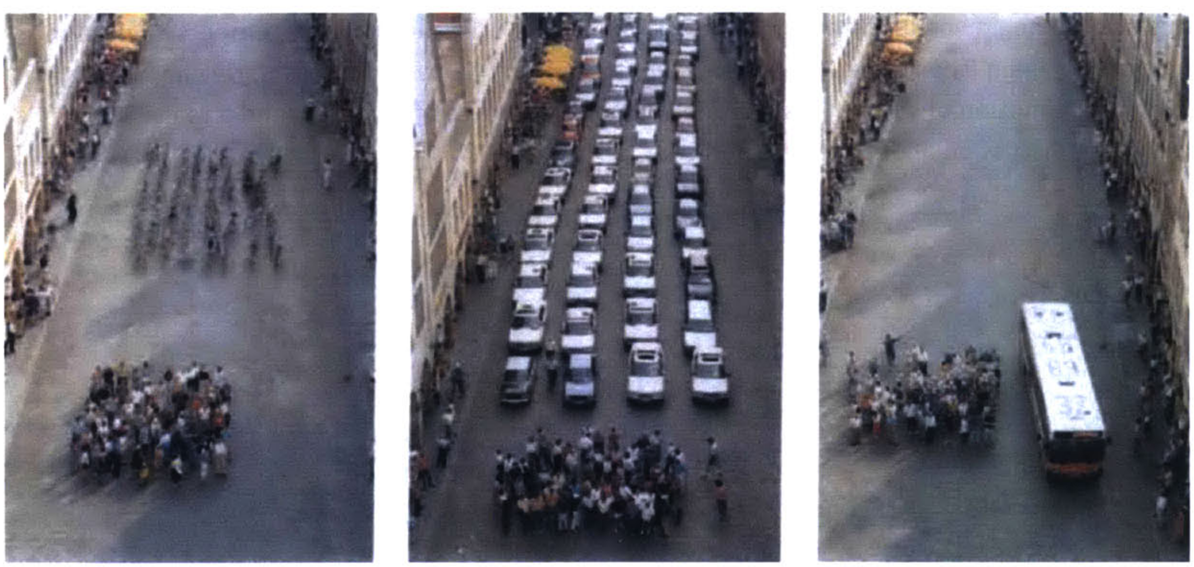
1.5.1 The Conversation in the Mainstream Media

While the discussion around automated vehicle technology in the mainstream media has been fairly broad and explored a wide range of issues, it has more or less taken place in a void of actual data or rigorous scientific analysis—and that is not to fault the media, since in many cases data and analysis is simply not available. As a result, much of the conversation has been more speculative and philosophical than scientific in nature. A common approach to the subject, as in a major *New Yorker* feature (Bilger 2013) has been to discuss the fundamental flaws of human drivers and explore the technical challenges Google and other developers are facing (and apparently overcoming). Other pieces, in the *New York Times*, the *Economist*, *Atlantic*, the *Wall Street Jour*nal, and many other major publications have tackled various issues around AVs, with attention largely focused on the technical challenges, the business case, the competitive environment, regulatory hurdles, and other issues of implementation (e.g., Marcus 2012, Kessler 2014, Bogost 2014, Economist 2015, and so on). Regarding the potential costs and benefits to society and to the individual, the conversation has been not been very different from that which arises around any new technology. And that discussion seldom penetrates deeper than the direct effects and the near-term outcomes.

On the other hand, far less attention has been devoted to the longer-term effects of the technology. In the relative absence of real data, opinions have sprouted all across the ideological spectrum—as one writer expressed it in *Forbes*, "Political ideology, as it tends to, may rush into the vacuum of facts" (Morris 2014). As an example of how public discussions can go astray, that same piece mentions debates that have arisen over whether AVs could replace public transit entirely, including the example of one Florida district where political opponents of transit investments have argued that public transit would be made obsolete by driverless cars. This argument has even been made to oppose high-speed rail (Winston 2012). It is worth noting the shortcomings in such thinking, which appears to ignore the fact that replacing highly spatially efficient vehicles such as buses, subways, and trains with AVs—even with an efficiently platooning fleet of AVs—will put tremendous additional demands on road space. For example, if all the passengers on a single six-car train on the MBTA's Red Line subway at rush hour were to disembark and get into AVs on the street overhead, those vehicles would fill two lanes of Massachusetts Avenue solidly for more than two miles, with minimal separation between vehicles (at almost bumper-to-bumper distances). Similarly, the passengers on one well-loaded rush-hour bus would take up several blocks of traffic if they were to be transferred to AVs (also at close to bumper-to-bumper distances). The tremendous advantages of mass transit over cars in terms of spatial efficiency have been known since the beginning of the automobile age (see Figure 1.1), and similar arguments have been gaining traction again (see Figure 1.2). Those advantages won't be overcome by merely improving the efficiency of the motion of cars. This is but one example of the need for context and a realistic framework for discussion about the pros and cons of AVs.

Figure 1.1. Advertisement for Chicago Surface Lines from 1925*, at the height of the conflict between automobiles and streetcars, highlighting the spatial efficiency of streetcars (from www.copenhagenize.com; accessed June 22, 2015).*

Figure 1.2. Photo from the Planning Office of the City of Münster, Germany. *It shows the street space occupied by 60 people in cars, on bicycles, and on a bus. (from* ***www.greatergreaterwashington.org****; accessed June 22, 2015).*



1.5.2 Major Institutional Reports and Studies

In recent years, a number of major studies by respected institutions have begun to address the potential longer-term outcomes from AVs.

Autonomous Vehicle Technology: A Guide for Policymakers, by the RAND Corporation (RAND 2014), provides a well-organized, thorough summary of the potential benefits and "perils" of AVs, the history and current status of the technology, the legal status of AVs, relevant standards and regulations, and liability implications. In terms of future effects, the report summarizes the expected immediate benefits, including:

- Potentially substantial improvements in safety
- Major, life-changing improvements in mobility for currently underserved populations (e.g., the elderly, disabled)
- Reduced "costs" of congestion for users of AVs (who will be able better use their time)
- Reductions in overall congestion due to "more-efficient vehicle operation and reduced delays from crashes"
- A reduction in energy use and pollution due to more-efficient driving and platooning

The report also includes a brief discussion of potential longer-term effects on land-use, including both dispersion of destinations due to AV users' willingness to travel longer distances and increases in urban density in some places due to the reduced need for parking at urban destinations.

Preparing a Nation for Autonomous Vehicles, by the Eno Center for Transportation (Fagnant 2013), summarizes some of the expected benefits of AVs, based on existing literature, including:

- Safety improvements, including a finding that fatality rates could fall by up to 99%
- Congestion reduction, due to "shorter headways, coordinated platoons, and more efficient route choices"

The study also covers barriers to AV adoption and implementation, "primarily from a consumer and regulatory standpoint."

Transforming Personal Mobility, by the Earth Institute at Columbia University (Burns et al. 2013), explores the opportunities of a "new mobility system" based on fleets of shared, driverless vehicles. The report finds significant economic, environmental, and consumer benefits, suggesting that such an approach could "provide better mobility experiences at radically lower cost."

Re-programming Mobility: the Digital Transformation of Transportation in the United States, by Dr. Anthony Townsend of the Rudin Center for Transportation Policy and Management at NYU (Townsend 2014) takes a very different approach. Unlike other major studies and most existing academic literature, this study examines scenarios that may evolve over the next 15 years, assuming "technology success" of AVs (complete or near-complete success in the development of AV technology). The scenarios explore a range of different driving forces, settings, financing schemes, with differing roles for planning organizations (from "marginalized" to "strong/paternalistic") and radically different effects on land use and the overall transportation system. Unlike other studies that tend to analyze individual costs and benefits in isolation, the four scenarios in this study explore costs and benefits together and consider how they might interact to evolve into four very different futures, with very different impact on key metrics, such as the total amount of driving that will occur.

1.5.3 The Academic Literature

Many of the findings in the academic literature are included in the major reports discussed above, and there appears to be little disagreement on the expected direct effects of AVs, including safety improvements and improved roadway capacity. To move beyond the more-established understanding of AVs and gain a sense of the substance and direction of the latest research, I conducted a review of publications that were presented at the 2015 Annual Meeting of the Transportation Research Board (TRB Meeting) was conducted. As the world's largest—and widely considered the most important—annual conference on transportation, the TRB Meeting provides a good sample of the current status of research in the field. Among the more than 50 papers dealing with AVs at the 2015 TRB Meeting, a number of topics were covered, as shown in Figure 1.3. While there is some attention paid to the longer-term effects, it is dwarfed by the research attention focused on immediate and near-term system integration issues.

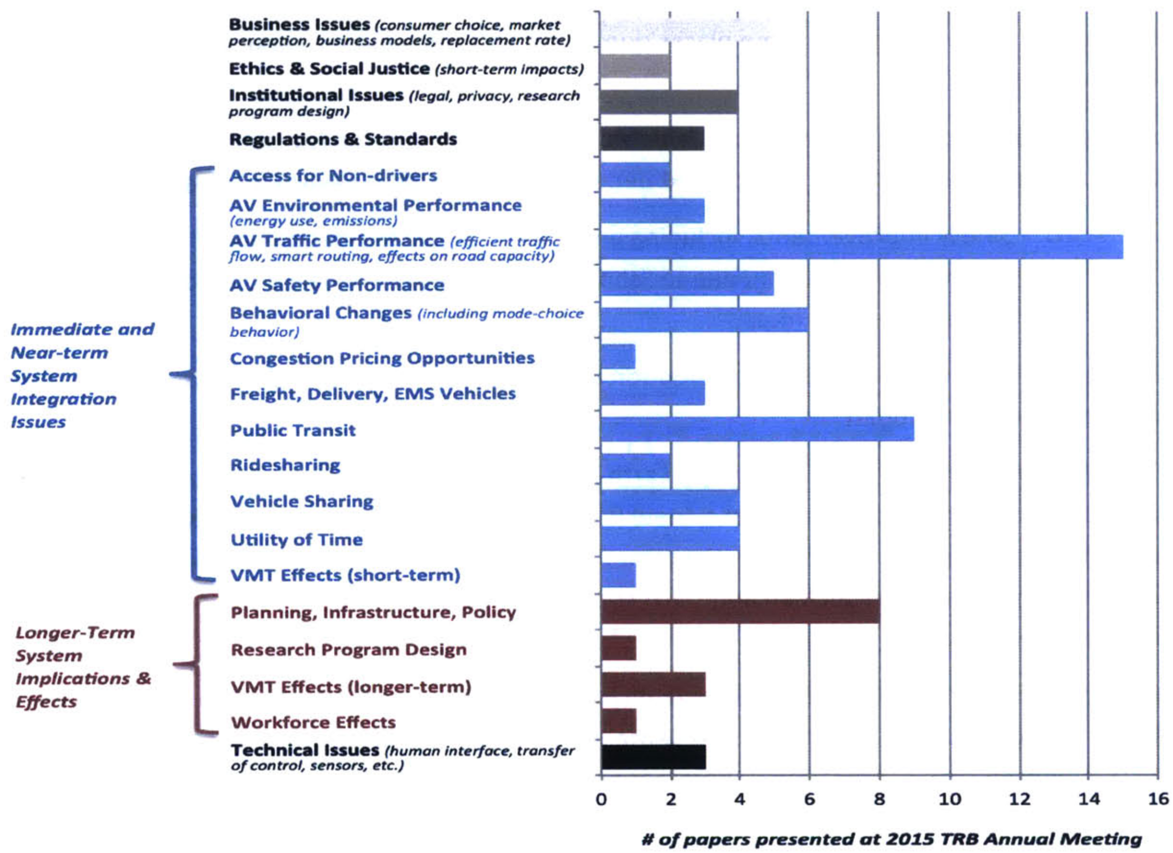


Figure 1.3. Number of Papers Covering Various AV Topics at the 2015 TRB Annual Meeting.

1.5.4 Gaps in the Literature

Of the major studies listed in section 1.5.2, the RAND and Eno Center reports provide the most comprehensive discussion of issues relevant to the longer-term impacts of AVs. However, as with many such reports and most of what has been written about AVs, there appear to be significant gaps in the analysis. To understand the effects of a major technological intervention on a complex system, a thorough analysis should take into consideration all of the following:

(i) Direct effects, including effects on current behavior
(ii) Indirect effects, including the emergence of entirely new behaviors
(iii) Longer-term effects, including changes to aspects of the system that may currently appear to be fixed (i.e., not part of the current dynamics), and especially considering the outcomes from full technology success and widespread adoption
(iv) System interactions among major components, including interactions among several components at once (by "components," here I am referring to major system components such as vehicles and streets, not individual technology components within an AV)
(v) Feedback effects among the system components, where appropriate

As good examples of much of what has been written about AVs, the RAND and Eno Center reports cover some, but definitely not all of these key considerations. For example, the RAND study identifies potential indirect effects on VMT, the possibility that AVs will "siphon away" riders from public transit, and longer-term effects on land-use, noting that significant uncertainties exist around these factors. However, their analysis stops there, and there doesn't appear to be any consideration of the interaction among these effects or the potential feedback effects that can arise from such interactions.

The Eno Center report also stops short of considering the multiplicity of system interactions and the potential feedback effects among them. For example, it states, "Unless new travel from AV use is significantly underestimated, research cites that exiting infrastructure capacity on highways should be adequate to accommodate the new/induced demand, thanks to AVs congestion-mitigating features … however, other negative impacts, such as sprawl may not be readily mitigated." Here, the report, like many others, only focuses on the induced demand resulting from the effective increase in road capacity that would occur with the more-efficient road utilization of AVs. This leads to the conclusion that demand would only increase by 10% at 90% market penetration. This analysis only addresses the reduction in one of the costs[2] of driving—the reduction in congestion. However, as all of these reports acknowledge, AVs are likely to reduce many other costs—e.g., by eliminating the cost and hassle of parking, increasing the utility of time in the car, increasing comfort, reducing driver fatigue, making driving safer, etc. None of these other factors are considered in this calculation for induced demand. In addition, there is no consideration of other indirect effects, such as entirely new behaviors that AVs will allow, especially those related to empty-vehicle operation. These factors may be difficult to quantify at this early stage, but it would seem likely that there are numerous ways in which drivers today might increase their VMT by far more than 10%, without even accounting for the additional people who will be able to use an AV who previously couldn't drive. In short, this kind of analysis, while useful and

[2] "Costs" is generally used here to indicate all manner of disincentives, not just monetary costs.

informative, treats the AV the same as any conventional car, just with a much better "driver," and assumes that all other aspects of the AVs' and the users' interactions with the system will remain the same.

Furthermore, as an example of a feedback mechanism that is absent from this analysis, the report identifies "sprawl" as an outcome of the increase in VMT and observes that it "may not be readily mitigated," but it doesn't mention the feedback effect that is likely to occur with increased sprawl leading to higher levels of VMT. This is based on the hypothesis that the dispersion of destinations that is inherent in sprawl would lead to more need for travel to reach those destinations and less accessibility to such destinations by non-automotive means, thereby increasing dependence on automobiles and ultimately increasing VMT. Identification of such feedback effects and the underlying system structure that generates them will be essential to understanding the potential behavior of the system.

Considering the research presented at the 2015 TRB Annual Meeting as a relatively current example, it appears that the coverage of AV-related topics was quite thorough and extensive. However, of the more than 50 papers on AVs or related topics, only 12 explicitly consider longer-term effects (at least beyond the first few years of adoption), and of those, there is only minimal consideration of multiple-subsystem or multiple-component interactions or feedback effects. And, even among those papers that do consider possible systemic interactions and feedback effects, there is no explicit, systematic framework presented for identifying and assessing such effects.

Of the work reviewed for this thesis, *Re-programming Mobility* (Townsend 2014) is by far the most thorough in its consideration of the full potential for transformation resulting from AVs. The scenarios developed in *Re-programming Mobility* involve extensive behavioral changes, long-term effects (e.g., changes to residential location, land use, infrastructure), multiple system-wide interactions, and feedback effects. However, the underlying mechanisms that drive these changes are not all explicitly addressed. The result is that, in some ways, the scenarios appear to arise from well-thought-out speculation, as opposed to emerging from a structural model of the overall system. Therefore, while the resulting scenarios are insightful, they do not illuminate a clear connection from the existing system today (and our understanding of its dynamics) to the emergence of new and potentially radically different system behaviors in the future. Without such an underlying framework, it is difficult to understand which factors and forces would lead to the specific changes presented, and, more importantly, which factors might evolve differently ***or be actively modified*** to produce very different outcomes.

1.6 Purpose of the thesis

The purpose of this thesis is to bridge that gap between data based analysis and informed speculation, by developing a framework to help understand how VMT might change under different future scenarios. This question about VMT, put more simply, is *how much more might people travel by automobile?* The goal is not to predict the level of VMT at a specific point in the future, but to understand the key variables and relationships among the variables in the system that will determine VMT, how VMT may change over time, and what complex system reactions (especially feedback effects) may emerge.

VMT is a valuable and important metric, because, as highlighted in much of the literature, it is essential to understanding the ultimate effects of AVs on the transportation system. For example, with many aspects of the system that could be improved by AVs—such as safety, energy use, and congestion—all of these benefits could be reduced, or even completely offset by increases in VMT. Furthermore, there are negative externalities associated directly with VMT (including road noise, sprawl, etc.) that may not be mitigated by the capabilities of AVs, so it will clearly be an important metric to measure in its own right.

To achieve this purpose, I have attempted to develop insights on potential system-wide reactions to the ***technically successful*** introduction of automated vehicles. These reactions consider the effects on—and reactions by—the transportation system and the "macro-system" that the transportation system dwells within. A more detailed explanation—including definition of key terms—follow in Chapter 2 ("Method/Approach").

1.7 A few guiding principles

An underlying hypothesis of this thesis is that AVs may have the potential to fundamentally transform the existing transportation system. To gain a sense of the scale of transformation that might take place, and how many aspects of that transformation may lie beyond the reach of our current mental models, we need only to consider the potential parallels between the "driverless car" of 2015 and the "horseless carriage" of 1900. The full scope of the potential impacts of the "horseless carriage" was not even widely recognized until the 1930s, roughly 30 years after automobiles began rolling off assembly lines in mass production. It wasn't until city planners' visions of de-concentrated urban cores aligned with growing calls for an expanded road infrastructure (to enable the full mobility potential of automobiles) (Norton 2009, pp. 14, 248-254) that the scale of the changes to come came into focus. While we, as a society, may hope to be better at anticipating outcomes and quicker to learn than we were 100 years ago, we still can't pretend to know exactly how such a large and complex system will evolve with such a major advance in technology.

We may also learn from history to consider outcomes beyond what seems realistic within today's mental models or what is acceptable by today's standards. If the history of the automobile teaches us anything it's that unimaginable or even seemingly intolerable changes can *and do* occur. For example, as early as 1910, the rate of automotive deaths on public streets was already generating widespread outrage. The dramatically higher rate of fatalities and injuries that would occur a few decades later would surely have been perceived as unacceptable or even unthinkable to many people in 1910, and yet they were accepted, at least enough to allow for continued growth in VMT and associated fatalities for many years to come. Furthermore, when automobiles first appeared on city streets, it was generally believed that the burden fell on automobile users to find a way to peacefully coexist with many other users of urban streets (Norton 2008, pp. 11, 37). Therefore, it was widely assumed that the harmonious integration of automobiles, pedestrians, horse carriages, and streetcars would be accomplished by restricting the newcomer (and in many opinions, the source of the trouble), the automobile. And it would have seemed unrealistic and unacceptable to restrict the most ancient mode of all, walking. However, within 20 years, the opposite had occurred: laws in cities across the country redefined streets as primarily for automobiles, with limited and highly regulated access for pedestrians (Norton 2008, pp. 164-165, 191-192, 220-225, and McShane 1994, pp. 187-189).

Furthermore, it is plausible that people will find ways to use AVs that will be difficult to extrapolate from the ways conventional vehicles are used today. Surely the originators of the first "horseless carriages" could not have foreseen some of the applications of automotive technology today—such as 90-minute-long commutes, 40-foot-long RVs, drive-in theaters, or "monster-truck" rallies—or even some of the more fundamental aspects of the automotive transformation today, such as the Interstate Highway System or the sprawling "bedroom communities" that have sprung up where farms used to be. Similarly, as we look to the future of AVs today, it is clear that not only is there tremendous uncertainty, but also that many of these unknowns will remain *unknowable* until years after commercialization.

Chapter 2. Method/Approach

2.0. Overview

To develop insights about the future, a common approach is to develop predictive models based on underlying patterns and dynamics in existing data. But what if there are no data to build models from? Perhaps we can look for proxy data, or useful analogous cases. What if the potential change we are interested in is truly unique and there are no closely related data to use as a reasonable proxy? And what if the change is potentially transformative, changing not just one or two isolated variables within the system, but altering its fundamental dynamics, with effects that could ripple throughout the system in unpredictable ways?

These are among the challenging questions we face in considering how fully automated vehicles (AVs) might affect the amount of traveling people will do by car (as measured by VMT). The answers to some of the most important related questions involve factors for which there is no data available. For example, what impact will automated driving have on individual driver behavior, particularly in the number and length of trips taken? And, while it may seem plausible that data could be generated from the right kind of studies, there is a tremendous—and probably unbridgeable— gap between these limited studies and the realities that we will encounter with thousands or millions of AVs in use all across the country. Furthermore, the realities of the operating environment make gathering this amount of data on user behavior in AVs nearly impossible. With so many demographics and varying environments involved, and with such a versatile multi-purpose product as an automobile, large numbers of vehicles would need to be demonstrated on actual roads in many different locations. By the time such a demonstration project were possible, the technology would be ready for commercialization, or so close to it that the resulting predictions would be of very little value for industry, planners, or regulators.

2.1. Scenario Planning

To develop insights about how the future might unfold in the presence of such uncertainty and in the absence of relevant data, a potentially useful alternative approach is to conduct scenario-planning exercises. To date, the only high-profile study that methodically examines future scenarios for AVs is *Re-programming Mobility* (Townsend 2014). This study's purpose was to examine longer-term scenarios, unfolding throughout the 2020s, with detailed consideration of how the world could look at the start of the 2030s. For this work, Dr. Townsend had initially considered using the what he calls the "traditional approach to scenario development," a technique that emerged from work done at Royal Dutch/Shell's "Long-Term Studies" activity in the 1970's (this technique was spun off into an international consulting firm, the Global Business Network (GBN), by futurist Peter Schwartz) (Wilkinson and Kupers 2013). However, Townsend rejected this particular approach, believing that the time frame he wished to consider was too long and the uncertainties too extensive for it to be effective. Instead, he selected the "Alternative Futures Method" developed at the University of Hawaii. This appears to have been a wise choice for his purposes, since his work aimed at crafting broad future scenarios that would unfold over at least a decade, and without addressing a specific strategic issue, which is an important aspect of Shell's scenario planning approach.

However, the timeframe of this thesis is shorter—focusing on the first few years after commercial introduction of AVs and loosely defined to include the "first wave" of early adopters. This is a near enough timeframe to limit the range of uncertainties to a manageable quantity. Furthermore, this thesis aims primarily to address one key issue: the effect of AVs on VMT. This narrower, more focused purpose is more suited to the methodology used by Shell and GBN.

Scenario planning enables consideration of outcomes that can span a range of variation in assumptions. One of the goals is to select a limited number of scenarios that span this range in an illustrative manner. The goal is not to be correct in any particular scenario, but to choose the most illustrative cases, providing the most useful insights for an uncertain future. Along the way, it is hoped, participants learn to abandon the goal of "hitting the target" with predictions and let go of their attachment to any one particular future that may have been viewed as most likely. As Peter Schwartz states in *The Art of the Long View*, "the point of scenario planning is to help us suspend our disbelief in all the futures: to allow us to think that any one of them might take place. Then we can prepare for what we don't think is going to happen" (Schwartz 1991). Most organizations instinctively plan for what they think will happen; the role of scenario planning is to methodically force them to think through how other futures may unfold and what the ramifications would be.

This approach, of creating and exploring several plausible scenarios, frees us from the constraints of trying to focus efforts on existing data, which would most likely be of little value anyway. By asking, "what if X, Y or Z unfolds?" instead of trying to argue that any one of these is the most likely outcome, we are able to focus on the implications and all the questions that emerge from those "what if?" scenarios. As Schwartz describes, in situations of extreme uncertainty, insights often come from "solely asking the right questions" (Schwartz 1991).

This thesis follows the approach laid out by Peter Schwartz's as closely as possible. Any divergence from this methodology is likely due to the fact that this thesis is not limited to considering the perspective of a single specific enterprise. Rather, it asks a broader question, and the answer to that question is likely to be of great strategic value to many different stakeholders. The GBN methodology, on the other hand, is generally used for a specific company and a specific context. In spite of these differences, the structure of this thesis follows the steps of the GBN approach as closely as possible.

2.2 System Dynamics

The transportation system in the United States today, like most transportation systems, is highly complex, with many components and stakeholders and countless interactions among them, often involving multiple feedback mechanisms. In addition, confounding delays often exist between action and reaction, making the underlying dynamics even harder to discern and the ultimate outcomes more difficult to predict. Any examination of scenarios involving the transportation system will have to contend with these complex system interactions. This thesis uses system dynamics to help conceptualize the system and visualize how it might react under various scenarios.

System dynamics is an approach to analyzing complex, dynamic systems developed by Professor Jay Forrester at the Massachusetts Institute of Technology in the 1950s. At the core of this approach is a mapping process, which identifies key variables and the causal relationships between them, with a particular goal of identifying causal loops, or feedbacks, within the system. Ultimately, these conceptual diagrams are often developed into operational software models, which simulate the behavior of the system, producing quantitative outputs.

Due to the extreme uncertainties involved and the absence of data, it is not practical in the scope of this research to construct an operational system dynamics model; therefore, the use of system dynamics methods is limited to causal loop diagrams (CLDs). Shepherd (2014) explains that CLDs serve as "qualitative models of a system which may be used to develop dynamic hypotheses." One of the aims of this thesis, then, is to develop those dynamic hypotheses, and in so doing, create a useful conceptual framework for developing additional hypotheses and refining those hypotheses as more information about the relationships in the model come to light. Abbas (1990) also observes that "the application of causal loop diagrams ... may be used to bring out the 'mental models' (how people think a system works) of different stakeholders..." Therefore, the framework provided by these CLDs could also serve as a platform for discussion and debate about the actual causal relationships involved, their relative strengths, and the degree of certainty around them.

Furthermore, while CLDs alone cannot provide predictive outputs, they can function as a useful conceptual language to help envision the interactions of the system and identify key issues and questions. That is precisely the role they are intended to play in this thesis. Therefore, the CLDs herein may contain variables that wouldn't be possible to translate into a fully operational model. Because the CLDs in this thesis are intended only as a systems-thinking aid (at least initially), many of the detailed variables that might be needed to create an operational model are omitted to maintain clarity, many complex concepts and relationships are simplified or aggregated, and some of the CLDs include variables that may be impossible to quantitatively integrate and relate to one another through actual formulas. Again, it is important to remember that in light of the profound uncertainty of this subject, the goal is to develop models and diagrams that identify high-level dynamics that may arise, narrow down and focus attention on the uncertain factors that are likely to play a critical role, and ultimately provide models and diagrams that are *useful* and *insightful* rather than *accurate* and *precise*.

2.2.1 Advantages and Limitations of System Dynamics

Abbas (1990) provides a thorough discussion of the advantages and limitations of system dynamics for analyzing transportation systems and related issues. Among the advantages he identifies are:

(i) "S.D. methodology lays for us a very deep foundation for structuring our thoughts and building a better understanding of the complex transportation system problems."

(ii) "S.D. conceptualization procedures provide rich, common media for communication and understanding between the various parties that have interest in the transportation system."

(iii) "S.D. provides us with a structured framework through which large scale systems, such as transportation systems, can be easily accommodated."

(iv) "Results of S.D. transport models are arrived at through the dynamic, causal, feedback interactions of the structural components of the model, a situation existing in reality. Non-linearities and time-delays are explicitly accommodated."

Abbas also identifies some of the limitations of the system dynamics approach, including:

(i) "S.D. ...works mainly through the time dimension. Spatial aspects and distribution effects are not easily accounted for."

(ii) "Most S.D models are aggregate models intended to show policy impacts in terms of approximate magnitudes and direction of change. Emphasis in S.D. is on aggregate simplicity."

(iii) "Some of the relations used ... are purely heuristic. They lack scientific evidence to support them, but in some cases this is the only way to model socio-behavioral relations."

Point (iii) above, is particularly relevant to this thesis, as most of the causal relationships depicted and discussed herein are hypothetical. While there may be evidence to support many of them, a large number remain completely unknown, and are considered to be hypothetical assumptions of the analysis. Abbas also observes, "In S.D., validity is interpreted as 'model usefulness,' rather than 'numerical exactness'." This point is very much in line with the theme of this thesis: in analyzing something as uncertain as the effects of a new technology on a socio-technical system as broad as the transportation system, and far enough into the future to involve unknowable critical uncertainties, we have no choice but to limit our goal to "model usefulness." In fact, it could be argued that pursuing "numerical exactness" would not only be an unwise use of resources, but would distract attention from the truly uncertain and highly variable nature of the potential outcomes. This is also very much in line with the Scenario Planning approach, which discourages analysts from seeking "predictive" scenarios and favors selecting the most insightful and most potentially informative ones.

2.2.2 The Basics of Causal Loop Diagrams (CLDs)

The conventions of CLDs are fairly simple, as they consist of only two main elements: variables and causal links. Variables are indicated just by their names, and causal links are indicated by arrows, with the arrow pointing from the independent variable to the dependent variable in the causal relationship. Every causal link has a positive or negative polarity to indicate the nature of the relationship. For example, a causal link with positive polarity from variable A to variable B means that an increase in A will cause B to be larger than it would otherwise be. This can also be thought of as: *an increase in A will cause an increase in B, all other factors being unchanged (ceteris paribus).* Note that there is an important distinction between asserting that B will be *larger than it would otherwise be* and *B will increase*. There may be cases where other forces acting on B will be strong enough to cause it to decrease, in spite of the effect from A. However, even in this case, the effect of A is still present and still felt in some way. Similarly, a negative polarity means that an increase in variable A will cause variable B to be smaller than it otherwise would be, and a decrease in variable A will cause variable B to be larger than it otherwise would be. Labels can also be added to causal links to indicate delayed causality, which can have a powerful effect on the resulting dynamics.

Once these CLDs are assembled, "loops" will arise when the causal links from one variable connect back to itself, after connecting to one or more additional variables. These loops play a central role in system dynamics modeling, so it is important to identify them and understand the role they may play in the overall behavior of the model. Therefore, they are labeled to indicate: (a) the dynamic behavior that the loop illustrates and (b) the polarity of the loop. A loop with positive polarity—also referred to as a ***reinforcing loop***—is one where the net effect of all the causal links in the loop reinforces a change in any variable in the loop. A loop with a negative polarity—a "balancing loop"— is one where the net effect of all the causal links in the loop opposes a change to any variable in the loop (Sterman 2000). Figure 2.1, below, shows a very simple example of two interacting feedback loops. In this case, if the R-loop were observed in isolation, we would expect exponential growth of eggs and chickens, as both quantities would increase at an increasing rate. On the other hand, if we were to observe the B-loop in isolation, we would expect both the number of chickens and "road crossings" to decrease at a decreasing rate, and, ultimately (in the absence of any exogenous factors, such as a fence to prevent road crossings) both chickens and road crossings would taper off to zero.

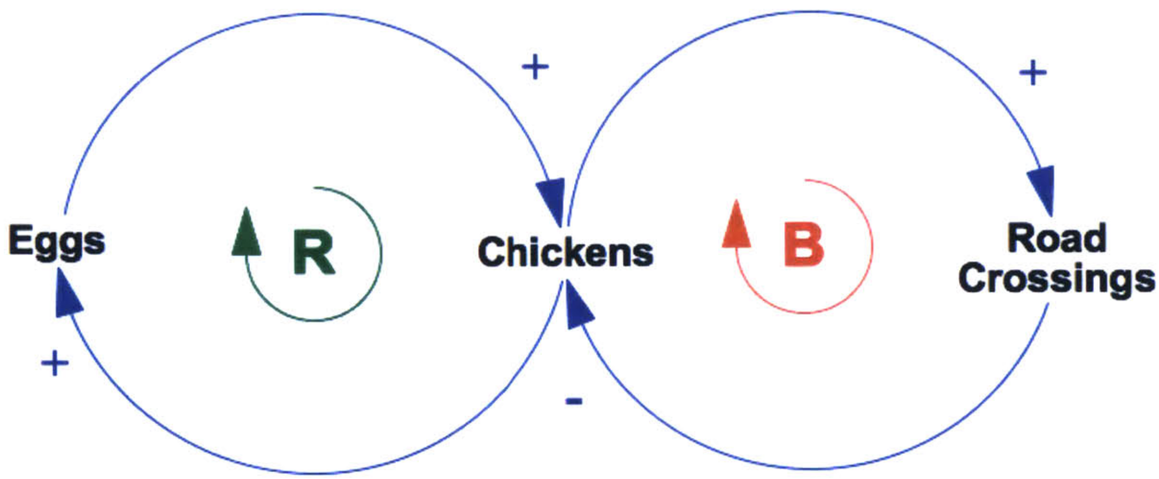


Figure 2.1. Example of interacting "reinforcing loop" and "balancing loop" (Sterman 2000). *From these basic dynamics, depending on the delays in the system, we could at first expect exponential growth of eggs and chickens, then a gradual tapering off as "road crossings" increase, and in the absence of unusual delay patterns, we could expect the population ultimately to stabilize at an equilibrium state.*

2.2.3 The Strength and Certainty of Causal Relationships in This Thesis

This thesis does not attempt to justify or rigorously support all of the causalities shown in the CLDs. Instead, it creates a hypothetical list of potentially relevant causal relationships. In each scenario, and for each new CLD shown, the list of relevant causal relationships is shown in a table. Table 2.1 below provides an example of the hypothetical causalities involved in Figure 2.1. The table identifies the independent variable, the dependent variable, and the polarity of the relationship. There is a column to indicate the hypothetical strength of the relationship; this shows a best guess regarding the relative strength of the effect that the independent variable has on the dependent variable. There is also a column indicating the "level of certainty that causality exists." This represents an estimate of how much uncertainty exists around the causal relationship, and it can range from an absolute causality that is established "by definition" (e.g., "traffic congestion" causes "slower speeds", because the definition of traffic congestion in this case requires that it results in slower speeds) to a causality with "low" or "very low" certainty (e.g., there is a very little certainty in the negative causal relationship between "Automated Driving Capability" and "perception of risk", because we can't know yet if users of AVs will actually *feel* safer).

Table 2.1

Causal Link					
Independent Variable	**Dependent Variable**	**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Chickens	Eggs	+	Very Strong	Very Strong	There is very strong causality here, as a very large fraction of chickens will contribute in some way to an increase in eggs, with a very high degree of certainty.
Eggs	Chickens	+	Very Strong	Very Strong	There is very strong causality here, as a very large fraction of the eggs will contribute to an increase in chickens, with a very high degree of certainty.
Chickens	Road Crossings	+	Moderate	Very Strong	The hypothesis is very strong, because we know for certain that some number of chickens will cross roads. However, the strength of the relationship is considered moderate, because it may only be a modest fraction of the chickens that actually do this.
Road Crossings	Chickens	-	Weak	Very Strong	The hypothesis is very strong, because we know for certain that some number road crossings will lead to fatalities. However, the strength of the relationship is considered weak, because it may only be a small fraction of road crossings that actually lead to fatalities and a reduction in the number of chickens.

The overall approach taken, therefore, is to develop a highly plausible list of hypothetical causal relationships and then assemble these into CLDs, in order to visualize how they will interact together in a system. This approach can be conceptualized as a series of "IF-THEN" statements, structured as follows:

"IF" one accepts the following hypotheses:

- A →(+) B ("an increase in A will cause an increase in B, ceteris paribus")
- B→ (+) C ("an increase in B will cause an increase in C, ceteris paribus")
- C → (+) A ("an increase in C will cause an increase in A, ceteris paribus")

"THEN" one must also accept that there is a reinforcing loop (a "positive feedback effect") among all these variables, with the following net causal effects:

- A → (+) A
- B → (+) B
- C → (+) C
  ("an increase in any individual variable in the loop will have a net effect that further increases that variable, ceteris paribus")

It is hoped that this approach will stimulate a better understanding of the key dynamics that may be affected by the introduction of AVs. And, while most of causal relationships used in this analysis are strictly hypothetical, the resulting insights should help focus attention on the relationships that might have the most effect and therefore deserve the most research attention. Additional research would be required to establish the true nature of the causal relationships with the ultimate aim of expressing these relationships as equations. This could ultimately allow some of these CLDs to be converted into actual operational system dynamics models, which would produce quantitative simulations of system behavior. The hypothetical CLDs in these thesis are a tentative, yet essential, first step.

Chapter 3. Scenario Development

This chapter follows the first five steps outlined by Schwartz (1991, pp. 241-247) for developing future scenarios. Throughout this process, it is important to remember that the goal of the scenarios is not to achieve the best prediction of a future state, nor is it to explore the effect of a scenario on every element of a system. Rather, the intent is to present a limited number of scenarios that collectively illuminate the most important decisions to be made in anticipation of future outcomes. Therefore, a certain level of simplicity must be maintained in order to provide the required clarity.

3.1. Step 1: Identify the focal issue/question

As discussed in section 1.5, this thesis aims to address the uncertainties that will exist in the early years of commercialization of AVs in order better understand how they might affect VMT. The focal question, therefore, is: How will the initial system reaction to AVs affect the overall use of automobiles (both conventional and automated)? To answer this, I will first consider how the transportation system might react to the market entry and initial deployments of AVs. I will then consider what the ensuing response of key stakeholders and the market might be, once the system reaction is observed and recognized.

As a note for clarity, in this thesis I have chosen to use the following terminology:

- ***Transportation System*** refers to the existing infrastructure and vehicles and the users of the system; it does not consider changes to the structure of the system, such as additional adoption of AVs, changes to investment in infrastructure, or even transit agencies' acquisition of new buses. In this thesis, the "transportation system" is sometimes just referred to as "the system," and it contains many of the key dynamics we are interested in.
- ***Macro System*** includes the transportation system, but also includes all the key stakeholders and relevant aspects of the political, social, market, and regulatory systems that will have an influence in changing the transportation system.

The focal issue or question here is not about the very first deployments of AVs, but rather, how those initial deployments may affect VMT, taking into consideration how the initial AVs behave in the transportation system, how they might alter the system, how those interactions may be perceived, and what external forces in the macro-system may act on the transportation system in response to those initial effects. While there are many interesting questions regarding the nature and extent of the very first deployments of AVs, this thesis does not address those questions. Instead, it assumes a variety of initial conditions for three different scenarios, and the level of initial deployments is directly implied by those assumptions. Although it is not directly part of the underlying assumptions, "initial deployments of AVs" has been grouped in the "assumptions" part of this process (as shown in figure 3.1). This is because no formal analysis was conducted to generate the level of initial deployments; instead, assumptions were made about initial deployments that fit well with each given scenario. Other levels of initial deployments could be assumed, generating new and different scenarios.

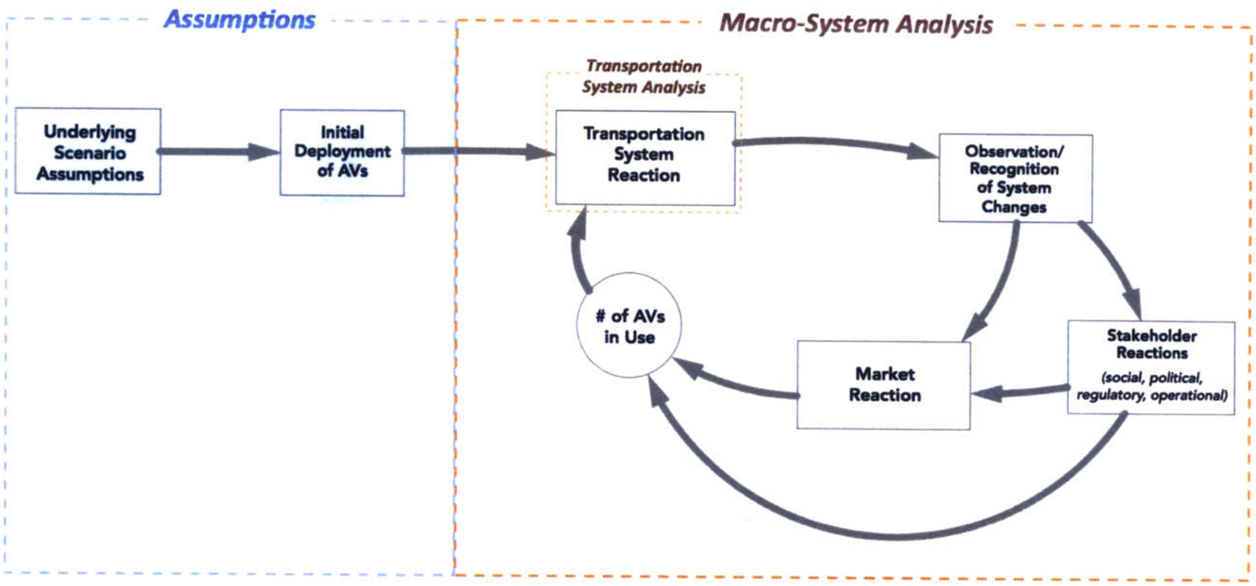


Figure 3.1. The Structure of the Analysis in This Thesis. *Each scenario includes* assumptions, analysis of the transportation system, *and* analysis of the macro-system *and how that may in turn affect the transportation system.*

To further clarify the question, it is important to note that analysis in this thesis does not consider all the dynamics that might emerge over the long term. Instead, it considers existing dynamics and additional dynamics that might become evident after the initial system effects are felt. Therefore, while Figure 3.1 shows this process as cyclical, this thesis will not consider numerous iterations of the cycle. While there are benefits to considering multiple cycles within the system, in this case, just considering one iteration of the macro-system dynamics should still reveal significant insights. Due to the delays in the effects along the way, we can expect a substantial accumulation of effects before the broader stakeholder community and the marketplace react. Some forces may have immediate effect on the macro-system, but the most important system reactions will take some time to emerge (delays that could be expected to be especially significant are shown in Figure 3.2, below). Furthermore, even once those system reactions do emerge, we can assume there will also be delays between the transportation system reaction, the observation of those changes, and the recognition of the new conditions that may exist. With these two delays, we can expect a substantial gap between the initial market entry of AVs and the resulting effects on VMT. Given this gap, it is reasonable to focus on the first pass of this cycle somewhat in isolation, focusing attention specifically on what will be the initial impacts on the market of the observed system changes.

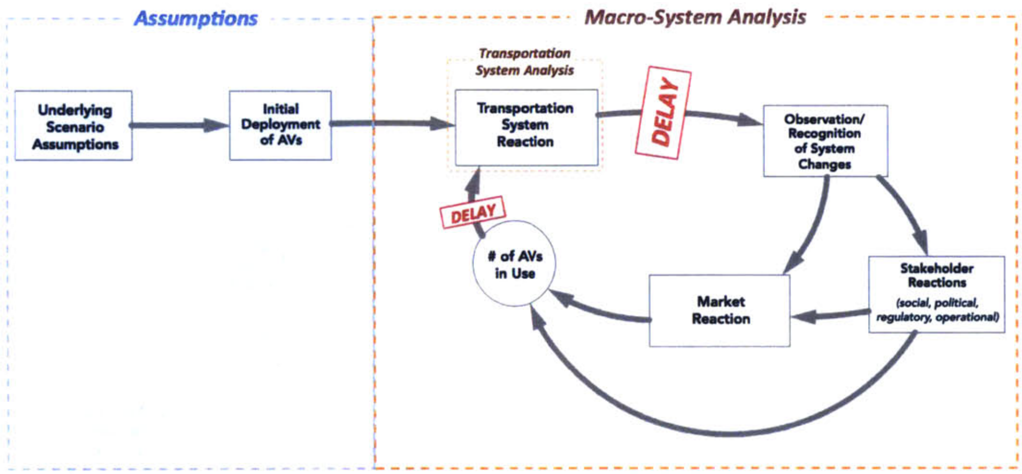


Figure 3.2. Potentially strong delays in the "Macro-System" reaction.

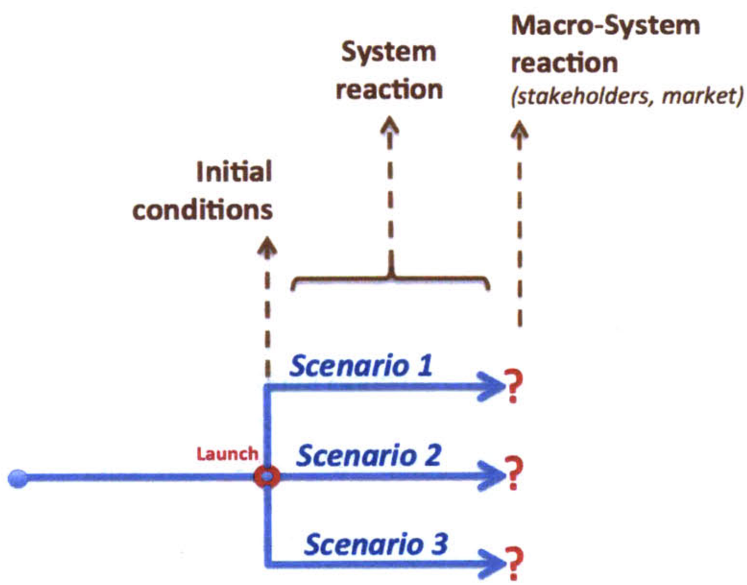
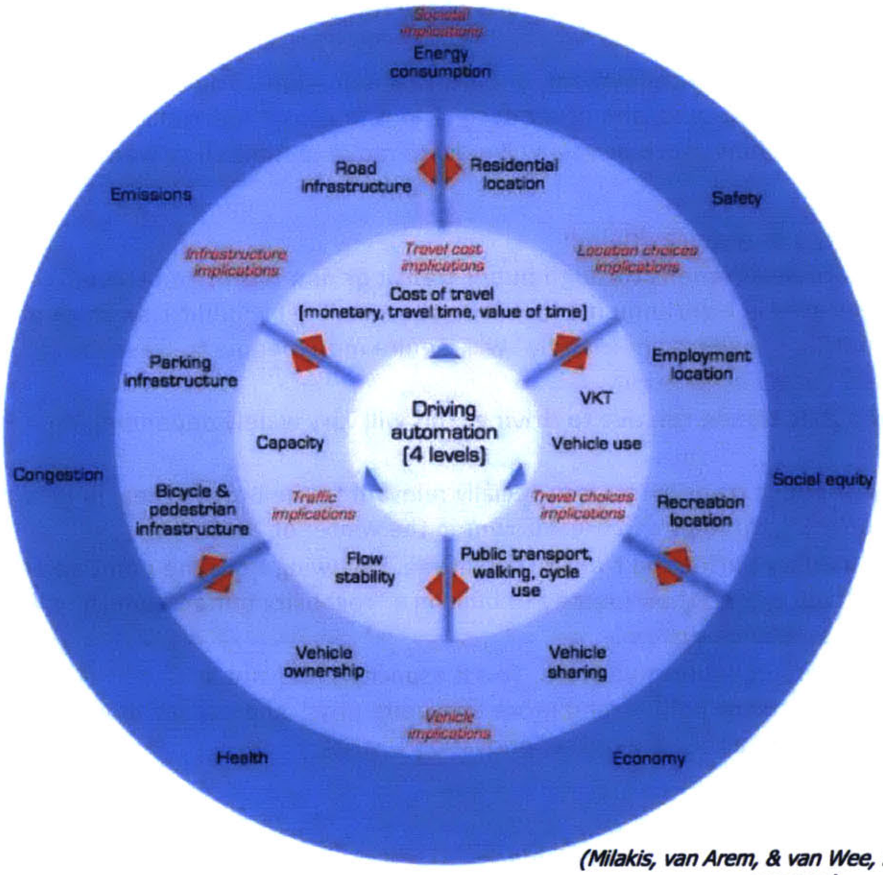


Figure 3.3. The aim is to explore the dynamics of the system under each of three scenarios and how it might react to the very first wave of adoption.

3.2. Step 2: Identify key forces in the "local environment"

To understand what may happen to the demand for use of automobiles (conventional and automated), my approach is first to identify the likely key forces in the "local environment." In this case, the "local environment" means the arena where travel and mobility decisions are made. Therefore, I am interested here in identifying the main forces that may shape travel behavior—specifically, those forces that will themselves be most affected by AV technology.

Figure 3.4 outlines the main effects of automated driving on the transportation system. Using this diagram as a framework, I have identified and inferred some of the key forces. The diagram can be read as follows: automated driving will affect all three factors in second ring from the center, and these three factors are all interdependent. For example, automated driving may improve traffic capacity and flow stability, which will reduce travel cost (time) and also affect travel choice (likely causing some switch to additional vehicle use). Due to the relatively short time frame of this analysis, I have omitted location choices and infrastructure effects from consideration.



(Milakis, van Arem, & van Wee, 2015; work in progress)

Figure 3.4. The Ripple Effects of Automated Driving (Van Arem, 2015). *The driving question of this thesis is the effect on VMT, shown here as VKT (vehicle kilometers traveled).*

These forces, which are identified below, are used in Step 3 to help identify what may be the important uncertain variables that should be considered in creating the scenarios. Then within each scenario, these forces are reassessed, to examine how they might change under the scenario assumptions. The list that follows is not meant to be comprehensive; rather, it is intended to provide a summary of what appear to be the most important factors, focusing on those that are most likely to affect—or be affected by—the use of AVs. Furthermore, most of these forces are applicable to many locations, but there may also be significant geographical variation.

While ***this thesis ultimately focuses on only a few key uncertain factors***, a longer list of forces is included here, as it can be used to focus interest on other uncertainties and create entirely different scenarios to illuminate other issues.

1) **FORCES THAT SHAPE TRAVEL BEHAVIOR.**
   a. **Forces that increase demand for mobility:**
      - **Number of destinations or "attractors."** Put simply, people travel to reach a destination. In the rare case, where someone goes for a drive just for the sake of sightseeing while driving, the attractive parts of the route of the drive can themselves be considered "destinations."
      - **Dispersion of residential, employment, and other destinations.** The distances between residences, employment sites, and other destinations (e.g., commercial and recreational sites) will determine how much people will need to move to fulfill their wants and needs.

   b. **Forces that encourage or require driving:**
      - **Limited access to destinations through public transit or non-motorized travel.** Destinations located in environments that are not accessible by public transit, or aren't "bicycle-friendly" or "pedestrian-friendly" will require more people to travel by car. This factor will vary widely by location.
      - **Time cost of public transit relative to driving.** This will vary widely depending on location.
      - **Unreliability of public transit.** This is especially relevant to the Boston area, in light of the MBTA's ongoing troubles and breakdowns in the winter of 2015.
      - **Impact of "reliability buffer" on transit travel time.** Following from the point above, travelers often will extend their journey to build in a "reliability buffer," which will be longer with a less reliable system.
      - **Trend toward more-collaborative work**. This is especially relevant in creative/innovative fields (which tend more to require physical presence in workplace) and in places like Kendall Square or the Innovation District
      - **Desire for control**
      - **Desire for privacy**
      - **Desire for uninterrupted, single-seat trips**

   c. **Forces that limit/discourage vehicle use**
      - **Time Cost of Driving (including parking) relative to public transit.** This will vary widely depending on location.
      - **Personal value of time relative to the low utility of time spent driving**
      - **Monetary Travel Cost (including parking, cost of car, repairs, cost of gas)**
      - **Impact of "traffic buffer" on driving travel time**
      - **Danger, stress, exhaustion involved in driving**
      - **Physical competency and minimum age requirements**
      - **Decision-making based on personal values, social perception**
      - **Desire for health/wellness**
      - **Workplace technologies.** Better communications/virtual environments may drive down need for commuting.
      - **Emergence of private bus services**—e.g., Bridj

2) **FORCES THAT SHAPE VEHICLE OWNERSHIP CHOICES**
   a. **Forces that encourage car ownership**
      - **Inherent perceived value of ownership**
      - **Lack of sharing options**
      - **Desire for customization**
      - **Inconvenience of sharing (sparse locations, not as close at hand as private car)**
      - **Perceived high per-use cost of sharing services**

   b. **Forces that encourage car sharing**
      - **Desire to reduce hassle, effort involved in ownership**
      - **Desire to reduce monetary and time cost of parking (including home/apartment parking space for permanent storage)**
      - **Reduced frequency of need for auto-mobility**
      - **Travel decision making based on personal values, social perception**

3.3. Step 3: Identify driving forces.

In this step, the goal is to identify the important and uncertain conditions and trends (or "driving forces") that could exist at the time of the commercial launch of AVs. At this stage, I consider a broad array of forces that may come into play, with a wide range of uncertainty among them, as well as a wide range of potential impacts. The goal is to identify the factors that may have the most significant effect on the key local forces identified in Step 2. Because the time frame of the analysis is limited to the first few years of commercialization, forces that will only unfold over the long term, such as land-use changes, are not considered. Given the size and scope of the question and the large number of factors that will affect the use of AVs, these effects have been grouped into eight categories, as follows:

Category 1: Status of Automated Driving Technology.

- **Performance of Automated Driving Technology.** This is one of the most widely discussed topics in the literature and it has been well analyzed. While considerable uncertainty exists around how well AV technology will perform (e.g., will it be safe enough? will it be reliable enough? how much will it improve traffic flow? etc.), these uncertainties are not the focus of this thesis. An essential aspect of the thesis question is the assumption of "technology success." In other words, the question is, if the technology is successfully developed, how might the system respond to it, and how will the new system conditions affect the market? **Therefore, an underlying assumption of all the scenarios considered is that the technology will be successfully developed—meaning that AV technology is capable of realizing all of the key benefits its developers are aiming for: improved safety, improved fuel economy, more-efficient flow of vehicles (possibly including smart, "system-optimal" routing), and full automation (allowing for the vehicle to reach its destination with no effort or attention from any human passenger).** It is also assumed that these facts are widely recognized and accepted by key stakeholders, so there is less risk of unnecessarily restrictive policies being enacted.

This is an important assumption that has a large impact on the forces identified in Step 2. The current status of automobiles and their capabilities today play a large role in the inherent disincentives for driving. And many of the most unattractive aspects of driving today stem from the fact that an active human driver is required. Therefore, it is only reasonable to expect that AV technology, which removes this fundamental requirement, would have a significant direct effects on many factors, including:

- The amount of time spent traveling by car (assuming potentially higher speeds, improved traffic flow)
- The danger of traveling by car
- The stress and exhaustion experienced when traveling by car
- The low utility of time spent in a car (especially for the driver)
- The physical ability and age restrictions on drivers

- **Cost of AV Technology**. According to Anderson (2014), the additional cost of AV technology could add a substantial premium to the price of an automobile: "Many of the existing demonstrations of AV technology involve suites of sensors that currently cost tens of thousands of dollars and would double or triple the cost of most cars." However, it is widely believed that additional substantial cost reductions are possible. In addition to the baseline cost of the technology, other factors may affect overall cost, such as: unforeseen architectural and engineering modifications needed to meet new safety requirements; testing and certification expenses; and liability and insurance issues. Liability and insurance issues could be especially significant, because removing the role of the human driver is likely to put all the liability on the manufacturer. As a result, all these costs would have to be factored into the purchase price or use-charges of the vehicles. This could also be a particularly significant factor in the very early stages, when there will be very little data for insurance companies to base policies on, and they may be inclined to charge very high premiums to cover unknown risks.

Category 2: Macro-Economic Conditions, Energy Prices, and Climate-Change Legislation. This grouping represents external factors that will affect consumers' ability to purchase expensive technology and to use automobiles.

- ***Macro-economic conditions,*** or the overall strength of the U.S. economy, will have an impact on consumer buying power and willingness to spend more on new technologies.

- Furthermore, the cost of using an automobile is particularly sensitive to ***energy prices***, which are among the more volatile and unpredictable aspects of the economy. Energy prices may also be closely tied to ***climate-change legislation***, because most of the mechanisms under consideration (such as carbon taxation or cap-and-trade schemes) involve higher pricing for fossil energy as part of the mechanism to effect change. If such legislation were to be successful in reducing CO_2 emissions from automobiles (both by petroleum powered vehicles and electric vehicles using power from the grid), it would need to do so by imposing costs steep enough to deter automobile owners from driving and potential owners from purchasing a car. Therefore, I will refer to this variable as "carbon price," which includes both carbon taxes as well as any price that would be paid under a cap-and-trade scheme. It is assumed that all such costs would be passed on to the end user. While it may be argued that these factors could all be alleviated by the use of electric cars and renewable power generation or fuel cell cars using renewable hydrogen, these scenarios would involve extensive uncertainties as well, especially regarding the costs involved in expanding the electric vehicle charging infrastructure or the hydrogen refueling infrastructure, and other the costs that would be passed on to drivers. Overall, the combined impact of a weak economy, high energy-prices, and punitive carbon pricing could have a substantial effect on the forces discussed in Step 2.

Category 3: Behavioral Reaction to AV Technology. Of all the uncertain variables, this one is arguably the least knowable and potentially the most influential. Most of the existing literature on AVs has ignored potential behavioral reactions, probably because there is no effective way to predict this factor and little data to examine. These behavioral changes may be the most influential, because there is essentially no limit to their impact: with most other variables, there is a "reasonable" range of values we can assign, but with this kind of behavioral change, it is difficult if not impossible to assign limits. As discussed earlier, the history of the automobile provides ample evidence for how uses for a new technology may arise that are vastly different from the designers' original intent (both quantity and kind). The potential behavioral changes involving AVs can be grouped in two categories, as follows:

- **Changes to existing behavior.** This encompasses changes where people are essentially using their cars for the same purposes, but with different behavioral characteristics that would either be unappealing or impossible in a conventional vehicle. For example, some changes to existing behavior could include:
  - AV users are willing to spend more time in their cars, because the utility of time would be higher, as attention would no longer be devoted to driving. This could lead to more trips, longer trips, and could alter the decision-making process involved in making travel-mode choices.
  - AV users are more tolerant of traffic, because it demands less attention and causes less stress. This could also alter the decision-making process involved in mode choices.
  - AV users who are too young to drive, too old, or disabled, will be able to use a car without depending on someone else to drive.
  - Attitudes about car sharing could be radically changed. Empty vehicle trips (or "deadheading") could address many of the most unattractive aspects of car sharing—eliminating the inconvenience of being tied to specific drop-off locations, providing access to a much larger network of vehicles, allowing real-time balancing of the system to meet demands, etc.
  - People in general may develop higher expectations for the behavior of users of conventional automobiles. Behaviors that are grudgingly tolerated today may become unacceptable when viewed in comparison to the much-better "behavior" of AVs.

- **New uses for automobiles enabled by automated driving: The mobility of empty vehicles could be an essential aspect of many new uses. For example:**
  - Empty vehicle trips could allow users to avoid parking costs. An AV could drop the user off at his/her destination, then continue on to find inexpensive or free parking, or even continue back to the user's home and park itself there.
  - Empty vehicle trips could allow people to pick up packages and run other errands without being present.
  - A wide array of businesses could emerge around driverless deliveries, as the economics of delivery services would be fundamentally changed by eliminating the need for paid human drivers.
  - Families may be able to get much more use out of a single car—by sharing among family members. In this way, the AV would behave as a chauffeur, picking up and dropping off family members where and when it is needed.
  - There may be substantial impact on car rentals, as families may be able to send their car ahead to meet them at their vacation destination. E.g., today, a family might fly to a vacation destination and rent a car for the week; with AV technology, it may appear cheaper and more convenient to send the family's AV ahead, with all the luggage inside, to the destination. Then, the family could be delivered directly to the airport by another AV (without even the burden of carry-on luggage), and when they arrive at the destination airport, their AV will be waiting there for them, with all their bags and anything else they may want to bring with them on vacation.

Category 4: Policy Climate for AV Technology. To date, there has been very little policy development for AVs. As of January 2015, "Only two of the 25 largest Metropolitan Planning Organizations (MPOs) mention autonomous or connected vehicles in official long-range regional transportation plans" (Guerra 2014). This remains a highly uncertain area, with the potential for a very wide range of impact on adoption: the impact of regulations is almost impossible to put clear limits on, as it could range from minor taxes that increase costs marginally to outright bans of the technology in certain areas. However, given the current anti-regulatory climate in the United States, it is difficult to imagine any substantially restrictive regulations coming on line before the technology is deployed and its impacts are assessed. Therefore, for the purposes of this thesis, the policy climate is considered to be *a reaction to* initial deployments, and not a factor that shapes those initial deployments.

Category 5: Demographic changes. Demographic changes are among the most predictable, but they could still have a substantial impact, which should be considered. The aging of the population in the United States could affect demand for mobility and for maintaining mobility after driving is no longer possible. Furthermore, if the trend toward delayed retirement and semi-retirement continues it is reasonable to expect that more seniors will continue to demand the same level of mobility they had when they were younger.

Category 6: Planning, Investment, and Policies Related to Transportation Infrastructure. This category is meant to encompass a broad range of policies and approaches. Changes in this category are likely to be slow, and therefore fairly predictable. However, they will vary substantially from region to region and they could have a substantial impact on the reaction to AV technology. For example:

(1) Many drivers need to contend with the cost, time, and effort spent looking for parking, and the time spent walking from the parking spot to their destination. For example, in the Boston area, parking policies and the limited availability of spaces have kept the issue of parking as a prominent consideration in the use of automobiles. Without any change, this could have significant impact on the appeal of AVs, especially if people are willing to use empty-vehicle trips to send their vehicles to alternate parking locations.

(2) Even in the absence of parking policies, there are also constraints on parking that would exist just due to the lack of availability of urban real estate in many areas, and these would have similar effects.

(3) The condition of the road infrastructure in in many parts of the country is deteriorating, and if this persists, we can expect this to continue to diminish the appeal of driving by increasing travel times, and increasing the danger and stress of driving. This could, in turn, have a mixed effect on the appeal of AVs: if roads continue to get worse, people may wish to just avoid them entirely, or they may find AVs even more appealing, because it will allow them to get to their destination without actually having to navigate the roads as the driver.

(4) The level of investment in public transit and the willingness to invest in public transit are widely recognized to be too low to adequately maintain the current services in many areas. If this continues, we can expect the reliability of public transit to diminish with a resulting increase in the demand for private transit services and an increase in demand for driving.

(5) In recent decades, the trend for urban planning and development in many metropolitan areas has shifted toward being more transit-oriented and less automobile-centric. However, even in regions like the Boston Area, there is often still a diverse array of development and development trends, so while some areas may become more transit-oriented, others may continue along a more automobile-centric path.

(6) There is also a growing trend toward investment in non-motorized transportation infrastructure. This not only has direct effects in terms of providing an alternative to automobile travel, but also by improving access to destinations from transit ("last mile" connections) and improving access to transit from the origin ("first mile" connections). If this trend is to continue, we should expect it to reduce demand for automotive travel.

Category 7: The socio-political climate of transportation. The socio-political climate, including the prominent topics of debate and discussion, will play a vital role in shaping attitudes and policy. In many areas with long histories of debates and conflicts around transportation issues, there are well-established coalitions that have emerged. The Boston Area is perhaps one of the best examples, with its history of transportation problems and high-profile controversies, including the Inner Loop, the Big Dig, and the parking ban. In the case of the parking ban, clear and well-established coalitions have emerged around this issue (Ferrentino 2014). These follow similar patterns as those that have emerged in the debates around congestion pricing in other municipalities. Based on these patterns, one could easily imagine similar coalitions emerging around AVs:

- *Anti-AV coalition:* This would represent the safe-streets (e.g., Livable Streets in Cambridge) and "smart growth" interests, including the pro-cycling, pro-pedestrian interests, and would tend to favor urban design solutions to increase accessibility without requiring increased mobility.
- *Pro-AV coalition:* This would be similar to the "pro-growth coalition" identified by Ferrentino, with a focus on increasing mobility, reducing congestion, and increasing choice ("freedom") among mobility options.

However, very large—and very interesting—uncertainties exist regarding other key stakeholder groups and where they will be aligned, including:

- *Public transit interests.* While at first it might seem obvious to pit public transit interests against any new automotive technology, AVs may be perceived as a boon to public transit, if they can provide efficient and inexpensive first-mile/last-mile connections.
- *Advocates for the aged and disabled.* These would normally be firmly aligned with the smart-growth coalition, as seniors and the disabled have traditionally relied on public transit, but may side with the Pro-AV coalition as AV's could radically expand the mobility of elderly and disabled people in ways far beyond the potential of public transit.
- *Environmental groups.* Traditionally, these groups have been aligned with safe-streets and smart growth coalitions, but this may change if they believe that AV's will have substantial environmental benefits due to more efficient driving, potentially better overall routing, and reduced congestion.
- *Pro-growth and pro-business.* Normally, these groups would predictably fall in favor of new technology, improved mobility, and anything that may be perceived as expanding access to locations and markets. However, if AV's come to represent an auto-centric attitude and suburban sprawl, many businesses, especially in places like Boston, which relies heavily on the vitality of densely built urban spaces, may oppose such a direction.

It is also far from certain whether there will even be a substantial debate around the technology before it is commercialized and deployed. So much uncertainty exists around how the technology will perform and how it will be used that it may be difficult for strong coalitions to form and present compelling opinions. Similar to category 4 (the "Policy Climate"), any strong trends here are likely to emerge ***in response*** to the initial deployments and the ensuing system effects, and not in anticipation of them.

Category 8: Social Behavior and Workforce Trends. A number of general trends in society and the workplace may also play a role in how people react to a new automotive technology.

- Healthy living and "wellness" trend. For example, with a large population of university students and young professionals in the Boston area, residents are even more likely than the general population to make decisions based on improving health and wellness. This is likely to dampen enthusiasm for additional travel by automobile.
- Urbanization/sustainability/"car-free" lifestyle trend. A continuation of this trend will further discourage AV use.
- Increased travel-decision-making based on personal values and social perceptions. A high value on sustainable living and related social perceptions will discourage additional use of automobiles.
- Work culture and technology: improvements in communications technology and increased acceptance of teleworking would drive down demand for commuting. However, this could just as well be offset by the trend toward collaborative/creative work (which is increasingly considered to be essential for success in the "innovative economy"), which would encourage co-location of employees.
- The general trend toward increased perceived value of time—due in part to access to information and entertainment around-the-clock—might lead to a lower tolerance for time spent commuting. This could improve the appeal of AV's if they are perceived to greatly increase the utility of travel time, but this could be offset by the more general desire to reduce travel time entirely.

Lastly, it is important to note that location choices and land-use changes have been excluded from the analysis, although these factors may have the most powerful effects over the long term. This omission was necessary to limit the scope of the analysis, and to reflect the short time frame under consideration. That is not to suggest that these effects are unimportant, or that none of these effects would be observable within this time frame (one could easily imagine a new transportation technology having an almost instantaneous effect on where a newcomer to the area will chose to live), but these factors are not expected to be *dominant* in the very early stages of AV deployment.

3.4. Step 4: Rank by importance of uncertainty.

This step involves assessing the forces identified in Step 3 in terms of their uncertainty and their relevance to the focal question. Of course, at this stage, it is impossible to say with any objective certainty which forces will be more important than others. And it remains essentially a matter of judgment which forces are more certain to exist or less. Therefore, this process relies on educated guesswork to create the most useful hypotheses. Ranking forces this way is meant to provide a framework for developing hypotheses that will lead to insightful scenarios and informative analysis.

Usually, once the forces are ranked, the variables considered to be *most uncertain* and *most important* are defined as "critical uncertainties," and these are used to develop the scenarios. The other variables are considered to be "predetermined elements" and are usually held constant across the scenarios under consideration. However, since this thesis is examining the potential system reactions to

successful early deployment of AV technology, it is not concerned with the uncertainties around the performance of the technology (even though it very important and very uncertain) so for the purposes of this thesis, that variable is treated as a "predetermined element."

The table below lists the main categories of uncertainties, with an initial assessment of importance (how relevant they are to the driving forces), uncertainty, and near-term impact. Near-term impact is also considered, because the scenarios focus on the effects of the initial adoption, and I am primarily concerned with forces that will play a role within a shorter time frame.

Driving Force	Importance	Uncertainty	Near-term impact?	Assessment: Predetermined Element or Critical Uncertainty?
Behavioral Reaction to AV Technology	**High** *The ways people use AVs could vary widely and have tremendous impact on the transportation system.*	**High** *Very little research has been devoted to this, and even if it were, it would be very difficult to predict to any degree of certainty how people will use the new technology.*	**High** *It is not likely to take long for users to explore the new and different ways to use a car without a human driver.*	**Critical Uncertainty**
Cost of AV Technology	**High** *Cost will have a major impact on adoption of AVs and how they are used.*	**Medium** *Based on claims of automotive OEMs and other industry players, the range of costs has been narrowed substantially, but many uncertainties remain between the predicted cost of manufacturing the technology and the actual final cost to the user*	**High** *Cost effects will vary over time, with possibly some tolerance for higher costs early on, but will still play a major role.*	**Critical Uncertainty**
Macro-Economy, Energy Prices, Carbon Prices	**Medium** *This could be considered medium or high, but the effect of these variables will be felt by both the conventional vehicle market and the market for AVs, so the net effect may not be as critical.*	**High** *The complexity of factors determining energy prices and the unpredictability of the global economy and political system surely render this a "high" uncertainty.*	**High** *This variable will affect attitudes about cars and driving before consumers even consider AVs, so the effect should be considered immediate.*	**Critical Uncertainty**

Performance of AV Technology	**High** *Performance—especially in terms of safety and reliability –will have a very large impact on the market.*	**Medium** *Based on claims of automotive OEMs and other industry players, technology success appears to be highly probable—and certainly more knowable and predictable than some of the other parameters.*	**High** *The impact of performance will almost certainly be nearly immediate, except in the case of performance that may degrade over time (e.g., reliability issues that may only emerge after certain components wear out or certain unanticipated stresses are put on the system.)*	**Predetermined Element** *Assume all performance goals are met—Level 4 AV technology is safe and reliable—for all scenarios.*
Policy Climate for AV Technology	**High** *Policies could have a very powerful effect—potentially even including banning use of AV technology in certain areas.*	**Medium** *Based on the extremely cautious pace of regulatory activity to date, the very anti-regulatory climate, and the lack of data to base regulations on, there is good reason to believe that the policy climate will be at least moderately permissive in the initial stages.*	**Medium**	**Predetermined Element** *I assume **initial** policies will be friendly (no obstacles). Policy reaction **after** technology is in the market will be part of the scenarios.*
Demographic Changes	**Low**	**Very Low**	**Low**	**Predetermined Element**
Planning, Investment, and Policies Related to Transportation Infrastructure	**Medium** *Only very extreme changes in this variable are likely to have major impact on the AV market.*	**Medium** *While this variable is certainly subject to change, any change is likely to be slow and therefore somewhat predictable.*	**Low**	**Predetermined Element**
Socio Political Climate of Transportation	**Medium** *The effects of this variable will ultimately be felt hand-in-hand with those of the "Policy Climate," as it will play a role in shaping policy.*	**Medium** *While this variable is certainly subject to change, any change is likely to be slow and therefore somewhat predictable.*	**Medium** *Because most of this variable's effects will be felt in terms of policy, they are likely to take some time to be felt in the market.*	**Predetermined Element**

Social Behavior and Workforce Trends	**Medium** *Even extreme changes in social behavior and workforce trends are gradual and tend not to be felt universally across entire populations.*	**Medium** *While this variable is certainly subject to change, any change is likely to be slow and therefore somewhat predictable.*	**Low**	**Predetermined Element**

3.5. Step 5: Select Scenario Logics

In the previous step, three "critical uncertainties" were identified: **Behavioral Reaction to AV Technology**; the **Cost of AV Technology**; and **Energy Prices, and Carbon Pricing** (the last variable has been modified, with "Macro Economic Conditions" eliminated from consideration to further simplify and clarify the scenarios). These are the dimensional variables that will be used to define the scenarios. In selecting which assumptions to make, the goal is to end up with just a few scenarios whose differences will be important and insightful for decision-makers.

The latter two of these factors affect the cost of owning and using the technology. To simplify the range of scenarios, these cost-variables have been linked: "***low*** energy/carbon price" has been linked with "***low*** AV technology cost," and vice versa. This simplifies the range of scenarios to choose from by reducing the dimensions from three to two. However, it still maintains a broad span of outcomes: low AV technology cost coupled with low energy prices will represent highly favorable conditions for commercialization, while high AV technology cost combined with high energy/carbon prices and will represent highly unfavorable conditions for commercialization. Therefore, decoupling these variables would only allow us to create additional scenarios that lie between these two extremes, and such scenarios may not be as insightful. (However, it may be worth considering them as distinct for examination of more detailed scenarios in the future, as they may change along different timeframes.) By exploring the extremes, it is hoped that insights can be interpolated for the more moderate cases.

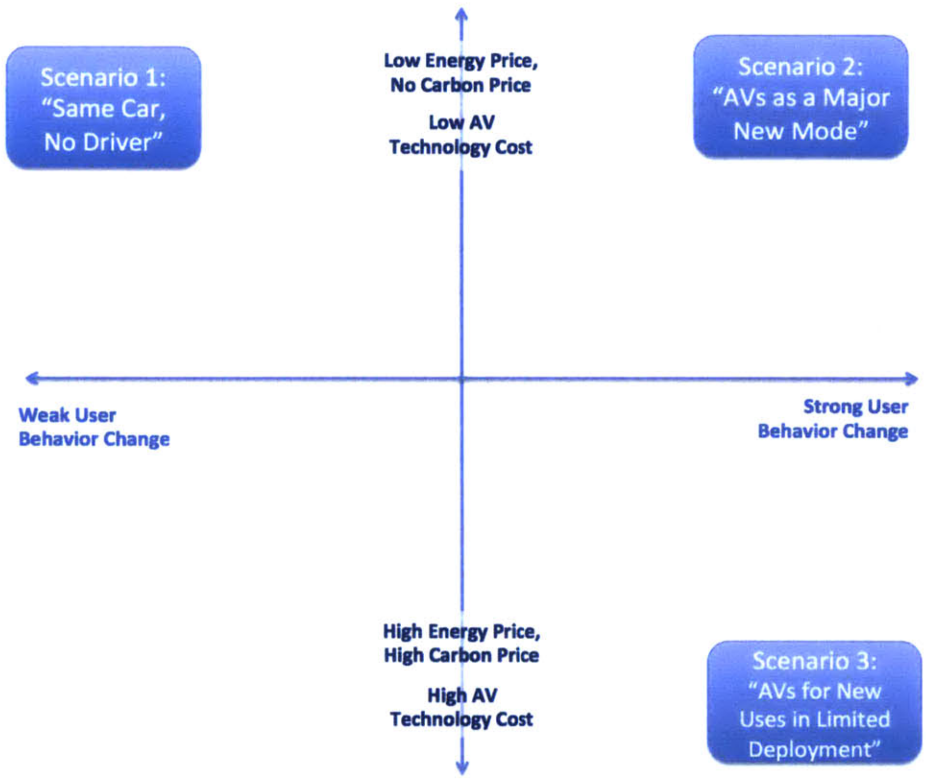


Figure 3.5. The Three Scenarios Selected.

As shown in Figure 3.5, the selected scenarios are:

Scenario 1: "Driverless Car: Same Car, No Driver", *which assumes*

- Low Energy Price, No Carbon Pricing (stays the same)
- Low AV Technology cost
- Low User Behavior Change (stays the same)

Scenario 2: "AVs as a Major New Mode", *which assumes*

- Low Energy Price, No Carbon Pricing (stays the same)
- Low AV Technology cost
- High User Behavior Change

Scenario 3: "AVs for New Uses in Limited Deployments", *which assumes*

- High Energy Price, High Carbon Pricing
- High AV Technology cost
- High User Behavior Change

Chapter 4. Scenario #1: "The Driverless Car: Same Car, No Driver"

Scenario 1 represents several key aspects of the conversation that has taken place around AVs to date. As discussed in Chapter 2, most of the research and analysis considers how the existing system—with existing traveler behavior—would react to AV technology. Most of this analysis has assumed no significant behavioral change in the way people use automobiles. In other words, a common underlying assumption is that users of AVs would enjoy the benefits of AV technology while essentially making the same travel choices and using their cars in the same way they use conventional cars today. This is also very similar to how proponents of AV technology present the expected benefits: assuming the system will not change, and that the key component in the system—the automobile—will perform much better (more safely, efficiently, comfortably, etc.). This scenario makes that assumption, and also assumes a very positive climate for AV technology—represented low technology costs, low energy prices, and no carbon pricing.

4.1. Summary of Assumptions

4.1.1 Underlying Assumptions

(1) **Low Behavioral Reaction to AV Technology:** AVs will be used the same way as conventional vehicles (CVs), with the only difference being that a human driver is not required. Under this assumption, automated driving will not change the nature of the forces governing behavioral choices about automobiles. However, this assumption ***does*** allow AV technology to affect the system in ways that will change behavior. In other words, AV users will drive no more and no less than they would drive an ordinary car. Any changes in behavior will be the result of system outcomes that affect conventional drivers as much as AV users. For example, while automated driving may affect travel time by improving the way cars move on the roads, this scenario assumes that travel time will still play exactly the same role in transportation decisions as it does today, and traffic will have the same deterrent effect on AV users as on conventional drivers. As part of this behavioral assumption, I also assume AVs will not be used for empty-vehicle trips, because this would represent a substantial departure from current behavior. While it may seem unrealistic to assume that people will simply choose not to use their vehicles for empty trips, there may, in fact, be other reasons why empty-vehicle trips would not occur (e.g., concerns about security or terrorism might lead to regulations requiring a human occupant in all moving vehicles). Therefore, I believe that this assumption remains valid and worthy of consideration.

(2) **Low Cost of AV Technology:** I assume this to be low enough to not be a significant deterrent to adoption by the majority of car owners.

(3) **Low Energy Prices, No Carbon Pricing:** I assume no substantial changes in energy prices and no carbon pricing or other significant tax on energy consumption.

In addition, as stated in the previous chapter, all of the scenarios assume:

(4) Full technology success for AV technology, with widespread acknowledgment of AVs' capabilities by key stakeholders
(5) Neutral policy climate for AV technology
(6) Demographic changes unfold along current trajectories
(7) Planning, Investment, and Policies Related to Transportation Infrastructure remain unchanged
(8) Socio Political Climate of Transportation remains unchanged
(9) Social Behavior and Workforce Trends unfold along current trajectories

4.1.2 Initial Deployment Assumptions

Based on the underlying assumptions of this scenario, which describe a very positive climate for adoption and use of AVs, it is reasonable to also assume that there will be a large and enthusiastic initial wave of adoption. The "initial wave" of adoption is intended to include the early adopters who will adopt the technology before it's clear how it will function in the overall system or what the effect of widespread adoption will be (in other words, these are the ones who *do not* take a "wait and see" approach). These are the people for whom the new technology has enough innate appeal to justify the added expense and the risk of the unknown.

4.2. Changes in Key Forces and their *direct* effects on CV drivers and AV users

The next step in the scenario analysis process is to assess the direct effects these assumptions would have on the key "local forces" (those forces driving potential consumer behavior, as identified in step 2 of Chapter 4) and how these changes will affect users of automobiles (both CVs and AVs). Since the assumptions in Scenario 1 leave energy prices low, assume no carbon pricing, and assume little or no behavioral changes, the only assumption that needs to be considered is the successful introduction of AV technology. Under this assumption, some of these effects will be felt by all automobile users (AV users and CV drivers), while other effects will be felt only by those using AVs.

The following table lists several of the basic factors influencing driving choices that could be affected by AVs in this scenario. While there are many other factors influencing driver behavior, I have chosen those that appear most likely to be affected by the introduction of automated driving technology.

4.2.1 Key Factors that Could Be Affected by Automated Driving

Table 4.1. Factors influencing driving-related choices that might be affected by Introduction of AVs

Causal Link: Independent Variable	Causal Link: Dependent Variable	+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Purchase/Lease Price	Per-mile Fixed Costs of AV	+	By definition	By definition	
Vehicle Lifespan	Per-mile Fixed Costs of AV	-	By definition	By definition	
Per-Mile Fixed Costs of AVs	Monetary Cost of Automobile Use	+	By definition	By definition	One important issue not addressed here is the likelihood that for some owners, the more they pay for their car, the more they will want to use it. This would likely be at least partially based on the common failure to consider depreciation of the value of the vehicle as a cost of incremental driving trips. This has the potential to create a perverse effect, where higher capital costs actually lead to higher utilization.
Variable Costs	Monetary Cost of Automobile Use	+	By definition	By definition	
Monetary Cost of Auto Use	Total "costs" of Auto Use	+	Strong	Strong	"Costs" is kept in quotations here as a reminder that this term should be interpreted very broadly—to mean any of the primary factors that might deter people from using an automobile.
Traffic Volumes	Traffic Congestion	+	Very Strong	Very High	Highly non-linear relationship.
Traffic Volumes	Accidents	+	Strong	High	Highly non-linear relationship.
Accidents	Traffic Congestion	+	Very Strong	Very High	
Traffic Congestion	Average Speed	-	By definition	By definition	
Average Speed	Accidents	+	Very High	Very High	
Accidents	Perceived Risk of Accidents	+	High	Very High	This relationship establishes a distinction between actual accidents and perceived risk.
Perceived Risk of Accidents	Stress	+	Moderate	High	
Stress	Total "costs" of Auto Use	+	Moderate	High	

Average Speed	Time Cost of Auto Use	-	By definition	By definition	
Time Cost of Auto Use	Total "costs" of Auto Use	+	Strong	Strong	
Attention Needed for Driving	Activities Possible While in Car	-	Strong	Very High	
Activities Possible while in Car	Utility of Time Spent in Car	+	Strong	High	Another potentially important variable not addressed here is the expected improvement in mobile computing and communications technologies, which could play a very strong role in increasing the utility of time spent in a car, especially once the need for an attentive driver is removed.
Attention Needed for Driving	Exhaustion	+	Moderate	Moderate	Stress could also be considered a cause of exhaustion, but for simplicity, I only consider the requirement of attention to be a factor.
Exhaustion	Total "costs" of Auto Use	+	Moderate	Moderate	
Driving License Restrictions	Potential Automobile Users	-	Strong	Very High	

To explore the interaction of the relationships in Table 4.1, these relationships have been translated into causal links and assembled into a causal loop diagram (CLD), Figure 4.1. As explained in Section 3.2, this is done by drawing causal links (arrows) from each independent variable to its associated dependent variable, based on the information in table 4.1. <u>*Total "costs" of automobile use*</u> and <u>*potential automobile users*</u> will play a major role in determining vehicle miles traveled (VMT), because <u>*Potential automobile users*</u> represents the population that is capable of using a car, and within that pool, the <u>*Total "costs" of automobile use*</u> will determine how many people buy cars, how often they drive them, and the length of the trips they take. At this point, the model is primarily linear, with only one true feedback effect identified, the balancing loop "self-regulation of speed," which shows that: as road speeds increase, accidents increase, which increases congestion, which reduces road speeds.

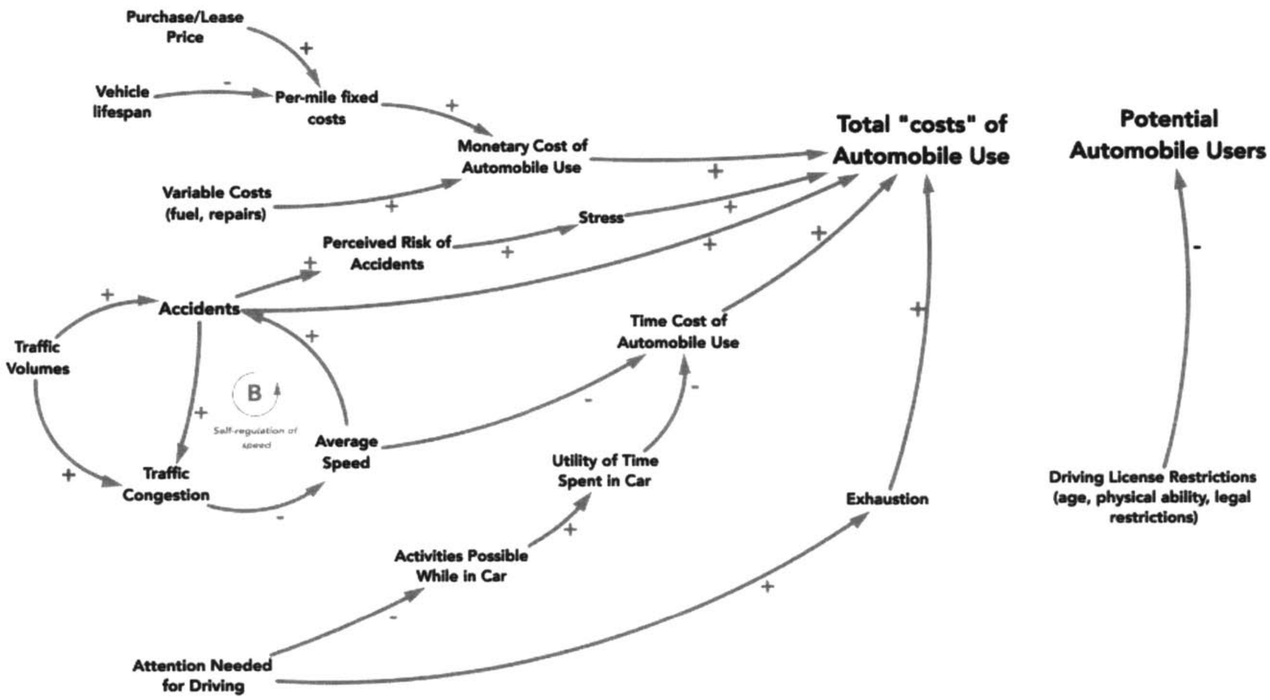


Figure 4.1. Key causal relationships that might be affected by the introduction of AVs.

4.2.2 *Effects of Automated Driving on Costs & Potential Drivers*

The table below shows some of the main potential direct effects of automated driving. (Note that *Automated Driving Capability* is a binary variable: for the purposes of this analysis, it represents full-automation (level-4), so either the capability exists, or it doesn't).

Table 4.2. Potential new causal relationships introduced by AVs

Causal Link		+/-	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Automated Driving Capability	Purchase/ Lease Price	+	Moderate	Assumed	In this scenario, it is assumed that AVs will cost more than CVs, but the difference is small enough not to deter the majority of potential adopters.
Automated Driving Capability	Perceived Risk	-	Weak	Low	This represents the potential perception that it's safer in an AV. It's shown as separate from the indirect effect from an actual reduction in accidents because some users may simply *believe* they are safer, without specific reference to actual accident data.
Automated	Attention	-	Very Strong	Assumed	Based on assumption #4, no human

Driving Capability	Needed for Driving				attention is required to operate the vehicle.
Automated Driving Capability	Driving License Restrictions	-	Very Strong	Very High	Physical competency and minimum age requirements will decrease or vanish entirely for AV users. Some might argue that regulators are likely to require a competent licensed driver to be present in every AV, but this requirement is presumably based on distrust of the technology. With assumption #4, it is also assumed that the successful performance of AV technology is recognized and accepted by key stakeholders, so there would be little reason to expect this restriction to remain in place.
% of fleet with AV capability	Accidents	-	Strong	Strong	Based on assumption #4, AV technology would enable safer vehicle operation. Estimates exist in the literature to show what % is needed to have a significant effect on safety.
% of fleet with AV capability	Traffic Congestion	-	Strong	Strong	Based on assumption #4, AV technology would enable more efficient movement of vehicles (this could also include system-optimal routing decisions to seek a system-wide optimal flow). Estimates exist in the literature to show what % is needed to have a significant effect on traffic.

As in section 4.3.1, the causal relationships identified have been assembled into a CLD, shown below in Figure 4.2.

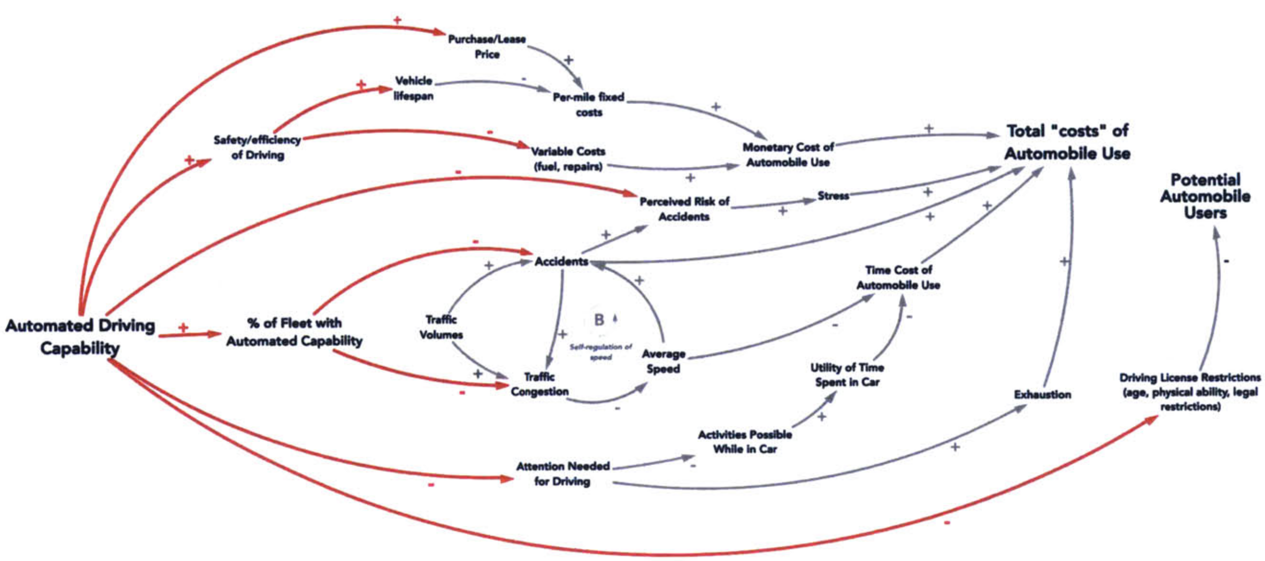


Figure 4.2. The initial effect of AVs on the *factors shown in Figure 4.1. (Red arrows indicate new relationships added in this section.)*

Tracing the effects throughout the model, a number of benefits become apparent. Some of these benefits are directly experienced by the user of the AV, such as:

- The reduction in *attention needed for driving* will reduce *exhaustion* and increase activities that can be undertaken while using the vehicle (*activities possible while in car*), which in turn will increase the *utility of time spent in the car*.
- If users trust in the improved safety performance of AVs, then they will immediately benefit through a reduction in the *perceived risk of accidents*, which should reduce the *stress* involved in traveling by automobile.
- The improved *safety and efficiency of driving* by AVs will increase the lifespan of an automobile (*vehicle lifespan*) and reduce the *variable costs*, thereby reducing the overall *monetary cost of automobile use*.
- The ability of AVs to operate without a competent human driver will reduce or eliminate restrictions on who can use an automobile (*driving license restrictions*), thereby providing access to millions of people who are disabled, too young, or too old to drive.

Other benefits will only begin to accrue as the stock of AVs in operation increases. For example:

- As more AVs are put in use and *% of the fleet with automated capability* increases, the overall efficiency of the flow of traffic will improve, thereby reducing congestion.
- Similarly, as more AVs are put in use and the *% of the fleet with automated capability* increases, *accidents* will decrease, due to improvements in overall safety of vehicle operation. This reduction in accidents will not only reduce *perceived risk*, but also reduce *congestion*. All of these effects reduce the *total "costs" of automobile use*.

From this diagram, it appears that the initial direct effects of AVs are overwhelmingly positive for the individual driver. The time-cost of driving, along with exhaustion, stress, and accidents, would be reduced. The monetary cost of driving would be increased by the higher purchase price of AVs, but this may be offset by savings resulting from safer, more efficient vehicle operation (including potential reduction or elimination of liability insurance costs for the vehicle user). The driving experience will be safer and congestion will be reduced, not only for AV users, but also for all travelers on the roads where AVs are present (due to better individual vehicle performance as well as system-optimal traffic routing to minimize congestion). Furthermore, mobility will be dramatically improved for disabled people who currently cannot drive, or people who are too young or too old to drive. This improved mobility will also have general societal benefits and will reduce the need for para-transit, which is often one of the most costly aspects of a transit agency's operations. The benefits identified here include a large part of the value proposition for AVs that is currently being promoted by advocates of the technology.

4.3. Potential System Effects

Table 4.3, below, lists additional causal links, showing how these changes in the system could affect VMT. A key effect ***of*** VMT ***on*** the system is also included.

Table 4.3 Effects on/from Vehicle Miles Traveled (VMT)					
Causal Link		**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
Total Costs of Automobile Use	Vehicle Miles Traveled (VMT)	-	Strong	Assumed	As the costs of automobile use fall, there will be more trips (and longer trips) where the benefits of the trip outweigh its costs. This relationship is limited by the overall "benefits of mobility," and the growth in VMT represents the conversion of latent demand to actual demand.
Cost of Alternate Modes	Advantage of Automobile Use	+	Very Strong	By definition	Here, *advantage of automobile use* is defined as difference between the costs of alternate modes and the costs of automobile use. This is included to reflect the fact that if the cost of alternate travel modes rises, there will be upward pressure on VMT. Note that *cost of alternate modes* is treated as exogenous here, when in reality, these costs are related to the costs of automobile use. For example, if a large number of people switch from using public transit to driving cars, this will increase the "costs" of public transit (i.e., if transit agencies have to cut back on service, creating longer wait-times). However, these effects are outside of the short-term scope of this analysis, which is concerned with the immediate system reaction.
Total Costs of Automobile Use	Advantage of Automobile Use	-	Very Strong	By definition	As above, this is based on the definition of *advantage of automobile use.*
Advantage of Automobile Use	VMT	+	Strong	Strong	As driving becomes more attractive than other options (its "advantage" increases), people will opt to drive instead of use transit or non-motorized modes. This relationship is limited by the overall *benefits of mobility,* and the growth in VMT represents the conversion of latent demand to actual demand.
Potential Automobile Users	VMT	+	Very Strong	Very Strong	Increasing the number of people who can use automobiles will apply upward pressure on demand for their use.

Benefits of Mobility	VMT	+	Strong	Very Strong	*Benefits of Mobility* is based on the benefits a person in one location gains by having access to other locations. This is "latent demand" plus actual demand. This wording is intended to capture the potentially limitless nature of total desired travel (if there were truly zero cost for travel).
VMT	Traffic Volumes	+	Very Strong	Very Strong	The variable, *Traffic Volumes* is highly aggregated. While there will be substantial variation in traffic volumes across different locations and times, the overall relationship is very strong.

4.3.1. Feedback Loops Affecting VMT

Figure 4.3, below, builds off Figure 4.2, adding the effects of system behavior on *VMT*, as well as an effect of VMT **on** the system.

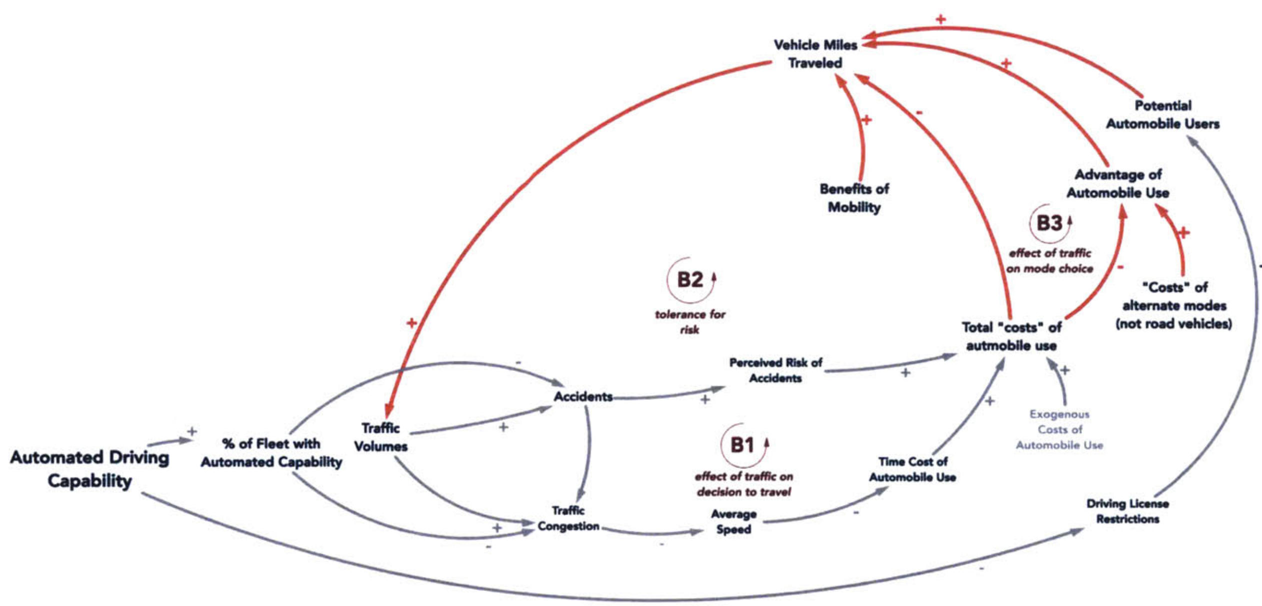


Figure 4.3. Basic System Feedbacks. *(Red arrows indicate new relationships added in this section.)*

Figure 4.3 introduces balancing feedback loops into the model.

- **B1 ("effect of traffic on decision to travel") can be read as follows:** if AVs are introduced into a congested system, we can expect *traffic congestion* to decrease, which will increase *average speeds*, and reduce *the time cost of automobile use*, thereby reducing the *total "costs" of automobile use*, which will increase *VMT*. The increase in *VMT* will cause an increase in *Traffic Volumes*, thereby increasing *traffic congestion*, and at least partially counteracting the initial effect of introducing AVs. This expresses the underlying logic of a decision to travel or not to travel: *if there is too much traffic congestion, the benefit of reaching the destination may not be worth all the costs of driving (of which traffic congestion is just one component).*

- **B2 ("tolerance for risk") follows a similar structure:** if AVs are introduced into the system, we can expect accidents to decrease, which will reduce *perceived risk*, thereby reducing the *total "costs" of automobile use*, which will increase *VMT*. The increase in *VMT* will cause an increase in *Traffic Volumes*, thereby increasing *the number of accidents*, and at least partially counteracting the initial effect of introducing AVs.
- **B3 ("effect of traffic on mode choice") follows most of the logic of B1:** if AVs are introduced into a congested system, we can expect a reduction in *traffic congestion*, resulting in a reduction in *total "costs" of automobile use*. This will increase the advantage of automobile use relative to other modes of travel, which will increase *VMT*. The increase in *VMT* will cause an increase in *Traffic Volumes*, thereby increasing *traffic congestion*, and counteracting the initial effect of introducing AVs. This expresses the underlying logic of mode-choice: *if there is too much traffic congestion, using other modes (e.g. train, subway, bicycle, etc.) may be more appealing.* Note that I have specifically excluded buses from "alternate modes," because the traffic affects buses as well as cars.

In the manner of these three balancing loops, the system resists the initial changes resulting from the introduction of AVs. Loops B1 and B3 represent well-observed behavior of transportation systems, where improvements in traffic congestion are notoriously difficult to achieve. A lot of effort can be expended on reducing congestion through external improvements (e.g., increasing capacity), but very often much—if not all—of the resulting benefits are consumed by additional VMT. The increase in VMT is often referred to as "induced demand," and this can be expected to arise as long as the benefits of mobility outweigh the costs. In this case, the relevant external improvement to the system is the introduction of AVs, which reduces congestion by effectively increasing road capacity (more AVs can use less space on the road, by driving more efficiently, following more closely, choosing system-optimal routes, etc.).

4.3.2. Discussion of Equilibrium States

The behavior resulting from balancing loops is often referred to as "goal-seeking," meaning that these dynamics cause the system to "seek balance, equilibrium, and stasis" and they "act to bring the state of the system in line with a goal or desired state. They counteract any disturbances that move the state of the system away from the goal" (Sterman 2000, p. 111). In this case, the "desired state" is not a consciously expressed goal or desired end-state ("Sometimes the goal is implicit and … not under the control of human agency at all" (Sterman 2000, p. 112)), but is the natural equilibrium state resulting from the structure of the system. The equilibrium state is determined by the relationship among the variables in the loop ***and*** by the influence of variables exogenous to that particular feedback loop. In this case, the equilibrium state of these three balancing loops can be thought of as follows:

- B1: Equilibrium occurs when the *total costs of automobile use* equal the *benefits of mobility*—where the total cost of each incremental mile of VMT is equal to its incremental benefit. A more descriptive narrative of this behavior would be: *more and more people choose to travel by car until the roads reach a point of congestion where no additional trips are generated, because people decide not to travel.*

- B2: Equilibrium here is similar to B1, when *total costs of automobile use* equal the *benefits of mobility*. A more descriptive narrative of this behavior would be: *more and more people choose to travel by car until there are so many cars on the roads that the* perceived risk of accidents *is high enough to deter additional trips.*
- B3: Equilibrium occurs when the *advantage of automobile use* is zero—when the *total "costs" of automobile use* is equal to the *total costs of alternate modes*. A more descriptive narrative of this behavior would be: *more and more people choose to travel by car until the roads reach a point of congestion where it's more appealing to use a different mode of travel instead of a car, and an additional incremental trip would be made using a different mode.*

Ultimately, the resulting equilibrium state of the system will be determined by all of these loops, interacting simultaneously. Changing the structure of the system by adding automated driving will alter these dynamics in ways that will shift the equilibrium point. Since the focal issue of this thesis is how AVs will affect VMT, the key question about the equilibrium state is: what will be the affect on the equilibrium state of VMT? To get a sense of the impact of introducing AVs, we can consider the variables exogenous to the balancing loops that are affected by introducing the variable, *Automated Driving Capability*. These are: *% of fleet with automated driving capability* and *potential automobile users*. There are also additional exogenous variables that help determine the final equilibrium state, but which are not affected directly by the introduction of AVs. In the very simplified version shown in figure 4.3, these variables are: *Benefits of mobility*, *Exogenous Costs of Automobile use*, and *"Costs" of Alternate Modes*. With the introduction of AVs, we can trace the following effects on the equilibrium state:

- As *automated driving capability* is introduced, the pool of *potential automobile users* will increase. As the figure 4.3 shows, VMT is a function of the pool of *potential automobile users*, the *benefits of mobility*, *total costs of automobile use*, and the *advantage of automobile use*:

  VMT = ***f*** (*Potential Automobile Users*, *Benefits of Mobility*, *Total Costs of Automobile Use*, *Advantage of Automobile Use*)

  Therefore, when *potential automobile users* increases, VMT will increase and settle at a higher equilibrium state. This analysis doesn't indicate ***how much*** VMT will increase; it only suggests that it will be higher, because with more auto users in the system, there will be more upward pressure on VMT in order to maintain the same level of mobility per person, and VMT will rise until the total costs of automobile use rise enough to counteract the effect of the increase in potential automobile users. This makes intuitive sense, and it's important to recognize that the "benefits of mobility" have a highly non-linear influence on the system: the benefit of being able to travel 1000 miles instead of 0 are surely far greater than the incremental benefits of being able to travel 10,000 miles instead of 9,000. People are more likely to tolerate much more traffic to get to work than they are to go for a casual trip with low benefits. Therefore, as more people are able to use automobiles, VMT will have to rise in order to meet the critical needs of those users (the "non-discretionary" trips). With more car users in the system (and therefore more "critical needs" to be met by VMT), users will tolerate higher levels of congestion before they decide not to travel by car.

- With an initial increase in the *% of fleet with automated capability*, the effect will be that the same traffic volumes will produce fewer accidents and less congestion. This will lower the total costs of automobile use, allowing VMT to rise before reaching the same deterrent level of congestion and accidents. Again, it will rise to a higher equilibrium state, which will be reached either when traffic volumes rise enough to increase the *total costs of automobile use* enough to restore the net value of additional auto use to zero, or when traffic volumes rise enough to restore the value of *advantage of automobile use* to zero.

4.3.2A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

Figure 4.3 raises a number of issues and questions, which will need to be better understood to truly comprehend the implications of the system structure in Table 4.3. That is very much in line with my intent for the CLDs in this thesis—they are intended not to answer questions but to help identify uncertain factors and better understand how they might affect overall system behavior. Based on the structure of the CLD in figure 4.3, the questions that appear to be most relevant to VMT are as follows:

1. How much of a direct impact will automated driving have on the efficiency of the flow of vehicles? And, based on this, how many more vehicles can the roads accommodate at the same level of congestion?
2. How much safer will *all* automobile users feel due to the presence of AVs on the roads?
3. How much will the perception of increased safety of traveling by car increase travelers' tolerance for traffic congestion? And vice-versa: How much will reductions in congestion increase travelers' tolerance for risk? These questions ask about the interaction of loops B1 and B2.
4. How many more people will be able to use a car, due to the elimination of driver's licensing requirements? And how much upward pressure will these new users add to VMT? To understand how much VMT will increase, it will be essential to know the relative strengths of the effects of the other causal links leading to VMT. If the relative effect of *potential automobile users* is much greater than the effects of the endogenous variables that serve to dampen or limit VMT, then the increase in *potential automobile users* will have a large effect on the final equilibrium value of VMT.
5. What are the benefits of mobility in the region, and how will they affect the equilibrium value of VMT? The answer will depend primarily on the location under consideration, and the answer can fall anywhere along a wide spectrum: from places where a high levels of mobility are essential because important destinations are widely dispersed, to places where only a small amount of mobility is required and the needs of most people can be met in their immediate vicinity. The *benefits of mobility* can be understood as a unique profile for each location, where different incremental levels of mobility have different incremental

benefits. An understanding of this profile will help shed light on the relationship between total costs of automobile use and VMT.

6. What are the costs of alternative travel modes in the region, and how will these compare with the costs of automobile use?

4.4 Potential Macro-System Responses

This section examines how systems external to the transportation system might react to the first years of adoption of AVs. While there are numerous stakeholders and a broad range of potential system interactions, two key examples are explored in sections 4.4.1 and 4.4.2, which consider the effect on potential individual adopters and policy responses, respectively.

4.4.1 Effect on potential individual adopters

Table 4.4 shows a list of causal relationships relevant to the decision-making process for potential adopters of AVs.

Table 4.4. Causal Relationships Affecting Potential Adopters

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Automated Driving Capability	Total "costs" of AV use	-	Strong	High	This is simplified/aggregated from previous CLDs, which showed numerous distinct causal links with a negative relationship to *Total Costs of AV Use.*
Traffic Congestion & Accidents	Total "costs" of AV use	+	Very Strong	Very Strong	This is simplified/aggregated from previous CLDs.
Total "costs" of AV use	Relative Advantage of AVs	-	Very Strong	By definition	Here, *Relative advantage of AVs* is defined as the difference in costs between AV use and CV use.
Total "costs" of CV use	Relative Advantage of AVs	+	Very Strong	By definition	Here, *Relative advantage of AVs* is defined as the difference in costs between AV use and CV use.
Relative Advantage of AVs	AV Adoption	+	Very Strong	Very Strong	There are many other factors that will determine the rate of adoption of a new technology, beyond its strict "relative advantage." For clarity and simplicity, those are not considered here.

AV Adoption	% of Fleet with Automated Capability	+	Very Strong	By definition	

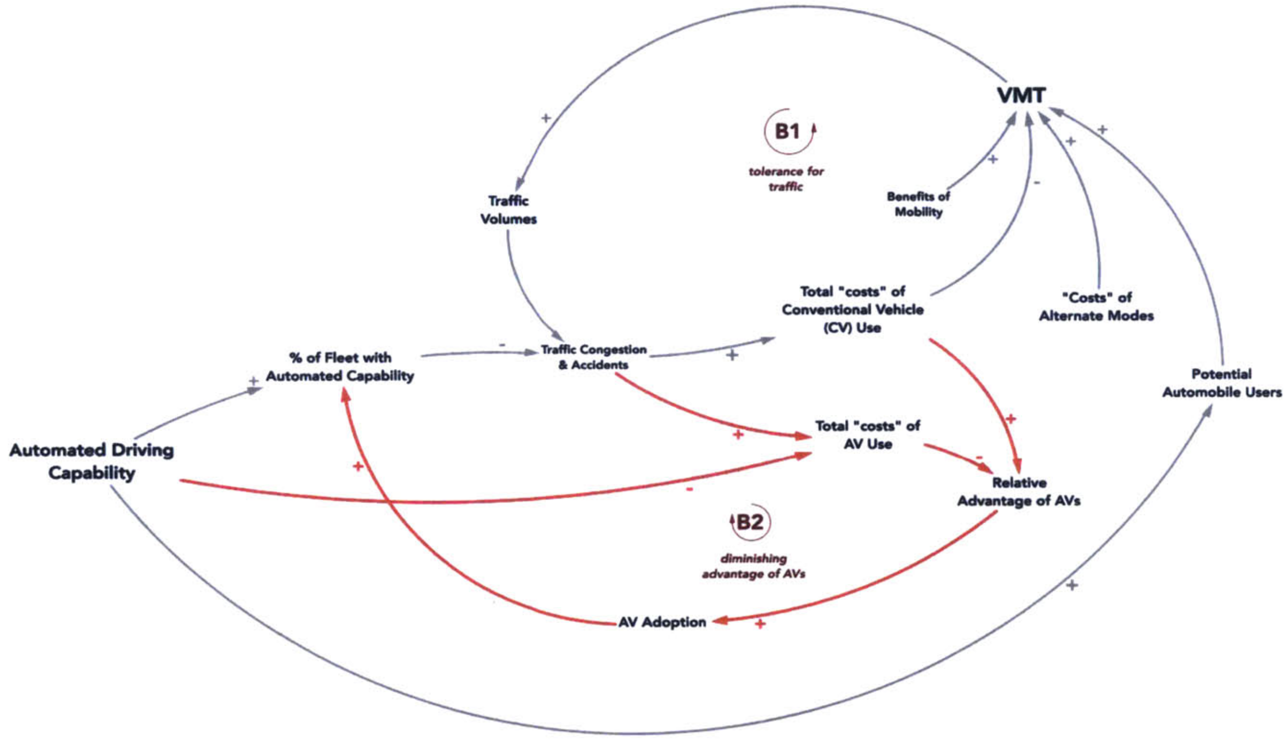


Figure 4.4. Macro-System effects on Decision-making by Potential Adopters. *(Red arrows indicate new relationships added in this section.)*

Figure 4.4 simplifies some of the relationships in Figure 4.3 and adds those from Table 4.4. It is important to note that *Total Costs of CV Use* is considered a driver of VMT, but *Total Costs of AV Use* is not. This is because Scenario 1 assumes that the behavior involved in the use of automobiles will not change due to the introduction of AVs; and, therefore, VMT will not be increased by the reduced "costs" of automobile use that one experiences in an AV. In other words, when people ride in AVs, they will not tolerate more traffic than they would in CVs, but they will be able to ride in the same traffic without suffering the full effects (they will not feel the same "cost" of that traffic as they would in a CV). Also, for clarity: all the individual benefits of AVs have been aggregated into one negative causal link from *Automated Driving Capability* to *Total Costs of AV Use*; and congestion and accidents have been aggregated into a single variable.

This CLD shows a new dynamic, the balancing loop B2, "diminishing returns of AVs," which can be read as follows: As more people adopt AVs, the *% of fleet with automated capability* will increase, which will reduce *traffic congestion and accidents*, which will reduce both the *total costs of CV use* and the *total costs of AV use*. However, because the cost incurred by traffic delays on CV drivers are greater than the costs incurred on AV users, a reduction in the system-wide effects of traffic reduces the relative advantage of AVs. In plain language, this means: *As more people use AVs, the streets will be less congested, which reduces one of the main reasons many people would pay more to own an AV (which is to increase the value of time spent in traffic).*

4.4.1A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

Figure 4.4 ("Effect on potential individual adopters") only adds one additional dynamic to the model, which is the balancing loop "B2: Diminishing advantage of AVs." Related questions and issues include:

1) How strong will the effect of B2 be?
    a. Based on analysis in prior sections, it appears that the introduction of AVs will ultimately reduce the equilibrium level of Traffic Congestion and Accidents. While the direct benefits of AV technology will be partially offset by increased VMT (due to B1), the resulting equilibrium value will still be lower. The key question, then, is, How much lower?
    b. Will improvements in traffic flow diminish the relative advantage of AVs enough to limit adoption? In other words, at what level of adoption/deployment will the traffic-flow-improvement of AVs be high enough that the relative advantage of an AV will not be enough to justify the cost for new adopters? Or is there even such a point?
    c. How much of a role does *Traffic congestion* play in *Total costs of AV use* compared to its effect on *Total costs of CV use*?
    d. Since an AV's advantage in congested traffic is only one of several benefits of AV use, it seems reasonable to speculate that the effect of this balancing loop will be limited: most potential AV adopters will adopt AVs for their other advantages as well. A small number may conclude that the benefits of AV ownership are only really worth the cost when traffic congestion is a major issue.
2) There is also a factor worth considering that is not reflected in the model. The points above highlight the fact that many people may adopt AVs to help themselves endure traffic more pleasantly, but there may also be a number of people who buy AVs in the hope that enough people will buy AVs for overall traffic congestion to noticeably diminish. In the latter case, if many people adopt AVs based on anticipated traffic-reduction benefits, and the full congestion-reduction benefits do not materialize (due to insufficient adoption), then this might discourage some new adopters. In layman's terms, a potential adopter might think, *"We were all promised that if we bought AVs, traffic would go away, but it hasn't, so why should I spend extra money on an AV?"* If this dynamic were to play a dominant role, the adoption of AVs would level off to a lower equilibrium level.

4.4.2 Societal Benefits and Policy Response

Table 4.5 shows some of the key causal relationships that are likely to emerge as AVs are adopted and used, focusing on factors that will affect both the overall benefits to society and the potential policy responses.

Table 4.5 Causal relationships involving societal benefits and policy					
Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	Dependent Variable				
# of AVs in Use	Daily observation of AV operation	+	Very Strong	Very Strong	This asserts that more AVs on the roads will increase the visibility of AVs and how frequently they are observed in operation.
# of AVs in Use	% of Fleet with Automated Capability	+	Very Strong	By definition	
Daily observation of AV operation	Perception of Safety & Efficiency	+	High	Strong	This asserts that as more AVs are in operation, not only will this increase their overall exposure, but their benefits will also become more readily apparent. That is, with more AVs, it may be clearer that the causes of delays and accidents are the CVs, which will stand out more from the crowd of harmoniously integrated AVs. For example, if most of the cars on a street are moving in perfect unison, evenly spaced, the one CV that is slow to react and doesn't follow in a close platoon will stand out and be very easy to identify as the source of the problem.
Daily observation of AV operation	Perception of Individual Benefits of AVs	+	Very High	Strong	As more AVs are observed in operation, more people will recognize their benefits for individual users.
Perception of Safety & Efficiency	Perception of Societal Benefits of AVs	+	High	By definition	
Traffic Accidents	Perception of Societal Benefits of AVs	-	Strong	Strong	If traffic accidents fall, with an increase in the number of AVs, perception should grow that AVs deserve the credit.
% of Fleet with Automated Capability	Overall Efficiency of Auto Fleet	+	Very Strong	Strong	More AVs in the fleet means that, in aggregate, the whole fleet's efficiency will improve.
Overall Energy Efficiency of Auto Fleet	Energy Consumption by Cars	-	Very Strong	By definition	More cars driving more efficiently means the overall fuel consumption per mile will go down.
% of Fleet with Automated	VMT	+	Moderate	Moderate	This link is a new assumption, and it follows from analysis in section 4.3. Generally, it appears likely that the overall effect of

Capability					increasing the penetration of AVs will increase VMT.
VMT	Energy Consumption by Cars	+	Very Strong	Very Strong	As cars are driven more, energy consumption will increase, all else being equal.
Energy Consumption by Cars	Perception of Societal Benefits of AVs	-	Moderate	Strong	If energy consumption falls, with an increase in the number of AVs, we might expect some growth in perception that AVs deserve the credit. If energy consumption increases with an increase in AVs, there may be some weakening of the perception of the benefits of AVs.
VMT	Other Negative Externalities of VMT	+	By definition	Very Strong	"Other Negative Externalities" include direct effects like noise pollution, air pollution, disruption/deterrence of non-motorized modes (walking and cycling), etc. In the longer term, these would also include sprawl, public health effects, the community disruption and displacement caused by road network expansion, etc.
Other Negative Externalities of VMT	Perception of Societal Benefits of AVs	-	Weak	Strong	This asserts that if VMT increases, people may connect the negative externalities to AVs, but this causality is expected to be weak, because it seems unlikely that everyone (or even a strong majority) will associate the negative externalities with AVs.
Traffic Congestion	Perception of Societal Benefits of AVs	-	Moderate	Strong	If congestion does decrease, it may be difficult for people to understand the role of AVs in accomplishing this, but it seems likely that enough people will make the connection, because it should be apparent that AVs drive more efficiently and cause less congestion on an individual basis. However, if traffic were to increase, it's very likely that people would *not* connect this causality to AVs, because it is counter-intuitive to think that a vehicle that moves more efficiently on an individual basis could cause more congestion in aggregate.
Perception of Societal Benefits of AVs	Policies & Incentives to Increase AV adoption	+	Very Weak	Strong	The link between a societal benefit and the development of policies seems fairly certain, but the actual strength of the causality is very weak. Many powerful social goods have no policies to support them.
Perception of Individual Benefits of AVs	AV adoption	+	Very High	Strong	This causality is expected to be much stronger than the link from "perception of societal benefits," based on the assumption that most people will adopt a technology for its direct benefits to themselves, not for its societal benefits.
Policies & Incentives to Increase AV	AV adoption	+	Moderate	Strong	It's reasonable to assume that most policies will have some desired effect, so the hypothesis is considered strong, but the actual strength of

adoption					the causality can vary widely, so it is considered moderate.
AV adoption	Used CVs on the Market	+	Strong	Strong	If CV owners replace their CVs with AVs before they ***need*** to get a new car, there will be an increase in the number and quality of used cars on the market. The strength of this causal relationship will depend on how many people buy an AV before they have to replace their CV (see discussion in Section 4.4.2A, below)
Used CVs on the Market	Affordability of Used CVs	+	Very Strong	Very High	Following the rules of supply and demand, prices will drop (and affordability will increase) as more used CVs are put on the market. In addition, demand for used CVs is also likely to fall—as many people will choose to "upgrade" to an AV rather than buy another used CV—further reducing used CV prices.
Affordability of Used CVs	Potential Automobile Users	+	Moderate	Very High	Many households in the US today can't afford a car, or would own more cars if they could afford them. Increasing affordability of CVs will allow more people to become automobile users.

The causal relationships in table 4.5 have been assembled into a CLD (Figure 4.5), which reveals four ***reinforcing feedbacks*** in the system. All of these reinforcing loops follow the same basic structure: (i) increased adoption of AVs leads to (ii) a growing positive effect of AVs, which leads to (iii) strengthened perception of societal benefits, which leads to (iv) stronger policies to encourage AVs (and potentially discourage CVs), and finally to (v) further adoption of AVs. These are some of the virtuous cycles that could be expected from the introduction of any highly beneficial technology. The structure of reinforcing loops often results in what are commonly referred to as "virtuous" or "vicious" cycles, where changes in variables accelerate in one direction. This holds true when other mitigating factors do not come into play; in most cases, a process will accelerate until other effects are triggered that will balance it out (see example of reinforcing loop of "chickens" and "eggs" in section 2.2). In this case, in the absence of balancing factors, these reinforcing loops can be read as follows:

- R1, R2 and R3 all follow the same structure, which is that: As AVs become a larger portion of the automotive fleet, the actual or perceived specific benefits will grow, which will grow the overall perception of societal benefits of AVs, which will lead to stronger policies and incentives for AV adoption, which will lead to more adoption, which will further increase the percentage of the automotive fleet that are AVs.
- R4: If traffic improves as the % of the fleet with automated capability increases, then the perception of societal benefits of AV will increase, which will lead to stronger policies and incentives for AV adoption, and so on. Note that loop R4 is in conflict with loop B3, discussed below.

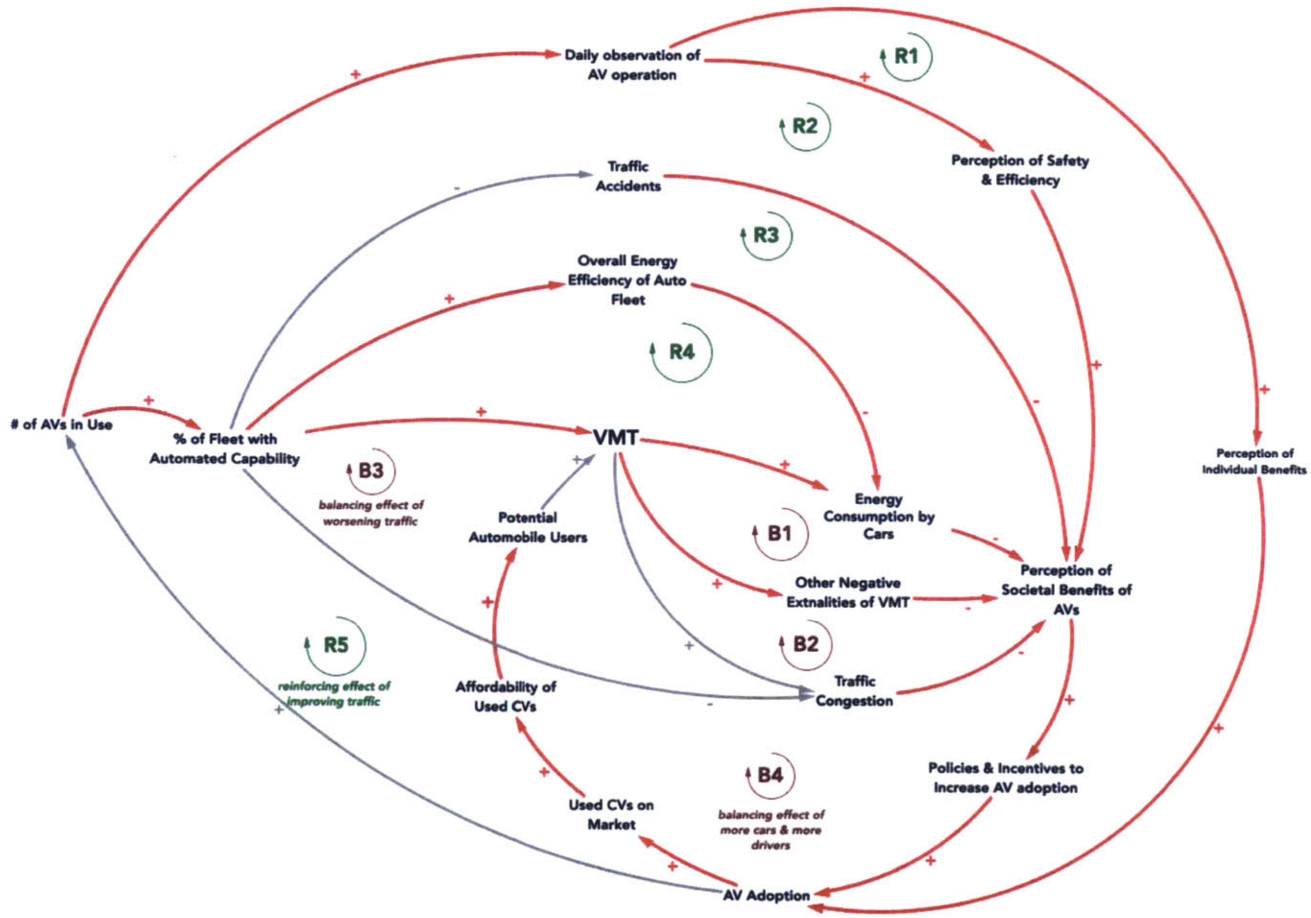


Figure 4.5. Macro-System Effects: Perception of Benefits, Policy Responses, and Adoption. *(Red arrows indicate new relationships added in this section.)*

The ***balancing feedbacks*** in the system are less direct, and therefore less expected. The relevance of these balancing feedback loops depends on the causal connection between AV adoption and VMT (the connection between *% of fleet with automated capability* and *VMT* was covered in figure 4.3 and the related discussion; the causal connection between *AV adoption*, used *CVs on the market*, and *VMT* is covered in Table 4.5). VMT is an essential link in all four of these loops. The four balancing feedback loops in Figure 4.5 are as follows:

- B1: increasing VMT increases energy consumption, which reduces the perception of societal benefits of AVs, which has a dampening effect on AV adoption.
- B2: increasing VMT increases other negative externalities of VMT, which reduces the perception of societal benefits of AVs, which has a dampening effect on AV adoption.
- B3 ("balancing effect of worsening traffic"): increasing VMT increases congestion, which reduces the perception of societal benefits of AVs, which has a dampening effect on AV adoption. As noted above, this loop is in conflict with loop R4.

- B4 ("balancing effect of more cars & drivers): if _AV adoption_ increases, the price of used cars may fall dramatically, allowing more people access to better cars, increasing VMT, then triggering the causality discussed in any of the other balancing loops above, thereby having a dampening effect on AV adoption. This effect could also be incorporated into figure 4.4, where it would counter the other dynamics by introducing more CVs, which would increase congestion, and therefore increase the advantage of AVs.

4.4.2A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

It is important to note that in **Figure 4.5 ("*Macro-System: Perception of Benefits, Policy Responses, and Adoption*")** all of the feedback effects shown depend on _perception of societal benefits of AVs_, _perception of individual benefits,_ and _policies and incentives to increase AV adoption_. One key assumption here is that there will be a policy reaction to AVs, but of course, that is far from certain, as many technologies with benefits to society lack the policy support they need to be widely adopted. In addition, the behavior of these reinforcing loops will only exhibit exponential behavior very briefly, as the number of policies and incentives that can be brought to bear is quite limited, and there will be other balancing factors, such as the resistance to additional policies or incentives, especially if they cost government money. The adoption of AVs may very well continue to grow exponentially but this will be due to other factors (which would be represented by other reinforcing loops, some of which are discussed later), and not due to endlessly improving policies and incentives—as there are practical limits to the amount that can be accomplished through policies and incentives, and these limits may be reached with a few cycles of policy-making.

Furthermore, it can be reasonably expected that significant time delays will exist in many places throughout this model; in particular, it may take some time between positive or negative effects of AVs occurring and the perception of these effects (either a reduction or increase in the _perception of societal benefits of AVs_). Other related questions and issues include:

1) Will Traffic Congestion increase or decrease? And how will this be affected by the level of adoption of AVs? Will the traffic-reducing characteristics of AVs be offset by the increase in VMT?
2) Will the increase in overall energy efficiency of the auto fleet be offset by the increase in VMT?
3) How much will people consider AVs as a "replacement" for their CV? In other words, how many people will wait until they are ready to buy a new car before buying an AV? It seems reasonable to assume that the value proposition of AVs will be strong enough that many people not consider them to be "replacements" for existing CVs—in the same way that the first automobiles were not viewed as "replacements" for horses and carriages. While some people may have waited for their horse to die or for their carriage to wear out before buying a car, it is safe to assume—from observing the rapid rate of adoption of early automobiles—that this was a rare exception in behavior. Of course, the difference between AVs and CVs may not be as extreme as the difference between a horse-and-buggy and a car. Many other scenarios might

occur with a mix of market reactions—some people will get rid of their CVs in order switch to an AV immediately, while others may only replace their current car with an AV when it reaches the end of its useful life.

4) If the negative effects of introducing AVs are substantial enough to be recognized (e.g., congestion and energy consumption noticeably increase), will key stakeholders recognize the introduction of AVs as the primary cause? It seems highly unlikely that all of them will. While some experts may trace the causality all the way back to the adoption of AVs, others may observe only the "most-proximate" cause—e.g., "congestion is going up because people are driving too much and there's not enough road capacity."

Chapter 5. Scenario #2: "AVs as a Major New Mode"

Scenario 2 expands on scenario 1, and takes a crucial step beyond much of the analysis that has been done to date. That step is to consider major potential behavioral changes from the way automobiles are used today to the way AVs might be used in the future. As in scenario 1, this scenario also assumes a positive climate for AV technology—with low costs, low energy prices, and no carbon pricing. This allows the ensuing analysis to consider how a *successful* deployment of AVs might affect the system *if user behavior were to change radically*. This scenario fundamentally challenges the notion that AVs will be used the same way as cars are today, with the only difference being that a computerized system will be doing the driving. This scenario treats the AV as far more than a 'driverless car' and aims to explore how automated driving might evolve into a whole new mode of transportation (similar to how the automobile did much more than just allow carriages to move without horses).

5.1 Summary of Assumptions

5.1.1 Underlying Assumptions

The key assumptions defining this scenario are:

(1) **Strong Behavioral Reaction to AV Technology:** Here, I assume that eliminating the requirement for a competent and qualified human driver radically alters the way people think about and use their vehicles. There are many possible ways people could change their use of cars when the presence of a driver is no longer required. This scenario assumes some impact from all plausible uses of AVs that might emerge within the timeframe of the analysis. Unlike in Scenario 1, in Scenario 2 AVs ***will*** change the nature of the forces governing behavioral choices about automobiles. For example, while automated driving may affect travel time by improving the way cars move on the roads, it is also assumed that the role of travel time may play a different role in transportation decisions than it does today, and the negative aspects of traffic may affect AV users very differently from how they affect drivers of CVs. Furthermore, it is also assumed that AVs will be used for empty-vehicle trips, and this opens up a wide range of opportunities for different uses of automobiles.

(2) **Low Cost of AV Technology:** same as in Scenario 1.

(3) **Low Energy Prices, No Carbon Pricing:** Same as in Scenario 1.

In addition, as stated in the previous chapter, all of the scenarios assume:

(4) Full technology success for AV technology
(5) Neutral policy climate for AV technology
(6) Demographic changes unfold along current trajectories
(7) Planning, Investment, and Policies Related to Transportation Infrastructure remain unchanged
(8) Socio Political Climate of Transportation remains unchanged

(9) Social Behavior and Workforce Trends unfold along current trajectories

5.1.2 Initial Deployment Assumptions

As in Scenario 1, this scenario assumes a large and enthusiastic initial wave of adoption. The "initial wave" of adoption is intended to include the early adopters who will adopt the technology before it's clear how it will function in the overall system or what the effect of widespread adoption will be (in other words, these are the ones who do not take a "wait and see" approach).

5.2 Changes in Key Forces and their direct effects on drivers and AV users.

5.2.1 Potential Direct Effects of Empty Vehicle Trips on Total Costs of Driving

The effects of these changes are similar to those outlined in section 4.2, but with several additional factors that could arise from potential behavioral changes. For example, allowing user-behavior to include empty-vehicle trips adds a number of effects to the system relating to parking. Additional relevant causal relationships are shown in Table 5.1, below.

Table 5.1 Additional Causal Relationships Involving Empty-Vehicle Trips

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Automated Driving Capability	Empty Vehicle Mobility	+	Assumed	Assumed	The scenario includes assumptions that cars will be able to operate without any occupants and that people will be willing to have them operate that way.
Empty Vehicle Mobility	Empty Vehicle Trips to/from Parking	+	Strong	Very High	This relationship will largely depend on the location under consideration. In some situations, where parking is limited or very expensive, the benefit of avoiding parking costs will be very high, so it will be almost certain that AV owners will use empty-vehicle trips to avoid those costs.
Empty Vehicle Trips to/from Parking	Cost of Parking	-	Very Strong	Very High	This asserts that as AV owners use empty vehicle trips to access parking, they will be able to access less costly (or even free) parking. Note that the variable "cost of parking" refers to the variability in costs actually incurred by car owners, not the changes in the market price of parking. The effects on market pricing of parking is a valid concern, but is not considered here.
Cost of Parking	Monetary Cost of Automobile Use	+	Moderate	By definition	The strength of this relationship also depends on location: in some areas the cost of parking can be hundreds of dollars a month, often adding up to more than the purchase (or lease) price over the life of the vehicle; in other areas,

					people may only occasionally need to pay for parking.
Empty Vehicle Trips to/from Parking	Time Spent Parking	-	Very Strong	Very High	This relationship asserts that as AV owners use empty vehicle trips to access parking, they will spend less of their own time parking and walking to/from the parking lot.
Empty Vehicle Trips to/from Parking	Time Spent Looking for Parking	-	Moderate	Very High	This relationship asserts that as AV owners use empty vehicle trips to access parking, they won't have to spend as much of their own time in the car looking for parking. This will vary significantly with location, as some areas have abundant street parking, while others may have none at all, and others still may have very limited street parking combined with very high garage prices. The amount of time spent looking for parking will vary widely among these areas.
Time Spent Parking	Time Cost of Automobile Use	+	Moderate	By definition	See comment above.

Figure 5.1, below, shows the causal links in Table 5.1 added to the CLD in Figure 4.2. This shows some of the effects of behavioral change on the system.

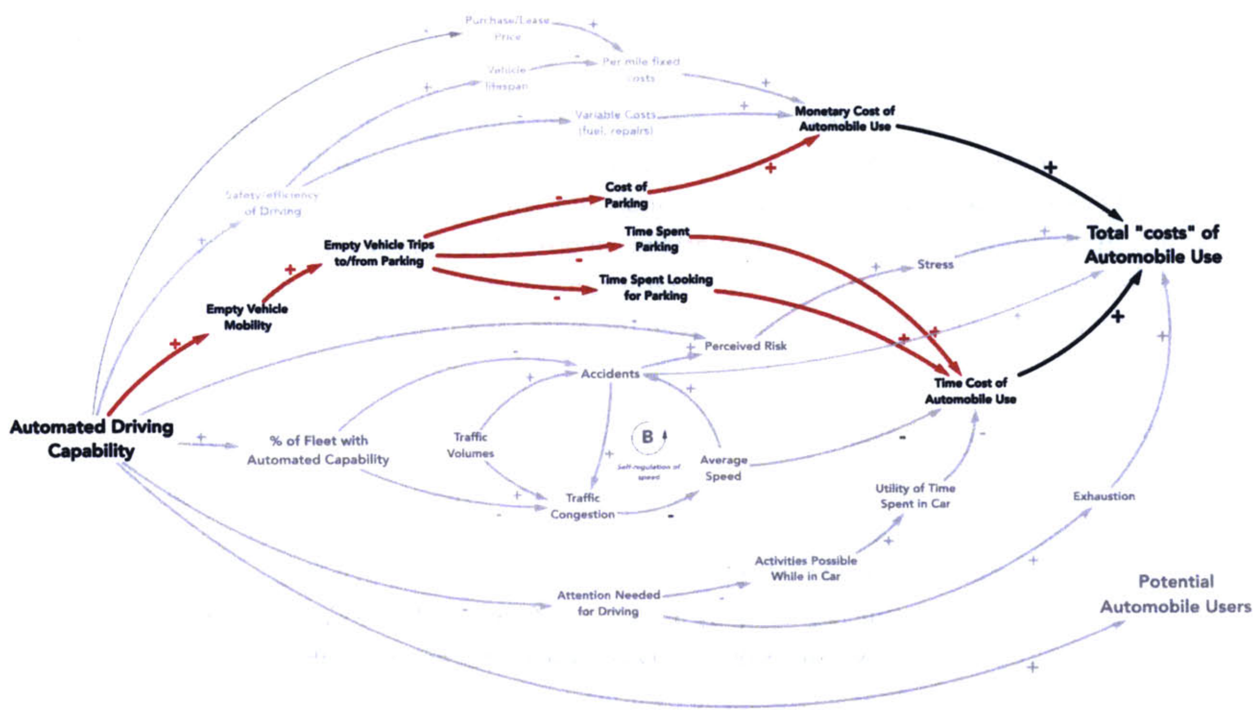


Figure 5.1. Causal Relationships Involving Empty Vehicle Trips. *This is the same as Figure 4.2, but with additional causal links showing the impact of empty vehicle trips on individual drivers. (Red arrows indicate new relationships added in this section.)*

Figure 5.2 is a simplified version of Figure 5.1, focusing on what are likely to be the four most powerful effects of automated driving: the capability of empty vehicle operation, the reduction in travel time due to more efficient driving, the quality of the user experience and the utility of his/her time while in the car, and the ability for a large number of non-drivers to attain full mobiity with automobiles.

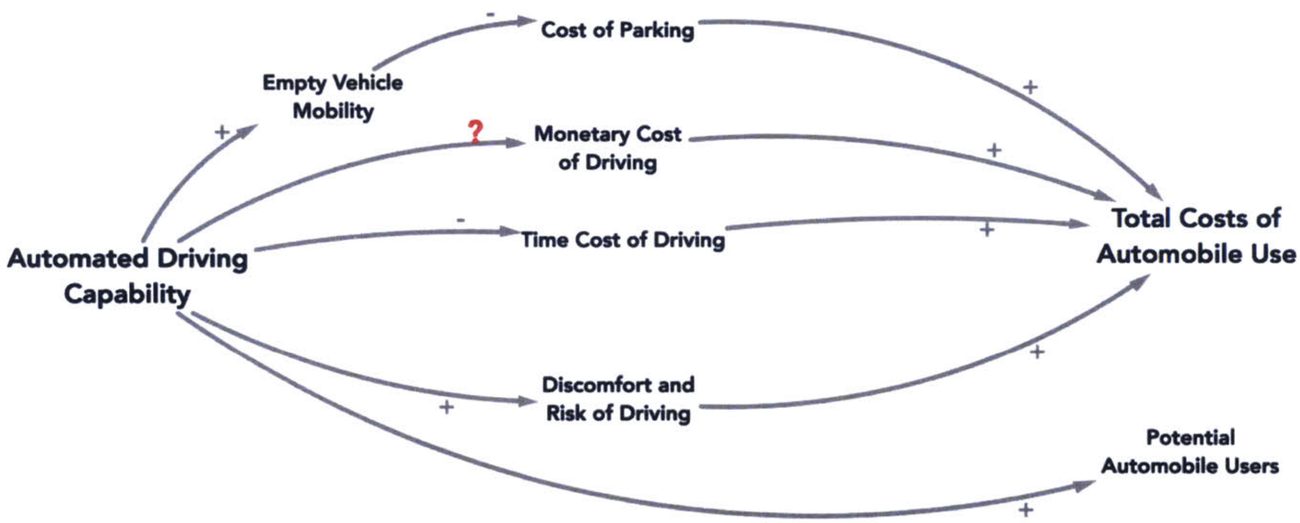


Figure 5.2. Fig 5.1 simplified. *This clarifies the assertion that AVs are likely to reduce three of the main costs/deterrents to driving: cost of parking, time cost, and the discomfort and risk of driving. It is much less certain how they will affect the monetary cost.*

In Figure 5.2, a question mark is shown on the link between *Automated Driving Capability* and *Monetary Cost of Driving*, because it is uncertain whether the savings achieved by avoiding parking costs through empty vehicle trips and through safer and more efficient driving will outweigh the extra expense incurred with the purchase of an AV. Certainly in places like downtown Boston—where street parking is unavailable for commuters and parking rates can exceed $400/month—the savings from avoiding the cost of parking might very easily exceed the extra costs of purchasing an AV.

5.2.2 Additional Potential Outcomes from the Empty-Vehicle-Operation Capability of AVs

Table 5.2, below, includes additional causal relationships involving empty vehicle use, to include new commercial applications for vehicles, additional ways to share cars within families, and use of empty car mobility to improve commercial vehicle-sharing programs. Note that improving the attractiveness/convenience of vehicle sharing by using AVs is functionally the same as reducing the cost of taxis and car services by using AVs. By using AVs, car-sharing services will be able to provide the same convenient mobility as taxis and car services; and by using AVs, taxi companies and car services will be able to provide the same convenient mobility that they do today, but at a much lower cost.

Table 5.2. Additional Relationships Involving Empty-Vehicle Operation					
Causal Link					
Independent Variable	**Dependent Variable**	**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Empty Vehicle Mobility	Empty Vehicle Trips for Vehicle Sharing Programs	+	Very Strong	Strong	For vehicle sharing programs, the advantages of empty vehicle trips could be substantial: services like Zipcar would no longer be limited to specific parking spaces; vehicles could be positioned virtually anywhere, in anticipation of demands, or they could remain in motion until called by a user.
Empty Vehicle Mobility	Empty Vehicle Trips for Family Vehicle Sharing	+	Strong	Very Strong	For families, the advantage would be that a single vehicle that could provide mobility for multiple individuals at once, almost without regard for their different destinations: after one member is dropped off at his/her destination, the vehicle could return home to run another errand, or to deliver another family member to another destination.
Empty Vehicle Mobility	Cost of Commercial Vehicle Operation	-	Very Strong	Very Strong	Without the cost of a driver, existing delivery services could potentially generate more business, with lower prices. Other applications that might see expansion in demand with lower costs could include tour buses, shuttle services, billboard trucks, and so on.
Empty Vehicle Trips for Vehicle Sharing Programs	Attractiveness / Convenience of Vehicle Sharing	+	Very Strong	Strong	Car-sharing services would also be much more convenient for the user than even private vehicles today—users could be picked up and dropped off at the doorsteps of their destination, without even needing to walk to or from a parking lot.
Attractiveness/ Convenience of Vehicle Sharing	Demand for Vehicle Ownership	-	Moderate	Strong	This asserts that overall demand for vehicle ownership will decrease as vehicle sharing becomes more convenient, because many people will be able to meet their mobility needs without owning a car.
Empty Vehicle Trips for Family Vehicle Sharing	Demand for Vehicle Ownership	-	Moderate	Strong	This asserts that families might be able to meet their needs with fewer cars overall, as one AV may be able to provide mobility for several different purposes simultaneously.

Cost of Commercial Vehicle Operation	Potential Commercial Applications for Vehicles	-	Strong	Very Strong	New delivery services may arise with new business models enabled by lower costs.

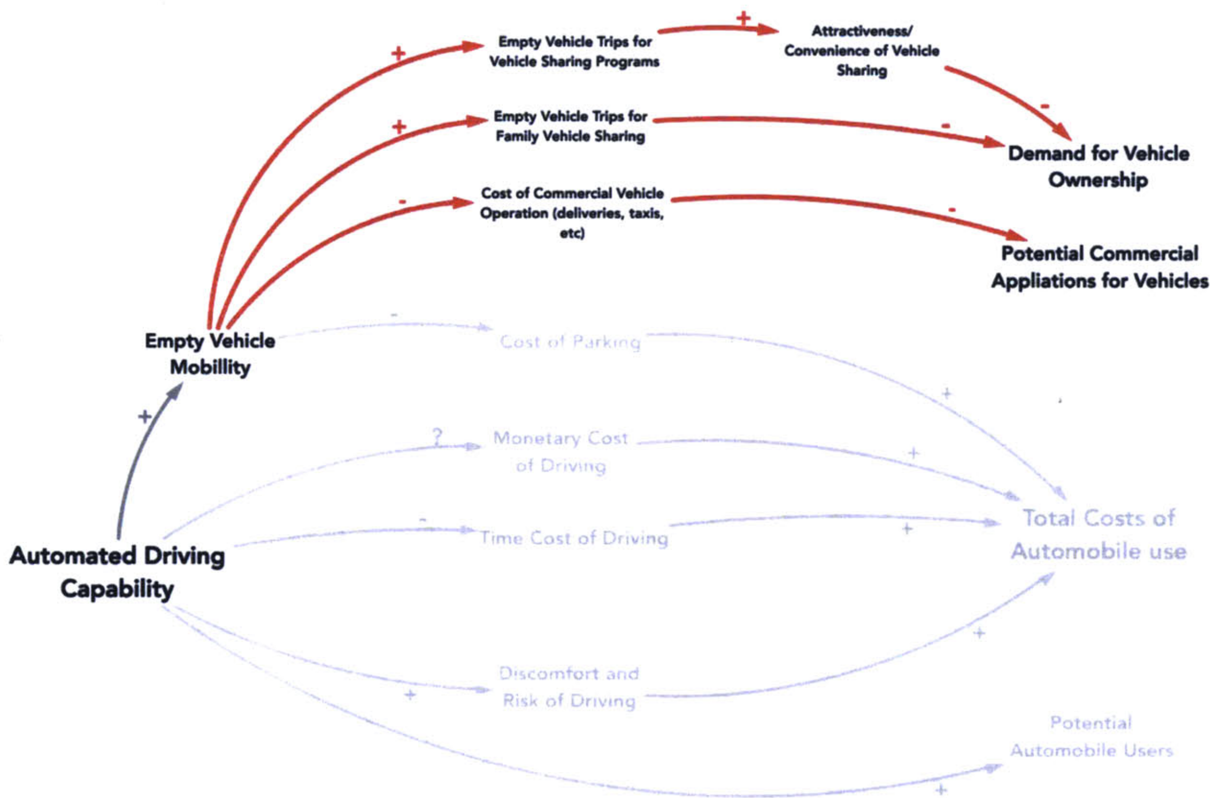


Figure 5.3. ***Additional Causal Relationships Involving Empty Vehicle Trips.*** *(Red arrows indicate new relationships added in this section.)*

5.2.3 Potential Effects on VMT

Table 5.3, below, shows how the variables identified up till this point might affect travel behavior, adding to trip length, the number of trips, and therefore ultimately to vehicle miles traveled (VMT). It includes the initial effects in the larger system, but does not account for how the system will react or respond to these changes. For simplicity, it also doesn't include the effect of additional vehicles miles required for empty vehicle trips to enable both family vehicle sharing and commercial vehicle sharing programs.

Table 5.3 Causal Relationships involving VMT					
Causal Link		**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
Empty Vehicle Trips for Parking	Average Trip Length	+	Moderate	Strong	While allowing empty-vehicle trips may not make all trips longer, the opportunity to save money on parking in urban areas seems very likely to incentivize AV users to send their cars farther away to access cheaper (or even free) parking.
Empty Vehicle Trips for Parking	"Cruising" to Find Parking	-	Moderate	Very Strong	This is expected to vary widely by location. This hypothesis should be fairly strong as most people are likely to consider "cruising for parking" to be a waste of time that could be avoided by sending the car to find its own spot.
"Cruising" to Find Parking	Average Trip Length	+	Modest	Very High	This depends very much on the location, and the overall effect on trip length may not be very strong, as most "cruising" for parking is done at lower speeds and probably doesn't cover a lot of distance.
Total "Costs" of Automobile Use	Average Trip Length	-	Very Strong	Very High	As long as there is latent demand for longer trips, as "costs" decrease, trips should get longer.
Total Costs of Automobile Use	Number of Vehicle Trips	-	Very Strong	Very High	As long as there is latent demand for additional trips, as "costs" decrease, the number of vehicle trips should increase.
Potential Commercial Applications for Vehicles	Number of Vehicle Trips	+	Strong	Very High	With more businesses operating vehicles, the number of trips should increase.
Potential Automobile Users	Number of Vehicle Trips	+	Strong	Very High	This was covered in chapter 4, but is shown here as a more-specific causal link to "number of trips" instead of just to VMT.
Benefits of Mobility	Average Trip Length	+	Very Strong	By definition	*Benefits of Mobility* is based on the benefits a person in one location gains by having access to other locations. This is "latent demand" plus actual demand. This relationship asserts that the characteristics of a given area and the relative benefits of each additional amount of mobility will play a role in determining the average trip length.

Benefits of Mobility	Number of Vehicle Trips	+	Very Strong	By definition	This relationship asserts that the characteristics of a given area and the relative benefits of each additional amount of mobility will play a role in determining the number of vehicle trips made.
Average Trip Length	VMT	+	Very Strong	By definition	
Number of Vehicle Trips	VMT	+	Very Strong	By definition	

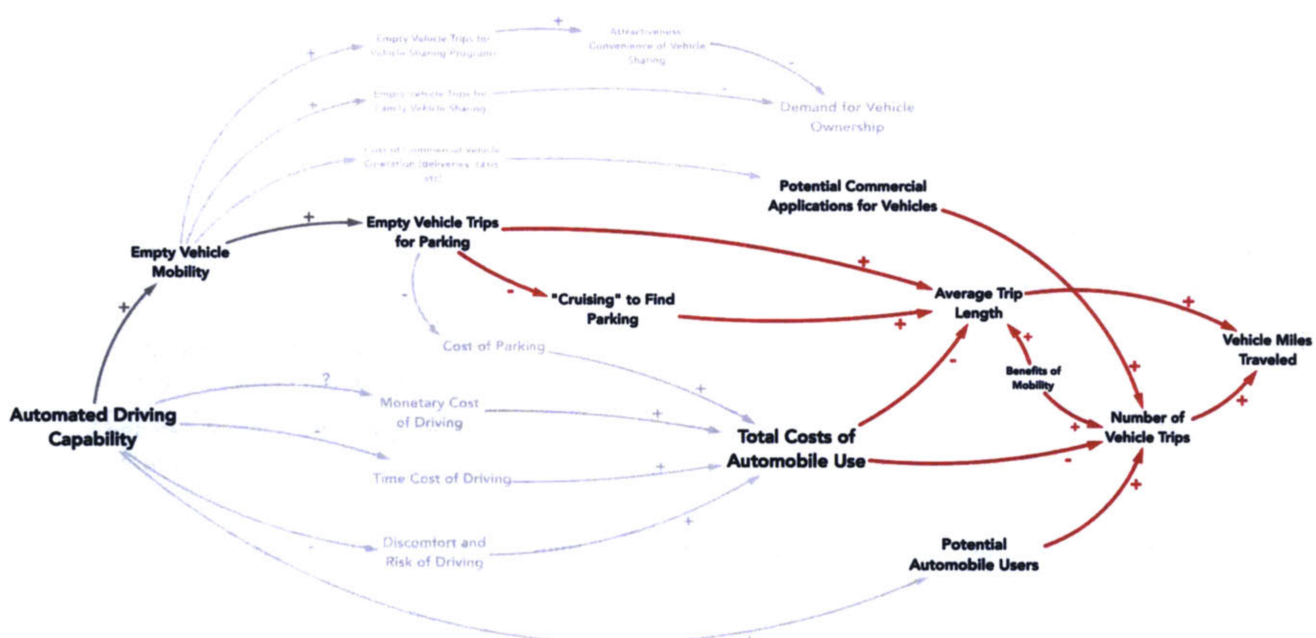


Figure 5.4. Relationships Among Empty Vehicle Trips, Travel Decisions, and VMT. *(Red arrows indicate new relationships added in this section.)*

One of the critical differences between Figures 5.4 and 4.3 is that 5.4 allows the reductions in *total costs of automobile use* directly experienced by AV users to influence *trip length* and *number of trips*. This rests on the assumption (assumption #1 in this scenario) that AV technology will significantly affect travel choice behavior.

5.2.4 COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The causal relationships used to develop the CLDs in this section involve a lot of uncertainty and so they remain essentially hypothetical. A better understanding of these dynamics will require further analysis of many of the causal relationships shown in tables 5.1, 5.2, and 5.3. Some questions also arise from the CLDs that are not apparent from the tables alone:

- Will the total monetary cost of automobile use (*Monetary Cost of Driving* plus *Cost of Parking*) increase or decrease overall by switching from a CV to an AV?
    - Will the savings from AV use (improved efficiency, fewer accidents, less wear and tear, lower cost of parking, less or no liability insurance) outweigh the higher per-mile capital cost?
- Will the reduction in VMT due to eliminating cruising for parking be outweighed by the extra driving to gain access to cheaper remote parking locations? Here, I would hypothesize that the extra driving to remote parking will increase VMT, because cars generally don't travel very far when they are cruising for parking, but one might have to drive several miles or more to gain access to cheaper (or free) parking, and many people may be tempted to just send their car back home.
- Will the reduction in congestion due to eliminating cruising for parking be outweighed by the extra congestion generated by additional VMT from vehicle trips to remote parking locations? Here, I would hypothesize that—*on a per-vehicle basis*—the added congestion from making an empty-vehicle trip to remote parking would be less than the added congestion of cruising, because cruising for parking is so often done in dense urban areas and it involves drivers moving slowly, distracted from efficient driving by their search for a parking spot. However, I would hypothesized that—*on an aggregate basis*—the effect on congestion might be higher with AVs traveling to remote parking, because many more people may engage in this practice to save money on parking.

Finally, it is also worth mentioning that none of these scenarios considers the possible effects of improvements in mobile computing and communications technologies. These could play a powerful role in increasing the utility of time spent in a car, especially once the requirement for "attention for driving" is removed. In other words, travel in an AV would be appealing now, as people could work on a laptop, relax, and even sleep, but with major improvements in mobile computing and communications technologies, the quality and quantity of work that could be done (or entertainment that could be enjoyed) may increase dramatically.

5.3 Potential System Effects

This section considers one primary system reaction, which relies on the assumption that significant behavioral changes will occur when AVs are introduced. This addresses potential changes to decision-making about whether or not to drive and how long of a trip to make. It essentially deals with the automotive decision-making process in isolation, without considering alternate modes.

5.3.1 *Effects on Decision-Making About Car Use*

Figure 5.5, below, is constructed of causal relationships discussed in prior sections, so I have not provided a table to document new hypothetical causalities. The CLD has been arranged slightly differently, with a different combination of causal relationships. Some of the causal relationships have also been aggregated or otherwise simplified.

The critical change here is that the causal relationships stemming from behavioral changes have been incorporated into the basic "tolerance of traffic" loop. In other words, the beneficial aspects of AV use are allowed here to reduce the *Total Costs* specifically for AV drivers, thereby allowing them to alter their decision-making based on the fact that they are using an AV instead of a CV. For example, in chapter 4, the improved utility of time for AV users was just considered a benefit of using an AV, but wasn't a decision-affecting factor. Here, it is. The utility of time reduces the time costs... which alters decision-making, allowing drivers to decide to take more and longer trips, based on the lower cost of automobile use. Similarly, in Chapter 4, I only considered the aggregate risk of accidents for all car users (of AVs and CVs) and how the introduction of AVs would affect safety for all. Here, I consider the fact that AV users may feel less risk than CV users, and this might prompt them to drive more (for simplicity, risk and discomfort have been combined into one variable).

The result is one loop (B1) showing the relationships that will play a role in determining VMT by AVs and another (B2) showing those that will play a role in determining VMT by CVs. Loop B2 is essentially the same as loop B2 in Figure 4.3. The expected effects on loop B1 can be read as: Introducing automated driving capability will increase the *Utility of Time Spent in a Car*, which will reduce the *Time Cost* and the *Total "Costs" of AV Use* which will encourage more and longer trips, which will result in higher *VMT by AVs*, which will lead to more *traffic congestion*, ultimately increasing the *time cost of AV use*. Similar to loop B2 in Figure 4.3, this expresses the underlying logic of a decision to travel or not to travel: *if there is too much traffic congestion, even in an AV, the benefit of reaching the destination may not be worth all the costs of driving (of which traffic congestion is just one component).* A more descriptive narrative of this behavior would be: *more and more people choose to travel by AV until there are so many AVs on the roads that the resulting traffic congestion is high enough to deter additional trips.* The critical difference between loop B1 and loop B2 (and the loop in Figure 4.4) is that the equilibrium state defined by B1 should be substantially higher. That is because the increase in the utility of time spend in the car and the reductions in the discomfort and risk of automobile use will mean that higher levels of congestion can be tolerated without increasing Total "Costs" of AV use. Therefore, if *Total Costs of AV use* will rise to the same level (which depends on *Total Benefits of Mobility*, a variable that has not been shown, for simplicity), *then Average AV Trip Length*, *Number of AV Trips*, *VMT by AVs* and *Traffic Congestion* will all arrive at higher equilibrium levels.

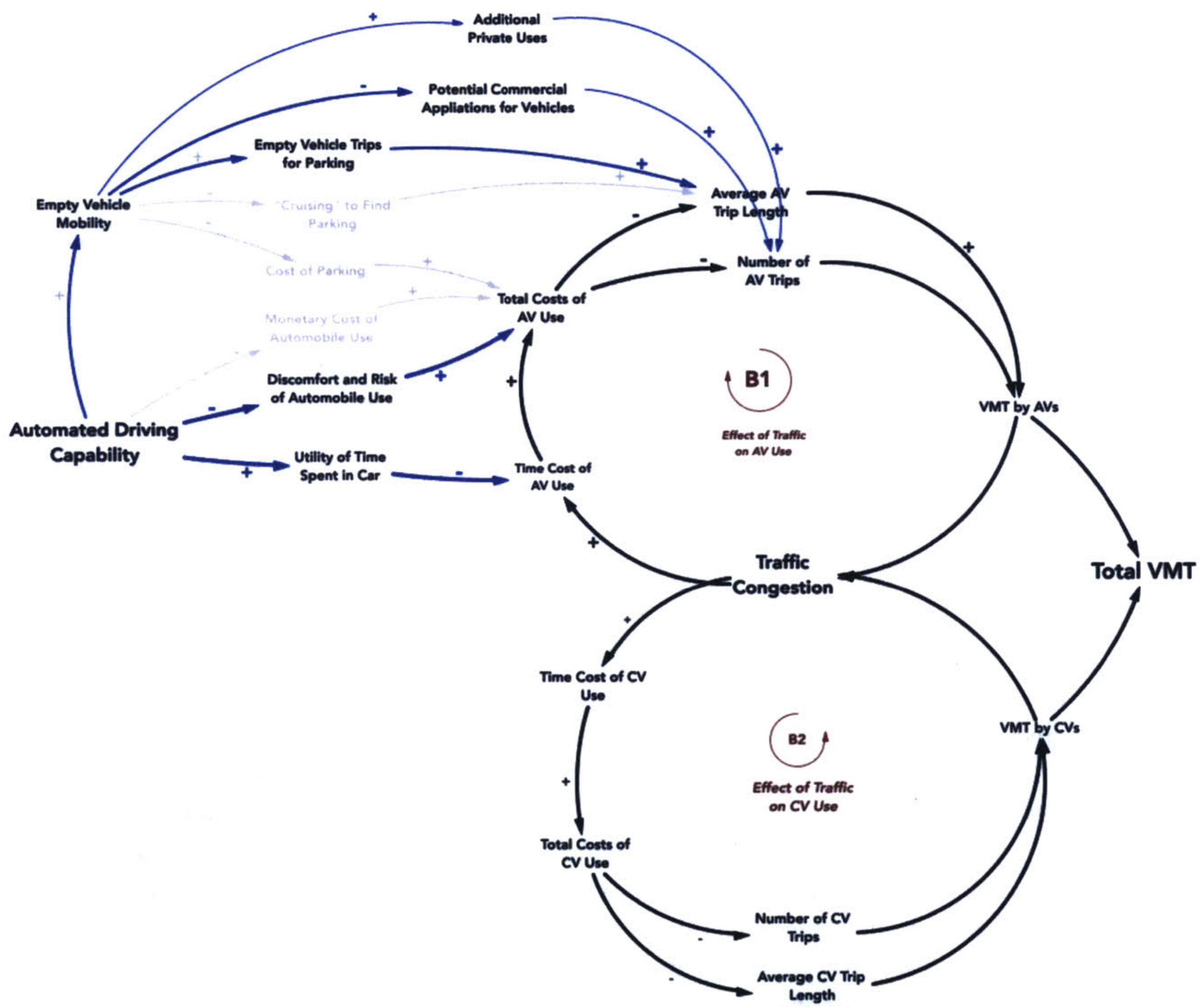


Figure 5.5. Effect of Automated Driving on Basic Traffic Dynamics (Balancing Loops of Traffic). *(Blue arrows indicate key relationships introduced by automated driving that were not incorporated in chapter 4, and are exogenous to these balancing looops.)*

5.3.1A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The key question of this section is: given the evidence in chapter 4 suggesting that overall VMT is likely to increase without considering behavioral changes, ***how much <u>more</u> will VMT increase due to the behavioral changes discussed in this chapter?*** Figure 5.5 suggests that we may gain insight into this question by considering the following points:

- The improvements provided by AV operation are exogenous to the balancing loops shown, so we can expect them to drive up the equilibrium levels.

    - How much will these improvements (in comfort, risk, and utility of time) allow traffic to increase while still maintaining the same perceived Total Costs of AV use? In everyday language, this could be: *How much more traffic am I willing to tolerate if I can get work done or sleep while I'm in the car?* Or it could be: *How much more traffic will I tolerate if my trip is much more comfortable and safe?*
- The additional uses for private vehicles that are enabled by empty-vehicle mobility are also exogenous to these balancing loops, so we can also expect these to drive up equilibrium levels.
    - How comfortable will AV owners be with sending their AVs on empty trips? Will they use them to run errands? Will they be much more likely to use them for formerly one-way trips that were previously cheaper via public transit (e.g., trips to the airport or train station)?
    - Will people use their AVs to facilitate long-distance travel? Will they be willing to send their AV full of luggage to another destination and then travel much more quickly and conveniently via airplane and have their vehicle meet them at the destination? Would this have a substantial impact on reducing car rentals?
- How strong will the deterrent effect be on CV users? If, as we expect, AV users are willing to drive more than CV users (the balancing effect of loop B1 is weaker than B2), then the total costs of CV use should rise. The structure of this system indicates exogenous benefits for AVs that will allow AV VMT to rise, but the CV loop (B2) remains the same, with no exogenous factors to allow for an increase in tolerance of traffic. This strongly suggests that with a fixed fleet size of AVs and CVs, in a congested system, AVs will be used more than CVs will. (Note that the assumptions of this scenario consider fleet size to be fixed—at this stage of the analysis, I am assessing the dynamics of the existing fleet after an initial period of adoption, not considering the changing size and composition of the fleet itself.)
- Furthermore, based on the assumptions in this scenario, it is to be expected that the effect of additional AV VMT on traffic congestion will be less than the effect of CV VMT. This suggests that even more AV VMT will grow even more before the level of congestion rises high enough to deter additional trips

These points suggest that total VMT could grow substantially, due to several interacting factors, and as it grows, the proportion of VMT that is due to AVs will grow as well.

5.4 Potential Macro-System Responses

This section examines how systems external to the transportation system might react to the first years of adoption of AVs and the transportation-system responses to AVs examined in sections 5.3: Section 5.4.1 considers the effects on travel mode-choices; Section 5.4.2 considers the effect on the perception of societal benefits of AVs; and Section 5.4.3 considers a few possible stakeholder reactions and related policy implications.

5.4.1 Effects on Mode-switching: further adoption of AVs

Table 5.5 below lists several of the causal relationships that will be affected by AVs and might play a major role in determining travel mode-choice. To simplify the model, I have considered a generic case of commuting, where there are four available modes of transportation available for completing the trip, each with varying costs. Many variables have been excluded, and the only exogenous variables I consider are the utility of travel time for each mode. Variables for "other exogenous factors" are shown in grey in the CLD that follows, just to acknowledge that additional factors exist. This model also omits other empty vehicle effects (commercial applications, family sharing, vehicle sharing programs), for simplicity. In reality, the role of avoiding vehicle parking costs is likely to play a very powerful role in commuting decisions. Currently in the Boston area, one of the most effective forces limiting traffic volumes and congestion to major work destinations (like the downtown area and Kendall Square) has been the limits on available parking, and the resulting high cost of parking. ***It is very reasonable to expect that there is significant latent demand for commuting by car to these locations, and if there were a way to avoid parking costs, commuting by car might increase dramatically.*** Furthermore, vehicle-sharing effects are not considered, because the cases examined are commuting trips, where vehicle sharing is less likely to play a major role as in other, shorter trips that aren't as unidirectional in nature.

Table 5.4

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Road Travel Time	Advantage of AV over CV	+	Strong	Strong	This asserts that as travel time increases, the relative advantage of AVs will increase, due to the higher utility of travel time in AVs.
Road Travel Time	Advantage of AV over Bus	+	Strong	Strong	This asserts that as travel time increases, the relative advantage of AVs will increase, due to the higher utility of travel time in AVs.
Road Travel Time	Advantage of AV over Subway	-	Moderate	Strong	This asserts that as road travel time increases, the relative advantage of AVs over Subways will decrease, because subway trips are unaffected by road travel times.
Utility of Travel Time in AV	Advantage of AV over Mode X	+	Very Strong	Very Strong	

Utility of Travel Time in Mode X	Advantage of AV over Mode X	-	Very Strong	Very Strong	
Advantage of AV over Mode X	Perceived Advantage of AV over Mode X	+	Very Strong	Very Strong	This relationship provides a distinction between the "advantage" and the "perceived advantage," which allows for *visibility, awareness, discussion of AVs* to play a role.
Perceived Advantage of AV over Mode X	Switching from Mode X to AV	+	Moderate	Very Strong	We can reasonably hypothesize that a perceived advantage will cause some switching, but many other factors may come into play so the strength of this relationship may be limited.
Switching from Mode X to AV	Adoption of AVs	+	Very Strong	Very Strong	At least in the early stages, before there are any used AVs on the market, every person who switches modes will be another new "adopter" of AVs.
Switching from Mode CV to AV	VMT	+	Moderate	Strong	This relationship is discussed in previous sections, and there is good reason to believe it exists, but it is uncertain how strong the relationship is.
Switching from Bus or Subway to AV	VMT	+	Very Strong	Very Strong	Buses contribute very little VMT per passenger mile and subways contribute none, so any switch away from these modes to automobiles will have a very strong impact on VMT.
Adoption of AVs	Visibility, Awareness, Discussion of AVs	+	Very Strong	Very Strong	AVs will be highly visible—in everyday traffic in full view of other drivers and pedestrians. Furthermore, if they are as distinctive as they are today, they will be very easy to recognize.
Visibility, Awareness, Discussion of AVs	Perceived Advantage of AV over Mode X	+	Strong	Strong	This relationship asserts that the overall public perception of the advantages of AVs will depend largely on their visibility, how much people are aware of them, and how frequently they are discussed (in the media, in casual conversations, etc.)

Figure 5.5 shows these relationships assembled into a CLD. Because there are several important feedback loops that arise from these relationships, I have created three additional CLDs (Figures 5.6a, 5.6b, and 5.6c), each focusing on a few specific dynamics, but those diagrams are not intended to suggest that those dynamics will function in isolation.

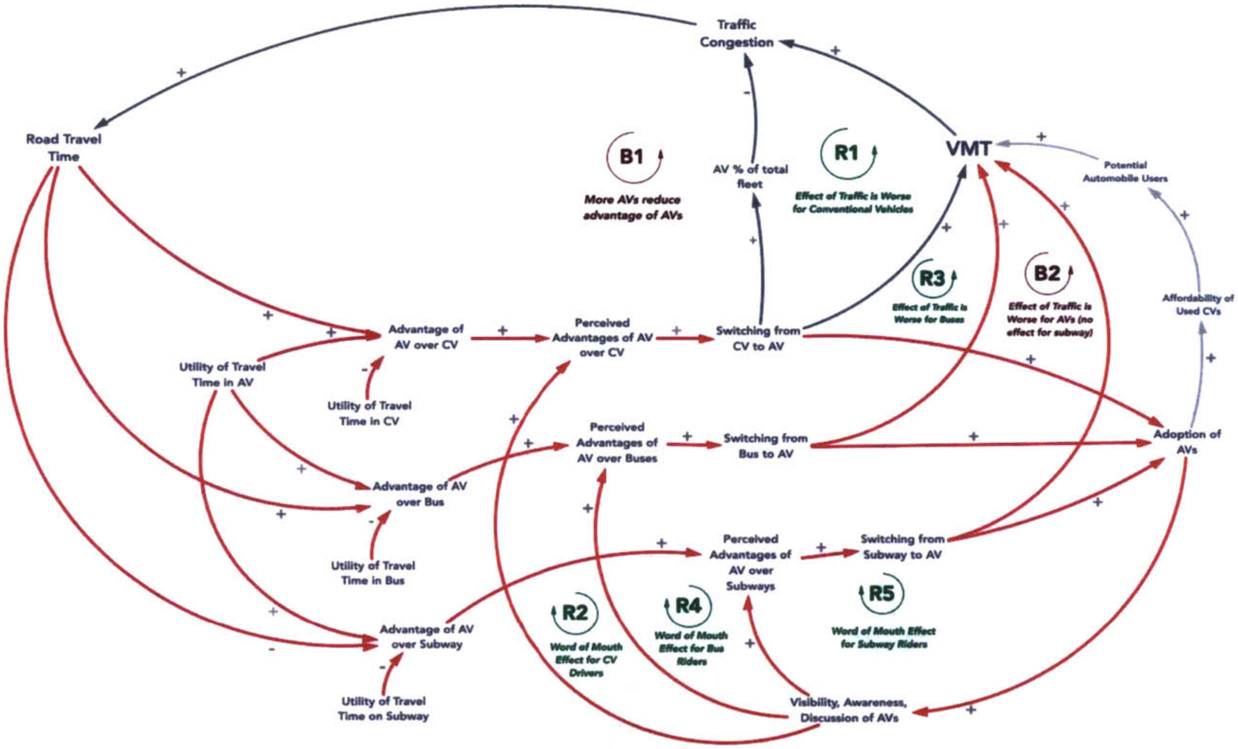


Figure 5.6. Effect of Automated Driving on the Key Dynamics Related to Travel-Mode Choice. *(Red arrows indicate new relationships added in this section.)*

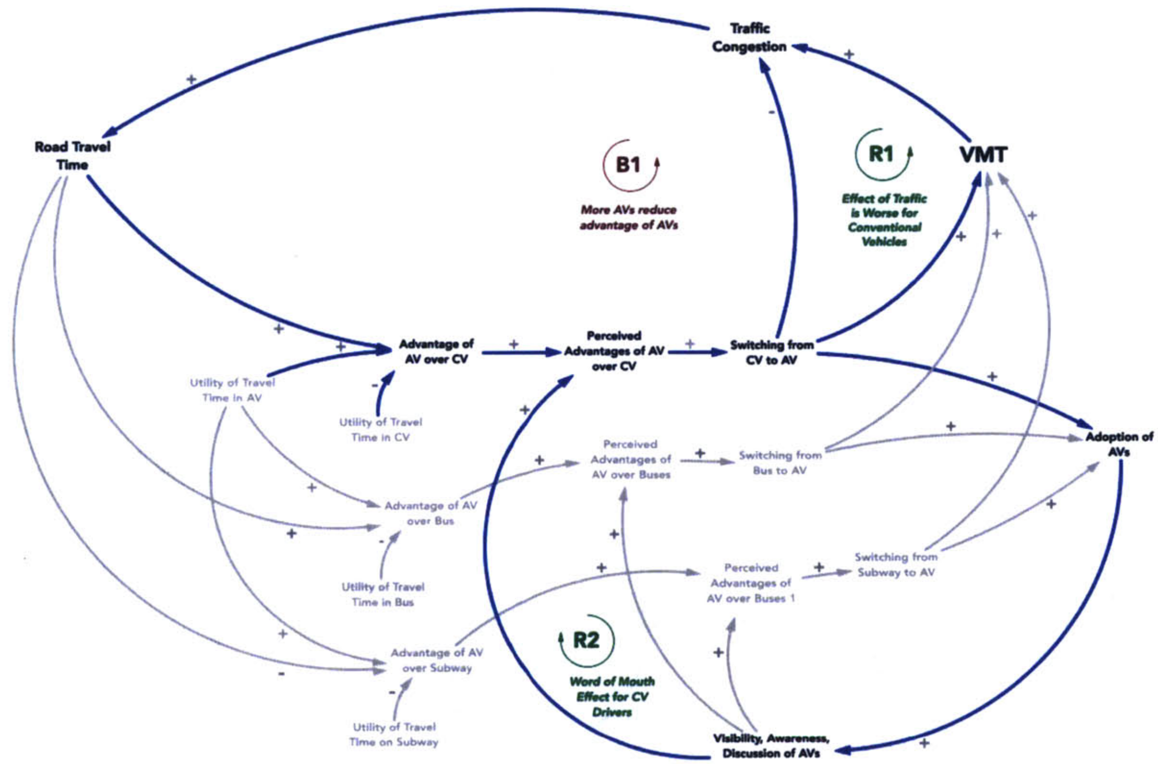


Figure 5.6a. Dynamics of Switching between CV and AV. *(Blue arrows illustrate specific feedback effects.)*

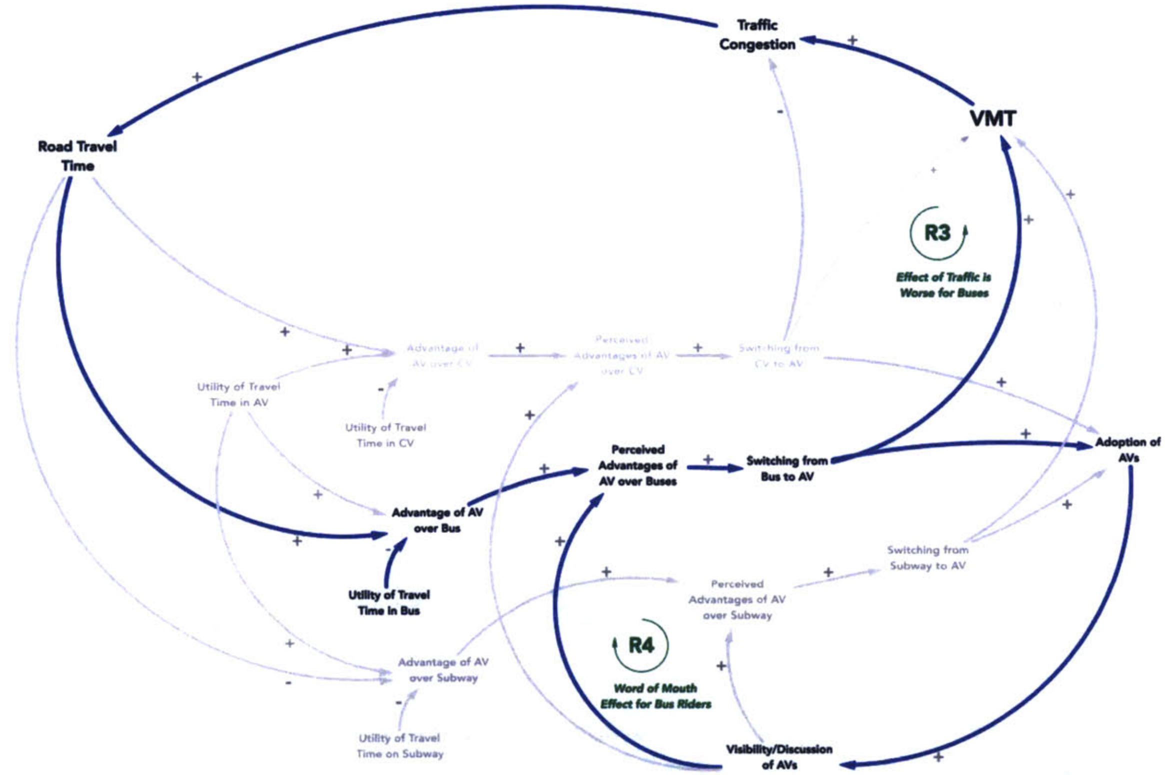


Figure 5.6b. Dynamics of Switching between bus and AV. *(Blue arrows illustrate specific feedback effects.)*

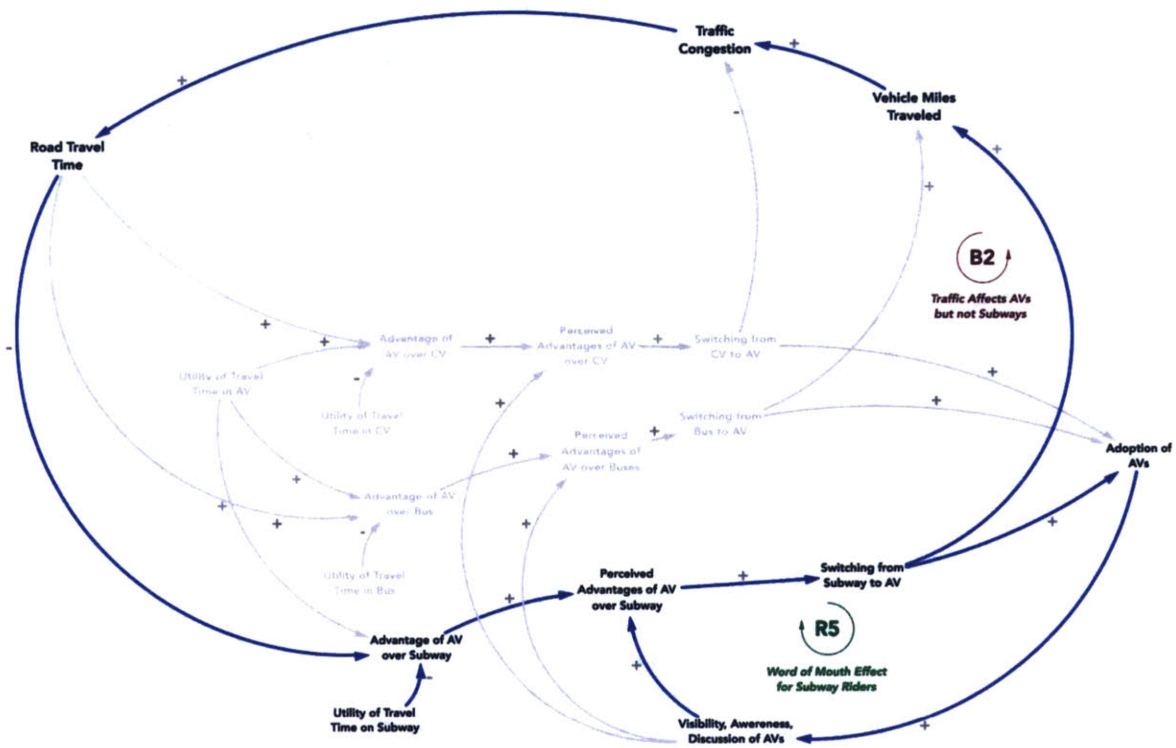


Figure 5.6c. Dynamics of Switching between Subway and AV. *(Blue arrows illustrate specific feedback effects.)*

5.4.1A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The core question addressed by Figures 5.6a-c is this: How does the reaction to AVs that takes place within the transportation system drive further changes in the encompassing "macro-system"? As stated earlier, the macro-system includes changes in adoption of new technologies, as well as changes in infrastructure, policies, and so on. These particular diagrams address the effect on travel-mode choice and its resulting impact on AV adoption.

Figure 5.6a considers the dynamics of switching between CVs and AVs, and it exhibits three feedback loops:

- **B1 ("More AVs reduce advantage of AVs"):** This can be thought of as potential "diminishing returns for AV adoption," which would arise if the net effect of switching from CV to AV were to decrease traffic congestion.
- **R1 ("Effect of Traffic is Worse for CVs")":** This can be thought of as a vicious cycle for CVs—assuming that the net effect of switching from CV to AV were to increase congestion. In this case, more AVs would lead to more VMT (through a variety of mechanisms discussed earlier in this chapter), which would lead to more congestion, which would further increase the advantage of AVs, which would further increase adoption, and so on.
- **R2 ("Word of Mouth Effect for CV Drivers"):** This can be thought of as a virtuous cycle for AV adoption, and these basic dynamics are fundamental to adoption models, capturing the reinforcing effect that occurs when an innovation's increasing visibility and growing rate of adoption reinforce each other.

A key question that emerges here (and which has emerged throughout this thesis) is: Will the net effect of switching from CVs to AVs be an increase or decrease in congestion? If it is an increase in congestion, then the reinforcing effect of loop R1 is likely to dominate over the balancing effect of loop B1. This would provide a powerful impetus for rapid growth in AV adoption, and ultimately higher levels of VMT. If congestion were to decrease, the net effect would still be an increase in VMT, but since it would not trigger the reinforcing loop R1, the increase is likely to be smaller.

Figure 5.6b considers the dynamics of switching between buses and AVs, and it exhibits two important feedback loops:

- **R1 ("Effect of Traffic is Worse for buses")":** This can be thought of as a powerful vicious cycle for buses, because the net effect of switching from commuting by bus to commuting by AV is certain to increase congestion. In this case increased congestion would further increase the advantage of AVs over buses, which would further increase switching from bus to AV, which would rive more adoption, and so on.
- **R2 ("Word of Mouth Effect for Bus Riders"):** This is the same virtuous cycle for AV adoption described above, but in this case the change is from bus riders to AV users.

In both figures 5.6a and 5.6b, the fact that the advantage of AVs increases as traffic increases rests on the notion that AVs have a distinct advantage in terms of reducing the cost of travel time by allowing freedom of activity in one's own private space. The hypothesis is that AV users will have the advantage over CV drivers that they do not need any attention for driving, so their time in the car is much more useful, while AV users will have an advantage over bus riders because they will be in their own car, with more space, more privacy, more comfort, less noise and disruption, etc.

Figure 5.6c considers the dynamics of switching between commuting by subway and by AV; it also exhibits two important feedback loops:

- **R1 ("Traffic Affects AVs but not Subways")":** This is a strong balancing loop that would tend to resist people switching from subway to AV. As more people switch, congestion will worsen, and because subway trips are not affected by traffic on the street, the advantage of riding the subway will grow, thereby reducing the incentive to use AVs for commuting.
- **R2 ("Word of Mouth Effect for Subway Riders"):** This is the same virtuous cycle for AV adoption described above, but in this case the change is from subway riding to AV use.

If commuters find the utility of time spent traveling in an AV is substantially higher than the utility of time spent traveling by subway, this is likely to cause some riders to switch to using an AV, even if the effect of traffic is to make the trip significantly longer. In many cases, this might have the adverse effect on the subway line of reducing ridership enough to cause a reduction in service frequency. However, in congested subways, like Boston's Red Line, which is already at or above capacity, a modest reduction in ridership is more likely to improve the experience of riding the subway (at least in the near term), by reducing crowding. The behavioral response of the system will result in a counteracting number of people who switch to the subway from other modes. Because this is a balancing loop, the amount of subway riders will gravitate toward an equilibrium state, but this value will be slightly lower than it was before, due to the increased attractiveness of using AVs.

Ultimately, to understand the likely outcome in terms of the new equilibrium levels of VMT, it will be necessary to consider all three of these interactions simultaneously, and to know the relative strengths of the feedback loops involved. The dynamics crudely outlined above suggest that the quality and availability of the subway will play a major role in determining the ultimate equilibrium state. If the subway service is good enough it provides enough access to destinations for commuters, then this will provide a strong stable floor on the number of people who will abandon transit for AVs. As the commuters choose to use AVs to get to work, traffic congestion and travel time will rise to the point where the subway again becomes the more appealing option. There is no similarly apparent floor preventing wholesale flight from use of the bus, other than the fact that some people will not be able to afford it. This could be put in more conversational terms as follows: *Why would I choose to ride the bus if I can get to work without worrying about or paying for parking, my trip will be shorter than the bus trip, because it will be direct, door-to-door, and won't involve any stops? And why would I ride the bus if all the time spent in the AV can be used for other purposes, instead of riding on a crowded bus with very little personal space and almost no way to get any work done?*

5.4.2 *Effects on Perception of Societal Benefits of AVs*

Based on the strong suggestion from analysis earlier in this chapter that VMT may increase dramatically in this scenario, it is important to consider ways in which the macro-system might be affected by increased VMT. This expands some of the discussion around Figure 4.5 in the previous chapter, adding the relationships shown in Table 5.4.

Table 5.5

Causal Link		**+/-**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**	**(polarity)**			
Automated Driving Capability	Individual Benefits of AVs	+	By definition	By definition	For simplicity, benefits for individual AV users discussed in previous sections have been aggregated into one variable here.
Individual Benefits of AVs	Total Costs of AV Use	-	By definition	By definition	
Other Externalities	Perceived Benefits of AVs	-	Weak	Moderate	This link assumes that some people will assign blame to AVs for the growth in VMT-related externalities. I hypothesize that this causality will be weak, though, because it is likely that many people will not make this connection.
Total Traffic Accidents	Perceived Benefits of AVs	-	Moderate	Moderate	This relationship is likely to be non-linear, because if there is a reduction in traffic accidents, it will be easy to assign credit to AVs, because they will be seen as safer. Therefore, the relationship is strong when traffic accidents decrease, but if they increase, due to growth in VMT, it is much less likely that people will assign blame to AVs, again because they will be seen as safer on an individual-vehicle basis.
Total Pollution & Energy Use	Perceived Benefits of AVs	-	Moderate	Moderate	Similar to the row directly above, this relationship is likely to be non-linear, due to the challenges in perceiving and recognizing causality here.
Pollution & Energy Use per VMT	Total Pollution & Energy use	+	Strong	By definition	
Traffic Accidents per VMT	Total Traffic Accidents	+	Very Strong	By definition	

Pollution & Energy Use per VMT	Perceived Benefits of AVs	-	Weak	Strong	While Pollution & Energy Use per VMT will be a very important metric to track, many people (and the news media) may focus on overall Pollution & Energy Use, not on the "pollution and energy use intensity" (measured per VMT). However, there is strong certainty that some causality will exist here, because some stakeholders who are more attuned to the issues in transportation will be likely to track this metric.
Traffic Accidents per VMT	Perceived Benefits of AVs	-	Weak	Strong	Similar to above, it's expected that most people (and the news media) will focus on overall traffic accidents, not on the accident rate per VMT. However, there is strong certainty that some causality will exist here, because some stakeholders who are more attuned to the issues in transportation will be likely to track this metric.

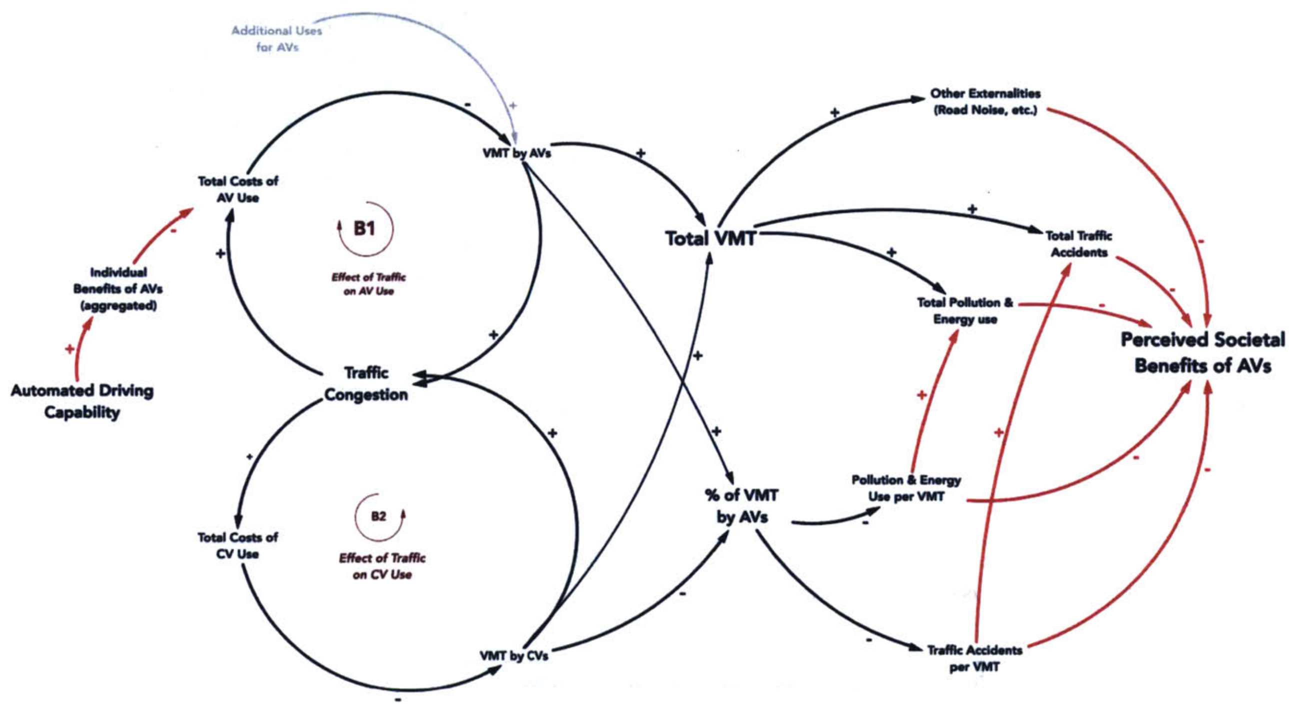


Figure 5.7. Causes and Effects of VMT. . *(Red arrows indicate new relationships added in this section.)*

One important aspect of the structure in Figure 5.7 is the dual effect of increasing VMT by AVs: as VMT by AVs increases, all the negative outcomes from VMT also increase; however, at the same time, as VMT by AVs increases, if some of this VMT is replacing VMT by CVs and the net effect is a higher concentration of AVs on the roads (increase in *% of VMT by AVs*), then the net effect is likely to reduce many of the negative outcomes from VMT. However, it's important to note here that there are several other externalities that are largely unaffected by whether VMT is due to CVs or AVs, such as: road noise, local air pollution, and deterrence from using non-motorized modes (as roads get more crowded with cars, it becomes less appealing to walk or ride a bicycle).

5.4.2A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The main questions here arise from the dual effect of *VMT by AVs*:

- Will the harm of more VMT outweigh the benefits of AVs?
- If the resultant harm of increased VMT does outweigh the benefits, will the benefits be recognized, acknowledged, and reacted to first, or will people recognize and react to VMT and all its related problems first?

Whatever the outcomes are, it appears highly likely that timing will play an important role in determining the perception that forms about AVs and whether they are considered beneficial or not.

5.4.3 Feedback reactions to increased VMT – How might the macro-system respond to traffic congestion issues after an initial round of increased VMT?

At this point, it is worth considering how the system might react to increases in VMT—with specific consideration for any feedback effects that will be triggered by VMT and that will also alter VMT. Some of the hypothetical causal relationships developed in this section are based on historical analogy. These hypotheses were developed using information about the key factors involved in the first three decades of adoption of the automobile (1900-1930), as discussed in *Fighting Traffic*, by Peter Norton (Norton, 2008). While the application of these historical dynamics to the present day is highly speculative and may not always be appropriate, due to fundamental changes in the macro-system, I have attempted to focus on the fundamental human and societal dynamics that are somewhat less subject to change.

Table 5.6 considers the key variables relating to VMT (shown in this case as "Urban Traffic Volumes") and some of the decision-making involved in public transit trips, non-motorized travel, and car use. This example focuses specifically on urban areas, where modes other than automobiles can play a significant role.

Table 5.6					
Causal Link		**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
Efficiency of Traffic Flow	Urban Traffic Speeds	+	Strong	Very Strong	This relationship will be highly non-linear, especially in denser urban environments, where speed improvements due to efficient driving will be limited by factors such as pedestrians, traffic lights, etc.
Urban Traffic Speeds	Attractiveness of Non-Motorized Transport	-	Strong	Very Strong	Here, I have used "attractiveness of non-motorized transport" instead of "total costs ...". This does a better job reflecting the subjective nature (e.g., what makes people "comfortable" with walking or bicycling) of the factors involved in deciding to walk or bike. High traffic speeds can have a very strong deterrent effect on cyclists, but probably less so on pedestrians, as they often occupy spaces well protected from automobiles.
Attractiveness of Non-Motorized Transport	Attractiveness of Traveling by Public Transit	+	Very Strong	Very Strong	This reflects the fact that most public transit trips involve non-motorized travel at the beginning and end.
Attractiveness of Traveling by Public Transit	AV Trips Downtown	-	Moderate	Very Strong	Causality is considered "moderate," because for many people, the decision to switch from public transit to use of an AV may not be easy or affordable.
Attractiveness of Public Transit	CV Trips Downtown	-	Moderate	Very high	Similar to above, the strength of this link is considered "moderate," because for many people, the decision to use a CV may not be easy or affordable.
AV Trips Downtown	Urban Traffic volumes	+	Strong	By definition	
CV Trips Downtown	Urban Traffic Volumes	+	Strong	By definition	
Urban Traffic Volumes	Attractiveness of Non-Motorized Transport	-	Moderate	High	This is also highly non-linear, as low levels of traffic may have almost no deterrent effect on walking and cycling. However, high levels of traffic, especially at higher speeds may make bicycling unappealing except for a small minority who are comfortable with the risk.
AV Trips Downtown	AV % of Total Urban Traffic Volume	+	Very Strong	By definition	

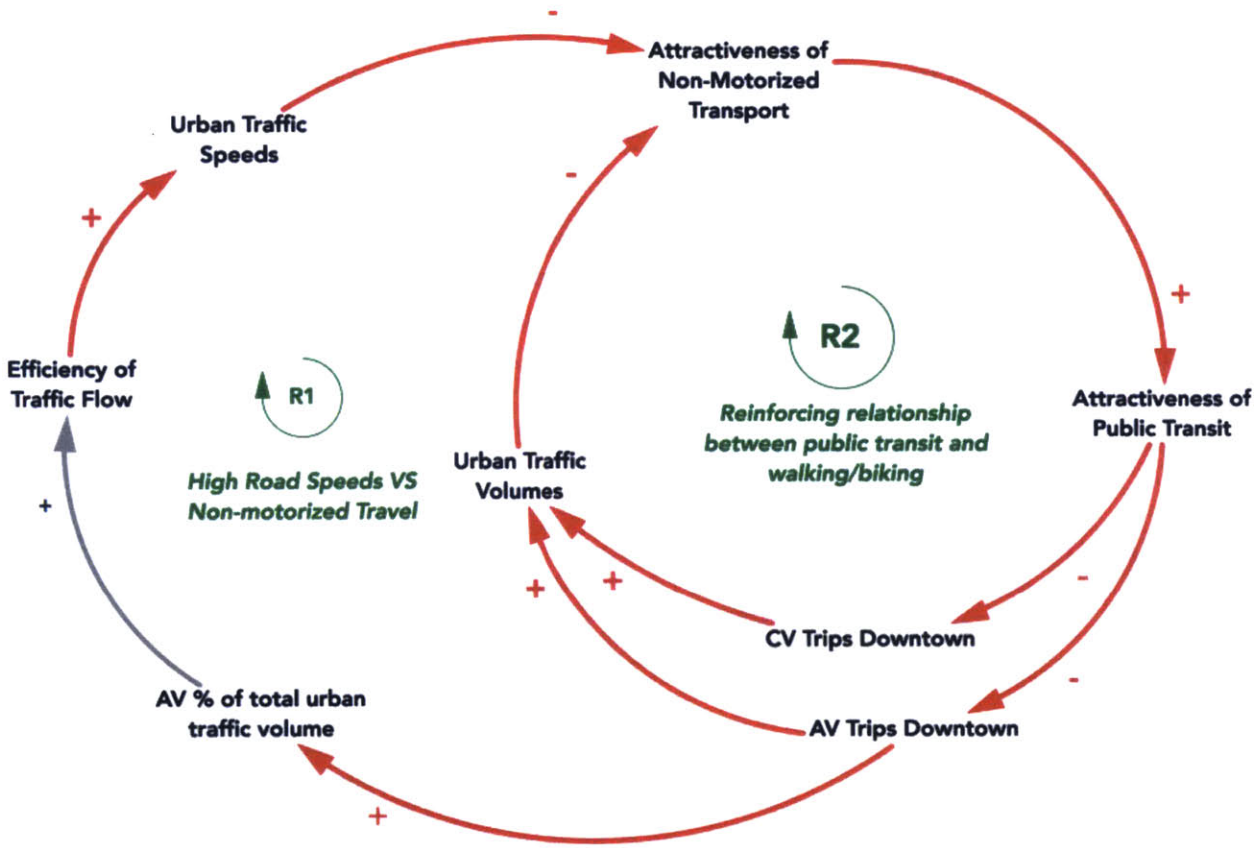


Figure 5.8. Relationships between traffic volume, public transit use, and non-motorized travel. . *(Red arrows indicate new relationships added in this section.)*

Two important reinforcing loops are evident in Figure 5.8:

- R1 suggests that traffic speeds may increase, due to more efficient traffic flow, as the proportion of AVs in the overall flow of traffic grows. This more-efficient flow will mean closer spacing of cars, and with faster response times among vehicles, it should allow for higher speeds. While this may be safer overall for vehicles, it may mean less room for error with pedestrians and cyclists, whose behavior will not benefit from the inherent safety protections of automation (they will still be unpredictable and relatively slow to react). In other words, pedestrians and bicyclists will still do unpredictable things and there is only so much safety that AVs can provide, especially if they are moving faster than conventional cars. Stopping distances may become the limiting factor in avoiding collisions (and, unfortunately, these are largely determined by the laws of physics, over which vehicle automation has very little say…). Ultimately, it will also depend on the perception, not just the reality, of how safe roads are for cyclists and pedestrians. If they do not feel safe on the road when a platoon of AVs passes close by at high speed, then pedestrians and cyclists will be disinclined to continue to travel by foot or bicycle, and therefore, accessing public transit will be more difficult, which is likely to push more public transit riders into using cars.

- R2 has the same structure as R1, but relies on the assumption that the *volume* of traffic, instead of the speed, will be the deterrent to non-motorized travel.

Table 5.7 shows one possible reaction by key stakeholders to increased VMT. The stakeholders in this case are owners of AVs, the AV industry, and related interests (which can be collectively referred to as the "AV Coalition"), along with agencies responsible for transportation regulations. The relationships shown here are based on the potential reaction to increased VMT and an underlying assumption that the increase in VMT will be enough to increase traffic congestion.

Table 5.7

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Traffic Congestion	Realization of Speed/ Efficiency Benefits of AVs	-	Strong	Strong	This represents the interference of traffic on AV users' ability to realize the full benefits of automated driving. If traffic is extremely thick (e.g., "bumper to bumper"), even the most efficient AV driving will not be able to make a trip much faster than a CV.
Realization of Speed/ Efficiency Benefits of AVs	Frustration of AV owners & industry	-	Moderate	Moderate	This represents the likely arousal of frustration in AV owners (and their advocates and allies) when they are unable to realize the promised benefits of AVs.
Frustration of AV owners & industry	Attention/ blame on modes that impede traffic flow	+	Moderate	Moderate	This represents one likely conclusion that will result from the frustration of AV owners—that the source of the problem is that other people are using the road in a much less efficient manner than AVs do. E.g., *"If everyone on the road were in an AV, traffic would flow much more efficiently, and if we didn't have to slow down for cyclists or wait for pedestrians to cross, traffic would move much faster, especially through intersections."*
Frustration of AV owners & industry	Focus on improving road conditions for AVs	+	Moderate	Weak	This represents another likely conclusion that people may draw, which is that the solution to the unrealized benefits of AVs is to improve roads to be tailored more for AV traffic.

Attention/ blame on modes that impede traffic flow	Restrictions on non-AV modes	+	Weak	Moderate	There is reasonably likely causality here, but the effect may vary substantially. Different locations may have very different attitudes about restricting non-AV modes.
Focus on improving road conditions for AVs	AV-Friendly Design of Infrastructure	+	Strong	Very Strong	If there is a true focus on improving road conditions for AVs, then it's very likely that the infrastructure will change in at least some ways to be more AV-friendly.
Restrictions on non-AV modes	Accessibility of Roads by CVs and non-motorized Transport	-	Strong	Very Strong	The only reason this relationship is not considered to be "by definition" is that the restrictions may not have the full desired effect.
AV-Friendly Design of Infrastructure	Accessibility of Roads by CVs and non-motorized Transport	-	Moderate	Moderate	Many of the measures to make the road infrastructure more AV-friendly may also make the roads more difficult—or impossible—to use by non-AV modes: for example, given the improved accuracy and control of driving by AVs, lane sizes could be safely reduced to add more traffic lanes; or the way traffic intersections work could be altered (perhaps even by doing away with some street lights and allowing fully connected AVs to self-coordinate the timing of passage through intersections).
Accessibility of Roads by CVs and non-motorized Transport	Use of Roads for Non-Motorized Travel	+	Very Strong	Very Strong	
Use of Roads for Non-Motorized Travel	Efficiency of Traffic Flow	-	Moderate	Strong	The presence of bicycles can slow down traffic, especially when there is not enough room for a dedicated bike lane and bicycles need to occupy an entire traffic lane. Bicycles and pedestrians can impede all turns during the green-phase and right turns during the red-phase of a light cycle. Therefore, reducing or eliminating these sources of "interference" would improve overall traffic flow.
Accessibility of Roads by CVs and non-	AV Trips replacing CV trips	-	Strong	Strong	As roads become less accessible—or even less comfortable—to use for CVs, it seems highly probable that those who

motorized Transport					can afford to will switch to AVs.

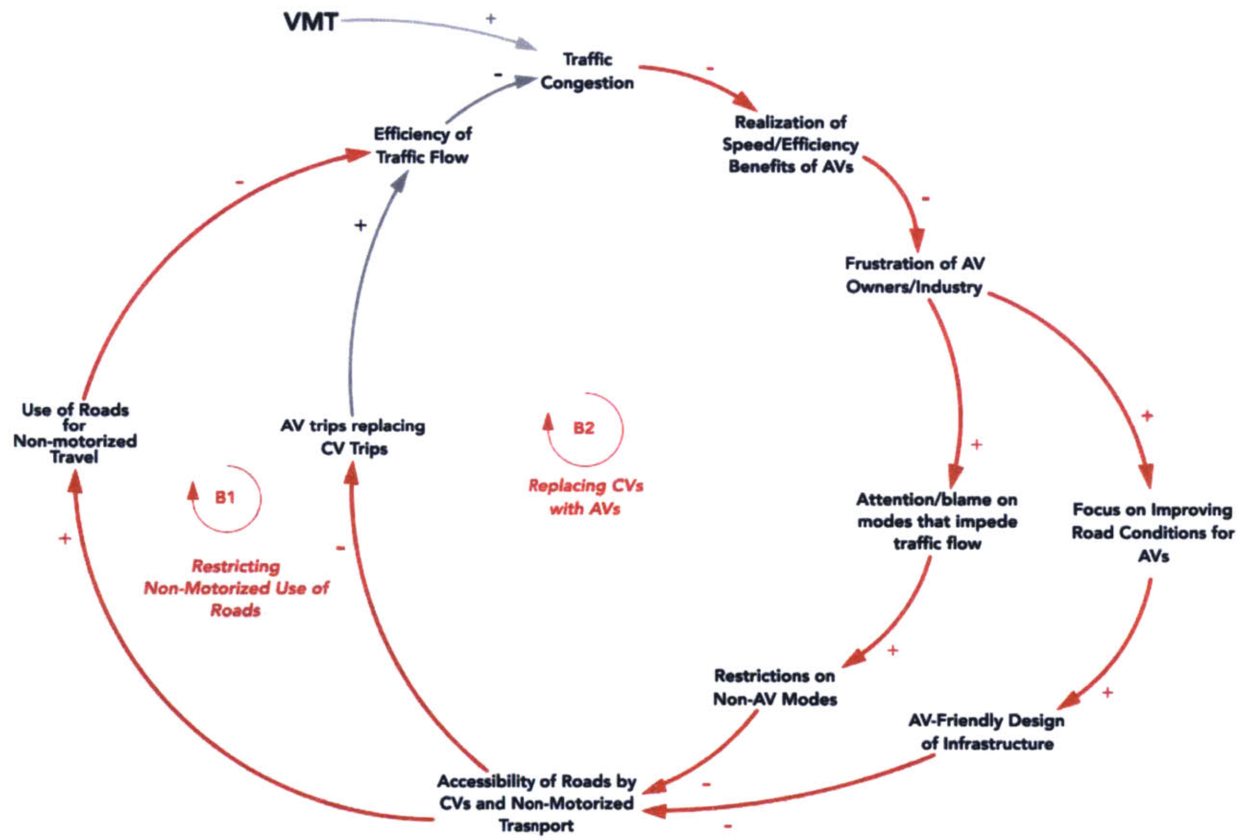


Figure 5.9a. Relationships representing the intended effect of potential restrictions in response to increased traffic congestion. *(Red arrows indicate new relationships added in this section.)*

If Figure 5.9a is read as a narrative, it tells what might be considered a successful story by the AV Coalition: *When members of the AV coalition recognize that traffic congestion is getting worse, they also realize that the hoped-for benefits of AVs are not being fully realized, because traffic is slowing down the journeys that should be getting faster. This leads to frustration among the coalition and a desire to seek remedies to help realize the full benefits of AVs, which leads to two parallel approaches:*

(1) Assign blame for traffic to non-AV modes, which has intuitive appeal to many, because most people would recognize that if the only thing on the streets were AVs, much more traffic could flow much more quickly. It would be relatively easy to see that the main impediments to faster traffic are pedestrians (long wait times at crosswalks), bicycles (which take up space, move slowly, and can block lanes), and CVs (which lack all the efficient-driving improvements of AVs).

(2) Seek to improve road conditions for AVs, which would most likely involve segregated zones

for AVs, meaning some space would have to be sacrificed by other modes.

If these approaches are successful, the accessibility of roads by CVs and non-motorized transport will be reduced, ultimately resulting in replacement of CVs by AVs and less use of road space for non-motorized travel, ultimately reducing traffic congestion.

Table 5.8 addresses some of the causal relationships that could be considered "unintended consequences" of the approach taken above.

Table 5.8

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Accessibility of Roads by Non-Motorized Transport	Accessibility and Attractiveness of Public Transit	+	Strong	Very Strong	Most public transit trips require non-motorized travel at the beginning and end of the trip.
Accessibility of Roads by Non-Motorized Transport	Use of Road Space for Non-Motorized Travel	+	Strong	Very Strong	As roads become less accessible—or even less comfortable to use—for Non-Motorized trips, it seems highly probable that those who can afford to will switch to other modes.
Accessibility and Attractiveness of Public Transit	AV Trips	-	Strong	Very Strong	This asserts a negative relationship between AV trips and Public Transit trips. It is not considered "very strong," because the effect may also involve some trips just not taken, as opposed to involving a mode-switch.
Use of Road Space for Non-Motorized Travel	AV Trips	-	Strong	Very Strong	This asserts a negative relationship between AV trips and Non-motorized trips. It is considered a "strong" relationship, instead of "very strong," because the effect may also involve some trips just not taken, as opposed to involving a mode-switch.
Accessibility and Attractiveness of Public Transit	CV Trips	-	Strong	Very Strong	This asserts a negative relationship between CV trips and Public Transit trips. It is considered a "strong" relationship, instead of "very strong," because the effect may also involve some trips just not taken, as opposed to involving a mode-switch.
Use of Road Space for Non-	CV Trips	-	Strong	Very Strong	This asserts a negative relationship between CV trips and Non-motorized

Motorized Travel					trips. It is considered a "strong" relationship, instead of "very strong," because the effect may also involve some trips just not taken, as opposed to involving a mode-switch.

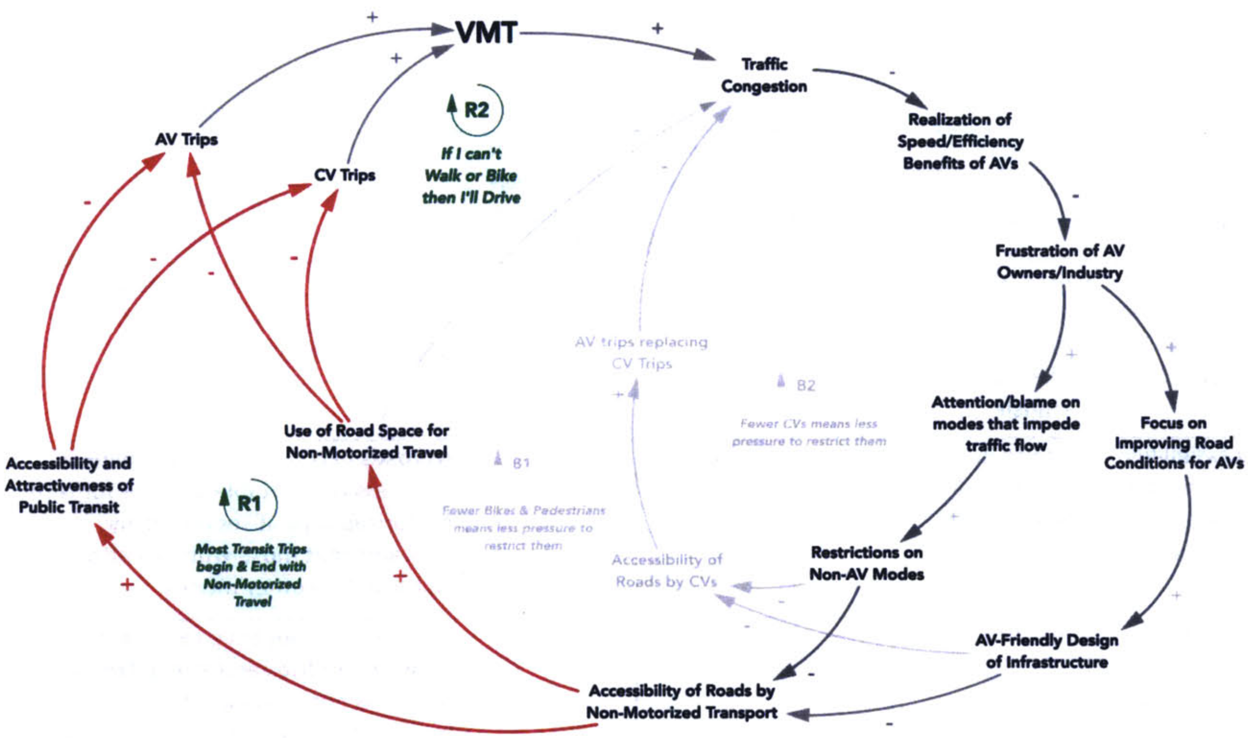


Figure 5.9b. Relationships representing potential unintended effects of restrictions in response to increased traffic congestion. *(Red arrows indicate new relationships added in this section.)*

Figure 5.9b introduces two reinforcing loops that appear likely to push VMT higher (and possibly increase traffic congestion as well).

- **R1:** By restricting non-motorized travel to gain roadway efficiency, public transit will become less accessible (as most public transit trips require non-motorized travel at the beginning and end of the trip), and some of these travelers will be forced to use AVs or CVs.
- **R2:** By restricting non-motorized travel, some cyclists (who are very spatially efficient travelers) and pedestrians (who are the ***most*** spatially efficient travelers) will be forced to use AVs or CVs instead.

5.4.3A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The narrative around figure 5.9a is well aligned with the history of cars and urban roads in the early part of the 20th Century. A turning point in that history occurred in the 1920s, when the pro-automobile coalition successfully promoted the notion that the solution to congestion and safety problems was to make roads more car-friendly (Norton, 2008, pp. 243-254) and to restrict access to the streets by non-motorized travel. In the latter case, it became almost universal practice to restrict pedestrians to sidewalks and dedicated road-crossings, which had not been done in the preceding thousands of years of history of human habitation in cities. The total transformation of the way people understand streets and their proper uses (the "social construction" of streets) is well illustrated by the popularization and universal acceptance of the term "jaywalker" which had not existed prior to the arrival of the automobile and the ensuing conflict over street space (Norton, 2008, pp. 65-104, and McShane, 1994, p. 188).

Figure 5.9b exhibits a potential behavioral response to traffic delays at higher levels of market penetration of AVs. This is analogous to the behavior of the pro-automobile coalition in the 1920s. A similar dynamic could arise here, stemming from the same psychological response: users of a new technology are frustrated by what they see as old and inefficient practices. Key questions from this model include:

- Which feedback loop will dominate? Will restricting access to streets for non-motorized transport push enough people away from public transit and into cars or AVs that the restriction will actually have the perverse effect of making traffic worse? Or will a modest level of restriction cause enough of a drop in congestion (without pushing too many people away from transit) that the pressure to restrict access diminishes? For many parts of the country, like the Boston area, where there are strong bicycle and pedestrian coalitions, it is highly unlikely that these dynamics will play a dominant role, but they could be worth considering in other locations.
- Will restrictions hit pedestrians harder than CVs? While this may seem unlikely, in parts of the country where the automobile coalition is strong and the bicycle/pedestrian coalition is weak, the argument that "roads are for cars" may carry a lot more weight, so efforts may first focus on improving the environment for all automobiles, before restricting CVs. In this case, the reinforcing loops will work strongly to push people to use cars. Furthermore, if there is a glut in the used-car market, and many more people have access to automobiles, this may further weaken the pedestrian/bicycle coalition and strengthen the automobile coalition.

This history also provides another potential outcome, based on similar dynamics. According to Norton (2008), in the early years of automobiles, there was initially something resembling an alliance between electric streetcar operators and automobile interests, because both saw the need to claim the street for motorized mobility and both would benefit from streets uncluttered by horse-drawn carriages, pedestrians, and even children playing. And indeed this did initially work to the advantage of both the automobiles and streetcars. However, as non-motorized travel became increasingly difficult, one effect was to make the use of streetcars less appealing, due to the newfound difficulty, discomfort, and danger involved in accessing streetcars, which were usually not well protected from high-speed traffic.

Furthermore, as more people drove, and congestion slowed down both the streetcar and the automobile, travelers found it far preferable to be behind the wheel of a car stuck in traffic than standing up on an overcrowded streetcar stuck in traffic. This served to give the automobile still more advantages over the streetcar, hastening its demise and further enshrining the automobile as the dominant mode of travel on the roads.

One could imagine a similar dynamic emerging among AVs and CVs, as both might benefit initially from increasing restrictions on non-motorized travel. And, especially in places where walking is already difficult or unappealing (e.g., in places with non-pedestrian-friendly urban design, extremely hot or cold climates, etc.), it is not unrealistic to expect that the environment could become so unappealing for foot traffic that even accessing a final destination from a parking lot would become difficult. Furthermore, parking lots and the space they occupy could be seen by AV users as further impediments to the efficiency of AVs (AV users might prefer larger "pick-up and drop-off" zones at destinations instead of parking lots), and may therefore be slowly phased out, making it still more difficult to use a CV. By this time, of course, the number of AVs on the road may have grown to the point that the constituency is able to effect major change in policy that goes against the incumbent interests of CV owners, so a decline in available parking may actually be a realistic outcome. And, as discussed earlier, if AV users are more tolerant of time spent in traffic, as traffic volumes increase with the increase in VMT, growing VMT could further amplify the advantages of AVs over CVs. Ultimately, what begins as a process to benefit all motor vehicles could deliver far greater advantages to AVs and hasten the demise of CVs. In short, dynamics similar to the ones that allowed the CV to push out the streetcar might come into play and allow the AV to push out the CV.

Norton also observes that there was a "saturation crisis" in the automobile industry in the early 1920s (Norton 2008), when sales began to slacken due to safety and congestion concerns that had arisen as VMT grew. Fortunately, for the automotive industry, it took enough cars in use (a high enough level of adoption) for these problems to truly come to the fore, that by the time they did, the power and influence of the automotive interests were strong enough to succeed in a "radical reconstruction of the city traffic problem." In other words, the problems directly caused by an excess of VMT, were redefined as problems of insufficient street capacity, and no blame was spared for streetcars, pedestrians, and other obstructions to the smooth and efficient flow of automobiles. One could easily translate this into a modern scenario, where AV interests might reconstruct the problems that might arise from excessive VMT in a similar way: insufficient street capacity, city buses, CVs, bicycles, and pedestrians, all standing in the way of a free and efficient flow of AVs.

5.4.4 Feedback reactions to increased VMT – How might the macro-system respond to safety issues after an initial round of increased VMT?

This section follows the same logic as section 5.4.3, but considers the macro-system response to potential changes in *safety*. Table 5.9 shows several causal relationships that may come into play as stakeholders attempt to realize the full safety benefits of AVs.

Table 5.9					
Causal Link		**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
Safety of Vehicle Operation	Accidents with Bicycles & Pedestrians	-	Moderate	Very Strong	If the potential safety benefits of AVs are realized, they should reduce all accidents. While there have been studies done estimating the reduction in vehicle-to-vehicle crashes, one can expect there may be a substantial difference between these improvements and the safety improvements involving bicycles and pedestrians, as they behave very differently from automobiles and may present very different challenges for AV technology.
Safety of Vehicle Operation	Accidents with CVs	-	Strong	Very Strong	This is based on the assumption of technology success for this scenario, which assumes full safety benefits are achieved.
Perception of AV Safety	Blame focused on non-AV modes	+	Moderate	Strong	It stands to reason that if AVs are perceived as inherently safe, then people will be more likely to place the blame for any accidents on the other parties involved. The stronger the perception of AV safety, the more blame will be put on non-AV modes.
Accidents with Bicycles & Pedestrians	Blame focused on non-AV modes	+	Moderate	Strong	As above, as long as there is sufficient perception that AVs are inherently safe, there should be more blame associated with non-AV modes
Accidents with CVs	Blame focused on non-AV modes	+	Strong	Strong	This effect is expected to be stronger because it will probably be easier for people to blame CVs as an "outdated, unsafe" technology than it will be for them to consider pedestrians to be at fault.
Blame focused on non-AV modes	Pressure to restrict roads for AVs	+	Moderate	Moderate	This has strong historical precedence (see section 5.4.3A), but may vary widely depending on location, as some areas have much stronger "complete streets" movements than others, and these movements would resist attempts to restrict non-AV modes.

Pressure to restrict roads for AVs	New Restrictions against NM Transport	+	Moderate	Strong	There should be some causality here, but it's uncertain how strong it will be, and the relationship is likely to be far from linear.
Pressure to restrict roads for AVs	New Restrictions against CVs	+	Moderate	Strong	There should be some causality here, but it's uncertain how strong it will be, and the relationship is likely to be far from linear.
New Restrictions against NM Transport	NM Trips	-	Moderate	Strong	There is a high degree of uncertainty here regarding the effectiveness of the regulations.
New Restrictions against CVs	AV trips replacing CV Trips	+	Strong	Strong	This effect should be stronger than the effect on NM Transport, as switching from a CV to an AV might seem like less of a change in behavior than switching from NM Transport to a motorized mode.
NM Trips	Accidents with Bicycles & Pedestrians	+	Very Strong	Very Strong	This simply asserts that there is a very strong causal relationship between the amount of NM travel and the number of accidents involving bicycles and pedestrians.
AV trips replacing CV Trips	Safety of Vehicle Operation	+	Very Strong	Assumed	This is a based on the assumption in this scenario that AVs will be safer than CVs.

The resulting structure of this aspect of the macro-system, as shown in Figure 5.10a, is closely aligned with Figure 5.9a, in that it shows the intended effect of regulations: in order to reap the full safety benefits of AVs, it might make sense to some to restrict access to the roads by other modes.

If Figure 5.10a is read as a narrative, it would also tell a story of success by the AV Coalition: *When it is observed that traffic safety is not improving as much as it could, because there are still many CVs, cyclists, and pedestrians using the roads, and AVs are unable to integrate with them and still achieve their full potential safety benefits. This leads to frustration among safety interests as well as the AV coalition and a desire to limit access to roads by non-AV modes. If such restrictions are put in place, the number of pedestrians and cyclists on the roads should diminish and more people will switch from CVs to AVs. With these changes, it would appear inevitable that safety conditions on the roads would improve, as roads would be dominated by AVs, all operating in a much safer fashion than conventional vehicles.*

Figure 5.10a. Relationships representing intended effects of regulations to attain the full safety benefits of AVs. *(Red arrows indicate new relationships added in this section.)*

Similar to Table 5.8, Table 5.10 shows variables related to potential unintended effects of regulations.

Table 5.10					
Causal Link		**+/-** (polarity)	**Strength of Causal Relationship**	**Level of Certainty that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
VMT	Accidents with bicycles & pedestrians	+	Very Strong	Very Strong	This asserts that the number of accidents will rise and fall with VMT, ceter paribus.
VMT	Accidents with CVs	+	Very Strong	Very Strong	This asserts that the number of accidents will rise and fall with VMT, ceter paribus.
New Safety Restrictions for NM Transport	Accessibility and Access of Public Transit	-	Moderate	Strong	This effect might be reduced by other changes, such as efforts to improve NM transport in other ways, without affecting the use of roads.
New Safety Restrictions for NM Transport	NM Trips	-	Moderate	Strong	This effect might be reduced by other changes, such as efforts to improve NM transport in other ways, without affecting the use of roads.
Accessibility and Access of Public Transit	AV Trips	-	Moderate	Strong	This asserts a negative relationship between AV trips and Public Transit trips. It is not considered "very strong," because the effect may also involve some trips just not taken, as opposed to involving a mode-switch.
Accessibility and Access of Public Transit	CV Trips	-	Moderate	Strong	See above
NM Trips	AV Trips	-	Moderate	Strong	See above
NM Trips	CV Trips	-	Moderate	Strong	See above
AV Trips	VMT	+	Very Strong	By Definition	
CV Trips	VMT	+	Very Strong	By Definition	

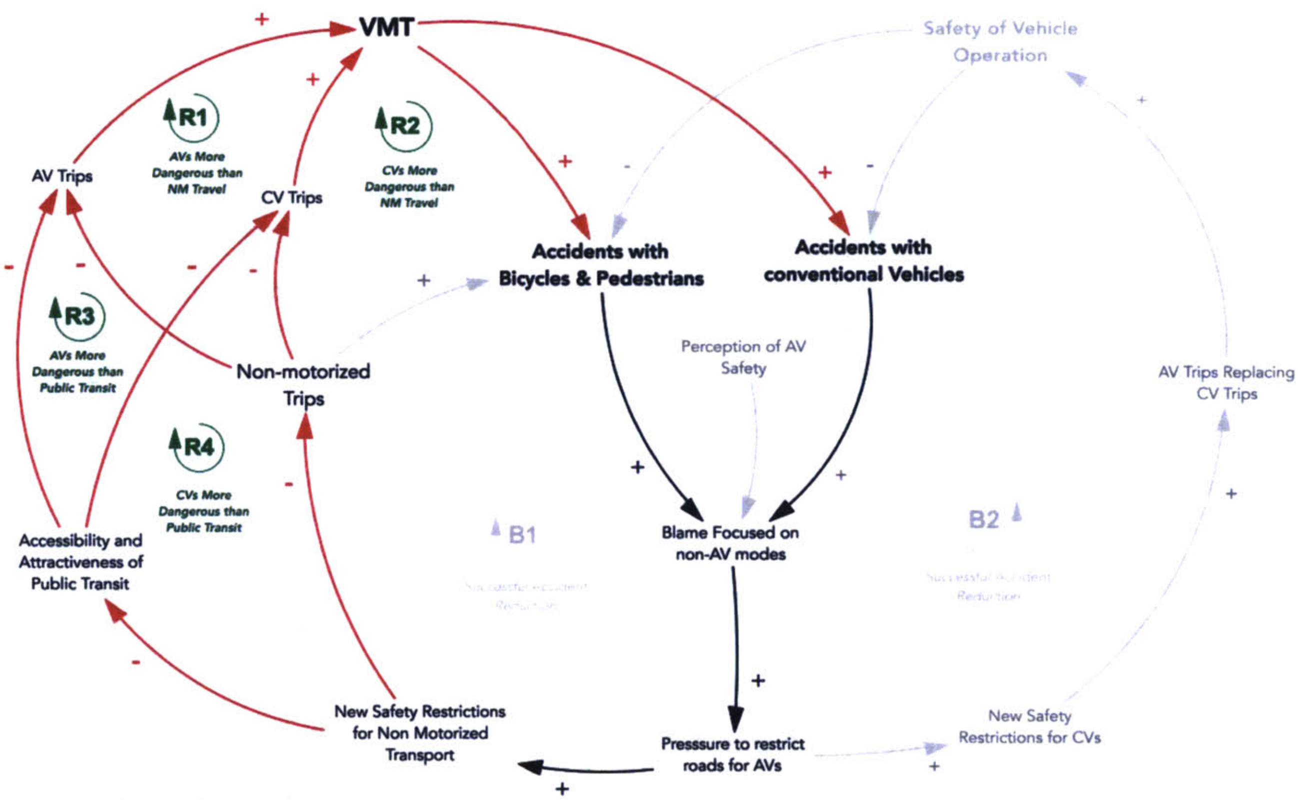


Figure 5.10b. Relationships representing potential unintended effects of regulations to attain the full safety benefits of AVs. *(Red arrows indicate new relationships added in this section.)*

Figure 5.10b introduces four reinforcing loops that appear likely to push VMT higher, and that would counteract the benefits of the potential regulations.

- **R1 and R2:** Facing increasing restrictions, those who used to travel by non-motorized means may switch to either AV or CV use.
- **R3 and R4:** Facing increasing restrictions to NM travel, and therefore facing obstacles to public transit use, those who used to travel by public transit may find access is diminished enough to cause a switch to either AV or CV use.

The historical inspiration for this section comes from the growing push in the 1920s and 1930s to define roads as primarily for motor vehicles and to restrict the access for all others—ultimately to remove what were seen as vulnerable and unpredictable users of the public streets. These improvements had a tremendous effect on improving the accident rate per VMT. However, in aggregate, the rapid growth in VMT and the extreme shift from the very safest modes (public transit) to the most dangerous one (passenger cars) resulted in many more deaths and injuries. As Norton observes, from the 1930s to the 1960s:

> *"... the conversion of surface passenger transportation to motor vehicles was so nearly complete that even though each mile of travel carried only one-third the risk, the total death tolls kept rising. The conversion of surface transportation to the most dangerous mode robbed American transportation of the fruits of making that mode safer."* (Norton 2008, p. 253)

Furthermore, some municipalities undertook new approaches to remove pedestrians from the streets entirely. In one striking example, in 1925, the Automobile Club of Southern California "... initiated a bond-issue proposal to finance pedestrian tunnels [in Los Angeles] that would protect children on their walk to school ... These passageways protected children and, according to Lefferts [then president of the automobile club], 'expedited vehicular movement' on streets, promoting a new proposition: that pedestrians do not belong in streets." (Norton 2007, p. 352)

For simplicity, Figure 5.10b aggregates the effects of AV Trips and CV Trips into a single variable for VMT. In reality, the VMT from these different modes would have different effects on both of the accident variables shown.

5.4.4A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The system behavior resulting from the structure displayed in figure 5.10b will depend on several uncertain factors, which prompt the following questions and observations:

- If restrictions against conventional vehicles are put in place, will these take hold first, improve overall safety enough to reduce regulatory pressure, and limit any new restrictions on non-motorized transport? Or will restrictions on non-motorized transport take effect and begin to drive the reinforcing loops that force people away from transit and non-motorized travel? The outcomes here will have a strong effect on VMT.
- One of the critical variables evident in Figure 5.10b is *<u>Perception of AV Safety</u>*. If it is widely believed that AVs are fundamentally safe and are not at fault in most accidents that occur, then the impulse to put blame on non-AV modes will be strong. For example, if AVs almost never have accidents with each other or with stationary objects, this could be viewed as an "objective" indicator that AVs are fundamentally safe, and any accidents involving non-AV travelers are more likely to be viewed as the others' fault.
- Even if AVs are safer on an individual basis, and if they achieve tremendous safety improvements when operating among other AVs, will the increase in VMT lead to more accidents involving pedestrians, cyclists, and conventional automobiles? In other words, will the increase in traffic volume increase the number of accidents more than they are reduced through safer operation of the individual AVs?

It may be may be difficult to predict the net effect of AVs on safety if VMT were to increase substantially, because the way accidents occur between NM travelers and AVs could be very different from how they would occur among AVs and other AVs, or among AVs and CVs. What ultimately matters here is the relationship between the improvements in safety and the increase in VMT. For example, if—on a per-mile basis—AVs cause 90% fewer accidents when they are operating among other AVs, 50% fewer accidents in mixed traffic, and 20% fewer accidents involving bicycles and pedestrians, then if VMT increases by more than 25%, we can expect an increase in injuries and deaths among pedestrians, while safety among CVs and AVs on the roads will improve substantially. And, it seems reasonable to assume that relative safety improvements will be lowest when pedestrians and cyclists are involved, because they will be more difficult to detect, and may move much less predictably than an automobile (e.g., a pedestrian steps off a crowded sidewalk without looking, or a cyclist hits a pothole and falls into the driving lane).

5.4.5 Feedback Effects and Potential Delays in Policy Responses

This section considers some of the stakeholder responses to the system effects of the initial deployments of AVs. These responses are considered in very broad, general terms; the aim here is to identify some of the potentially critical timing issues in how different stakeholders might respond. These effects are inspired by the important role played by the timing of some stakeholder responses to the rapid adoption of automobiles. One of the interesting themes that emerge from the early history of the automobile is the almost total failure in some regards by interests that were attempting to control or restrict automobile use in order to avoid some of the more extreme externalities. For example, one key factor was that many in the pro-Automobile coalition (e.g., owners of cars and industry stakeholders) had very strong interests in promoting pro-automobile policies from the very beginning—for new car-owners, the moment they paid for their vehicles, they had a strong interest in a positive regulatory climate to ensure that they would get the most benefit out of their expensive investment (e.g., early attempts to install mechanical speed governors in cars were strongly opposed, with much of the argument fueled by the notion that this would negate the inherent benefit of the automobile, which was speed (Norton 2008, pp. 98-99). By the time safety interests gained strength and calls were made for speed limits and mechanical speed governors to reduce accidents, these efforts met with well-organized and vocal resistance, and the advantages provided by the automobile were widely accepted, as expressed by a tire-company executive in 1923: "The automobile is too effective a tool to have its efficiency curtailed in the slightest by half-baked ideas ... which have as their object a reduction in the number of cars which shall use the streets" (Norton 2008, p. 185). One could easily imagine similar objections to any efforts to curtail the use of AVs in the coming years. Furthermore, by the time the potential harm from automobiles was fully understood, they had evolved from being considered a frivolous toy of the wealthy (the "pleasure car") to being widely perceived as an economic necessity, thereby making efforts to restrict or regulate them far more difficult (Norton 2008 p. 220).

Table 5.11					
Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	Dependent Variable				
# of AVs in Use	VMT	+	Moderate	Assumed	This relationship is discussed in previous sections, and there is good reason to believe it exists, but it is uncertain how strong the relationship is.
VMT	Observation & Recognition of Harmful Effects	+	Moderate	Very Strong	This is considered a "moderate" causal relationship here, because people may not notice certain outcomes, especially if they emerge very gradually.
Observation & Recognition of Harmful Effects	Pressure to Restrict or Regulate AVs	+	Weak	Strong	This is considered "weak" here, due to the difficulty people may have in connecting the negative outcomes arising from additional VMT to the adoption of AV technology.
Pressure to Restrict or Regulate AVs	# of AVs in Use	-	Moderate	Strong	The strength of this causality (identified here as "moderate") could vary widely, depending on the effectiveness of the policies implemented.
# of AVs in Use	Perception of AVs as necessity	+	Strong	Very Strong	As more people adopt AVs, it stands to reason that they would adapt their behavior in ways that may make them dependent on them, much the way people have become dependent on the automobile.
# of AVs in Use	Political Clout of AV Users and Industry	+	Strong	Strong	A larger base of AV users means more voters that will support AV-friendly policies, and more people who depend on the AV industry for their livelihoods.
# of AVs in Use	Investment by Industry	+	Strong	Strong	With overall growth of AV use, it would be expected that industry would continue to expand investment.
# of AVs in Use	Observation & Recognition of Societal Benefits of AVs	+	Very Strong	Strong	The causality here should be very strong—not only will more AVs in use increase their visibility on an individual basis, but as they become a larger fraction of the total automotive fleet, their direct systemic benefits (in terms of safety, traffic-flow, energy consumption) will increase.

Observation & Recognition of Societal Benefits of AVs	Support from People who Don't Own AVs	+	Moderate	Strong	People who do not benefit directly from owning an AV may recognize that some of the systemic benefits they provide are beneficial to all.
Perception of AVs as necessity	Pressure to Enable and Support AV Adoption	+	Strong	Strong	This relationship may also be interpreted as: the perception of AVs as a necessity will counteract the pressure to restrict or regulate them.
Political Clout of AV Users and Industry	Pressure to Enable and Support AV Adoption	+	Strong	Strong	This assumes that there will be inherent pressure from AV users and industry, and that this will grow with their political influence.
Investment by Industry	Pressure to Enable and Support AV Adoption	+	Strong	Strong	This asserts that the level of pressure exerted by industry will vary to some degree with their level of investment in AV technology.
Observation & Recognition of Societal Benefits of AVs	Support from People who Don't Own AVs	+	Moderate	Strong	The strength of this relationship is considered "moderate" because it involves people with no vested interest in the success of the technology.
Support from People who Don't Own AVs	Pressure to Enable and Support AV Adoption	+	Moderate	Strong	The comment in the cell above also applies here, but there may also be some additional strength to this relationship, because some policy-makers and other stakeholders (e.g., the press) may treat this political pressure differently when it comes from people without vested interests.
Pressure to Enable and Support AV Adoption	# of AVs in Use	+	Moderate	Strong	The assumption here is that this pressure will lead to favorable policies, which will lead to more AVs in use. As with other causalities involving policy interventions, there is a lot of uncertainty around their effectiveness, so the strength of the causality is considered "moderate."

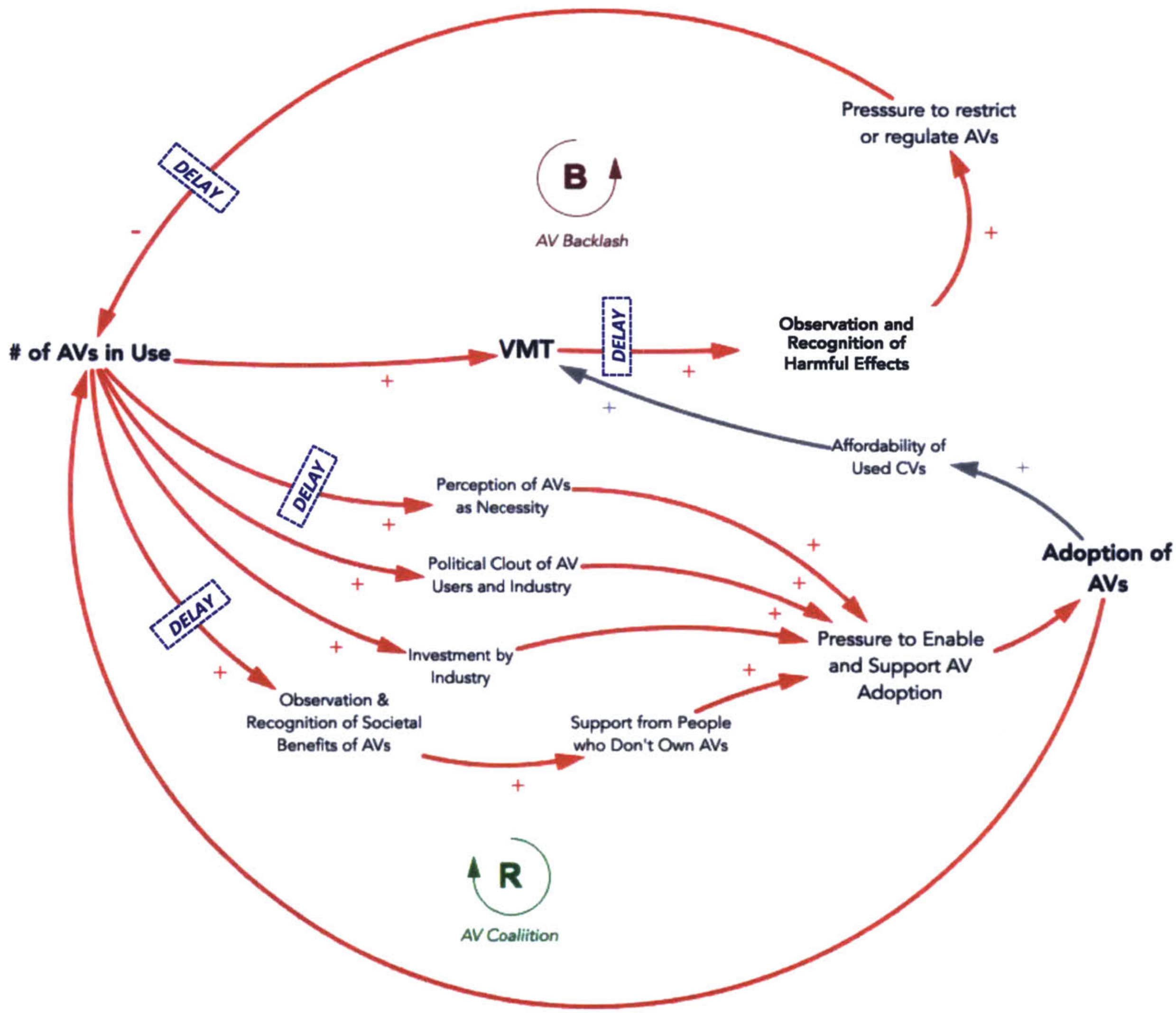


Figure 5.11. The potential regulatory response to AVs, showing critical delays. *(Red arrows indicate new relationships added in this section.)*

The causal links in Table 5.11 have been assembled into essentially two general loops in Figure 5.11: the balancing loop "AV backlash" and the reinforcing loop "AV Coalition." The figure actually shows four separate reinforcing loops, but they are labeled as one, because the dynamics are similar and they all contribute to the same general end, which is building of pressure to support and enable AV adoption. As stated above, it appears that the behavior resulting from these dynamics, and their ultimate impact, will depend largely on the timing of these causal relationships. Several observations can be made about the reinforcing feedback effects that closely parallel historical facts relating to the history of the automobile:

- AVs may be perceived as a novelty or a luxury at first, hence the "delay" in the causal link to "perception of AVs as necessity".
- The <u>*Political Clout of AV users and Industry*</u> and <u>*Investment by Industry*</u> are likely to be strong

even before the deployment of AVs (most of the current developers of AVs are very large, very powerful companies, and they have already invested large sums in the technology.

- There may be a substantial delay between the increase in VMT and the observation and recognition of negative outcomes. Those effects may actually emerge fairly rapidly, but observing, acknowledging, and recognizing them for what they are is likely to take some time. Furthermore, based on prior analysis in this chapter, there is good reason to believe that it will be difficult—and unlikely—for many to make the connection between individual AVs (a safe and efficient technology on an individual basis) to the unsafe and congesting effects of widespread deployment and use.

5.4.5A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

It appears likely that *Political Clout of AV Users and Industry* and *Investment by Industry* will exist well before any observation of societal benefits or overall negative outcomes is even possible. Furthermore, the first users of AVs are likely to be the more wealthy citizens, able to wield more influence in the political arena, where the regulatory debates will play out. A critical related question is one that has been raised earlier in this thesis: Which will be evident first, the negative externalities, or the societal benefits? One factor that might tip the scales is the political clout and investment by industry, who can be expected to spend heavily promoting the advantages of AVs, with the likely outcome that at least some members of society will be psychologically primed to see the benefits of AVs and totally unaware that any problems may arise.

One plausible narrative to illustrate these dynamics is as follows: *Even before AVs enter the market, industry will spend heavily to promote the benefits of the technology, building expectations among the general public. After an initial deployment of AVs, they will first be seen as a novelty or luxury, but as time goes by, people who use them will begin to depend on them, and they will be seen as a necessity. Furthermore, as time passes and more AV's are sold and used, the political clout of the AV users, user groups, and the industry will continue to grow. As sales grow, industry will invest more, and will therefore be even more committed to the success of the technology. And, as more AVs enter the market, statistics emerge about lower accident rates and how highway capacities are growing due to the growing fleet of AVs. At the same time, confusion emerges because it is also observed that roads are more congested than ever, there seem to be more cars around than ever before, and while highway fatalities have gone down, urban streets have become more dangerous for pedestrians and cyclists. People are also puzzled because gas prices keep going up as demand has risen, while the average fuel economy of cars has improved. As concerns rise, AV industry players lead the conversation, providing well-documented analysis of the improvements in fuel economy, safety, and traffic-flow efficiency of their AVs. While some interest groups point to solutions that would limit or reduce VMT, the solution that gains the most support is to further promote AV adoption and replace the fleet of aging, inefficient, dangerous CVs. The dominant belief is that the best way to solve congestion, energy use, and safety problems is through improved technology—in this case, ensuring full, unrestricted deployment of that most promising new technology, the AV.*

Chapter 6. Scenario #3: "AVs for New Uses in Limited Deployments"

Similar to the previous scenario, Scenario 3 assumes there will be major behavioral changes from the way automobiles are used today to the way AVs might be used. However, it differs from the first two scenarios by assuming a very challenging climate for early adoption of the technology—with high technology costs, high energy-prices, and high carbon prices. With these assumptions, in this chapter, I consider how the transportation system might react to a gradual or weak initial deployment of AVs, under a changing economic climate for new transportation technologies, and in potentially different applications from the conventional model of private vehicle ownership.

6.1. Summary of Assumptions.

6.1.1 Underlying Assumptions

1) **High Cost of AV Technology:** Initial costs are assumed to be high enough to make the perceived value (benefit/cost) of AV technology to be too low to justify private ownership of AVs for the vast majority of the population. These high costs could simply be due to the expensive and complex nature of the technology and difficulties faced by developers in reducing costs, especially in the early years with low production volumes. Or, it could be a result of liability issues: if the full burden of insurance falls on the manufacturer, then this will be factored into the purchase or lease-price of the vehicle. And, in the absence of real-world user data, insurance companies may seek to protect themselves with extremely high premiums until the technology is widespread and potential risks are known. It is important to acknowledge, however, that even with very high prices, with almost any new technology there will be some wealthy "innovators" and "early adopters" who will pay almost any price to try something new. Therefore, we do not conclude that there will be ***no*** private ownership of AVs, but that the level of private ownership will remain too small of a niche application to have significant effect—something comparable to the role of private limousine services.
2) **High Energy Prices, High Carbon Prices:** These factors are assumed to be strong enough to have a dampening effect on demand for use of private automobiles. While it might be unrealistic to expect a strong carbon policy to be implemented when energy prices are already high, there is reason to think that there could be a surge in energy prices ***after*** a strong policy is enacted (either as a response to that policy, or as an unrelated occurrence). On the other hand, a strong carbon policy could also go hand-in-hand with higher energy prices, as more-expensive renewable technologies would be put on the market to replace low-cost fossil-fuel-based sources.
3) **Strong Behavioral Reaction to AV Technology:** As in the previous scenario, this scenario assumes that eliminating the requirement for a competent and qualified human driver has the potential to radically alter the way people think about and use automobiles. Since the first assumption suggests that private ownership of AVs will be very limited, Assumption #3 will not play much of a role in how people use their own private vehicles, but how they conceive of ways

to use vehicles that they do not own. The implications for car- and ride-sharing are therefore central to the analysis in this chapter.

For this scenario, categories 4 and 5 (below) remain unchanged. However, the following assumptions could also be considered:

- **Planning, Investment, and Policies Related to Transportation Infrastructure Make a strong shift in favor of public transit.** This assumption aligns well with high energy-prices and a strong climate policy. If the public were committed enough to support carbon policies, then it is also likely that support for public transit would also grow.
- **Socio-Political Climate of Transportation Makes Strong Shift away from Automotive Travel.** This assumption would also align well with this scenario, because it could arise as a reaction to high energy prices and a stronger public commitment to addressing climate change.

While these assumptions are not necessary to observe the dynamics of this scenario, they align well with its overall theme and they could play a role in reinforcing its behavior—driving down automobile use and pushing the same general changes in key forces. They may also be worthy of consideration in case high energy-prices and high carbon prices do not materialize, as these alternate conditions could still arise and potentially produce similar behavior.

4) **Planning, Investment, and Policies Related to Transportation Infrastructure**
5) **Socio-Political Climate for Transportation**

The remainder of the assumptions are unchanged in this scenario:

6) **Full technology success for AV technology**
7) **Neutral policy climate for AV technology**
8) **Demographic changes unfold along current trajectories**
9) **Social Behavior and Workforce Trends unfold along current trajectories**

6.1.2 Initial Deployments

The underlying assumptions of this scenario describe a climate that could allow only limited adoption and use of AVs. The assumed high costs of AV technology would put private ownership of AVs out of reach of all but the wealthiest citizens. The resulting per-mile cost of AVs would be less than using a taxi or car-service, but far more than driving a conventional vehicle. The following characteristics of the initial wave of deployments follow from these assumptions:

- Ownership is primarily limited to commercial car-sharing services, so this scenario doesn't consider the impact of private ownership.

- The per-use cost is high enough that users will only hire an AV for short trips—potentially longer than the average taxi or car-service trip today, but not as long as trips made in rental cars or car-sharing-service vehicles.
- Commercial applications may still grow, but not as much in Scenario 2, as the high cost of paying drivers will only be partially offset by using AVs, due to their high capital cost. The growth in commercial traffic volumes is assumed not to be large enough to dramatically affect traffic congestion.

6.2 Changes in Key Forces and their direct effects on drivers and AV users.

The direct effects in this scenario are fairly limited, due to the prohibitively high cost of AV ownership. In addition, due to the assumptions about energy prices and carbon prices, the overall costs of AV and CV use will rise, having a deterrent effect on all automobile travel.

However, this scenario might represent a more favorable climate for vehicle sharing, especially when the role of empty-vehicle trips is considered. Some of the relevant potential causal relationships are shown in Table 6.1.

Table 6.1

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Energy Prices/Carbon Taxes	Perceived Relative Cost of Vehicle Sharing	-	Moderate	Strong	Perception of the Per-Use Cost of Vehicle Sharing may decrease due to the relative increases in per-mile costs of private vehicles. The per-use or per-trip costs of shared vehicles today appear high relative to the incremental per-use or per-mile costs for private vehicles (Anderson, 2014). This is due in part to the fact that the perceived per-mile costs of private vehicles is very small—the cost of gasoline accounts for less than 20% of the total of the total cost of vehicle ownership (AAA, 2015). If the cost of fuel were to double or triple, then shared vehicles would compare more favorably, as the proportion of total costs driven by non-fuel costs (fixed costs, depreciation, maintenance) would shrink, and the difference in perceived costs between shared vehicles and private vehicles would shrink.

Perceived Relative Cost of Vehicle Sharing	Attractiveness of Vehicle Sharing	-			
Empty-Vehicle Mobility	Door-to-Door Service	+	Strong	Very Strong	Empty-vehicle mobility would enable shared vehicle services to provide direct origin-to-destination (or "door-to-door") service.
Door-to-Door Service	Attractiveness of Vehicle Sharing	+	Very Strong	Very Strong	This could be one of the strongest factors in improving the attractiveness of vehicle sharing, because today vehicle sharing usually involves picking up and returning the vehicle to exactly the same location, and locations are sparse and seldom at the desired origin or destination.

Figure 6.1 connects these causal relationships, showing the overall positive effect on attractiveness of vehicle sharing. As discussed in Section 5.2.2, attractiveness/convenience of vehicle sharing by using AVs is functionally the same as reducing the cost of taxis and car services by using AVs. Figure 6.2 shows the similarly positive effect of this scenario's assumptions on the *Attractiveness of Using Car Services*.

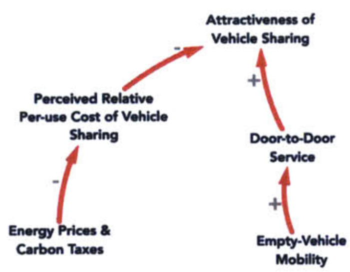


Figure 6.1. The Effects of Scenario 3's assumptions on Attractiveness of Vehicle Sharing.

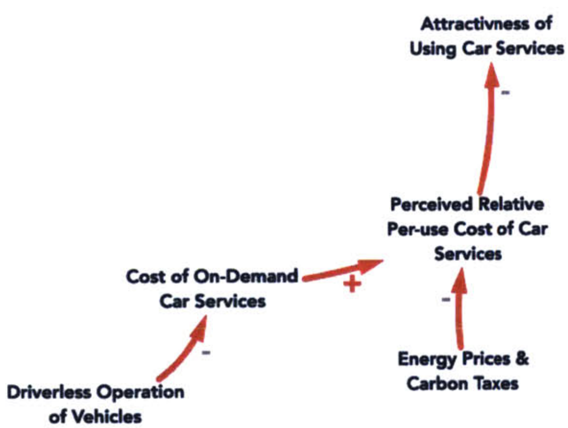


Figure 6.2. The Effects of Scenario 3's assumptions on Attractiveness of Using Car Services.

6.3 Potential System Effects

The overall conditions affecting the transportation system in this scenario are very different from the first two. To assess the system impacts, the key effects to consider are: (1) a number of factors are combining to reduce the attractiveness of private automobile use; (2) the cost of owning AVs is prohibitively high for most people; and (3) high energy prices and the arrival of AVs have greatly improved the appeal of car-sharing.

6.3.1. Effect on Self-Regulation of Traffic

To begin, we can consider some of the basic effects of this scenario's assumptions on travel behavior. Figure 6.3 shows how high energy prices will affect the balancing loop that "self-regulates" traffic congestion.

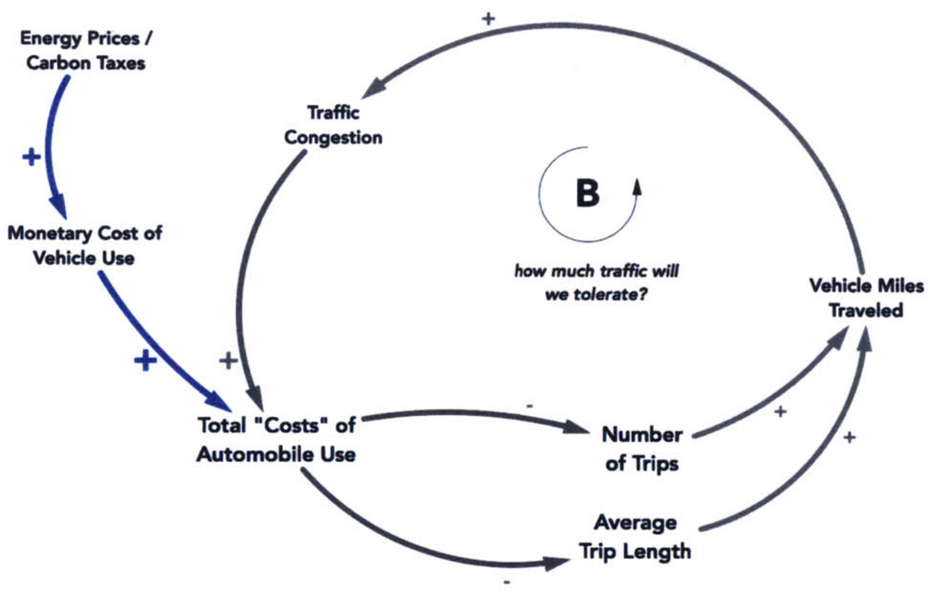


Figure 6.3. The Effects of Scenario 3's assumptions on Total "Costs" of Automobile Use. *(Blue arrows indicate previously identified dynamics newly incorporated into this model.)*

As discussed in Chapter 4, a balancing loop will tend to seek an equilibrium state, and that state will be determined by exogenous parameters and the strength of the relationship between those parameters and the variables in the feedback loop. In this case, high energy-prices and carbon taxes will have a strong—and very direct—effect on raising the monetary cost of vehicle use. If we hold other parameters constant, we know that this will cause the equilibrium values for the other variables to simply settle out at a lower level—with fewer trips, shorter trips, less VMT, and less traffic congestion.

6.3.2. Dynamics of Public Transit and Vehicle Sharing

The figures in this section—6.4, 6.5, and 6.6—illustrate several of they key dynamics of public transportation systems, particularly focusing on bus operations. As we consider the effect of AVs on the whole transportation system, it is important to understand these dynamics and how AVs might affect them. Later, in section 6.3.3, these dynamics will be combined with the automotive traffic diagram to help examine key interactions among the public transit and private automobile systems.

Table 6.2

Causal Link		**+/-**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**	**(polarity)**			
Traffic Congestion	Bus Speeds	-	Very Strong	Very Strong	Traffic Congestion, by definition, slows down traffic, and unless buses have their own dedicated lanes, they will also be slowed down.
Bus Speeds	Bus Frequencies	+	Very Strong	Very Strong	If buses are able to complete their routes faster, the same number of buses will provide more-frequent service.
Bus Speeds	Level of Bus Service	+	Very Strong	Very Strong	The level of service (or the quality experienced by the user) is improved with higher speeds, as trips will take less time.
Bus Frequencies	Level of Bus Service	+	Very Strong	Very Strong	The level of service (or the quality experienced by the user) is improved with higher frequencies, as average waiting time will be reduced.
Level of Bus Service	Time Costs of Public Transit	-	Very Strong	Very Strong	Both of the aspects of "level of service" considered above will reduce time costs.
Time Costs of Public Transit	Public Transit Trips Taken	-	Strong	Very Strong	This asserts that people will take more bus trips if the time-cost of the trip will be reduced.
Public Transit Trips Taken	Private Automobile Trips Taken	-	Strong	Very Strong	This asserts that some number of people who decide not to take public transit will decide to drive a private car instead, and vice versa.

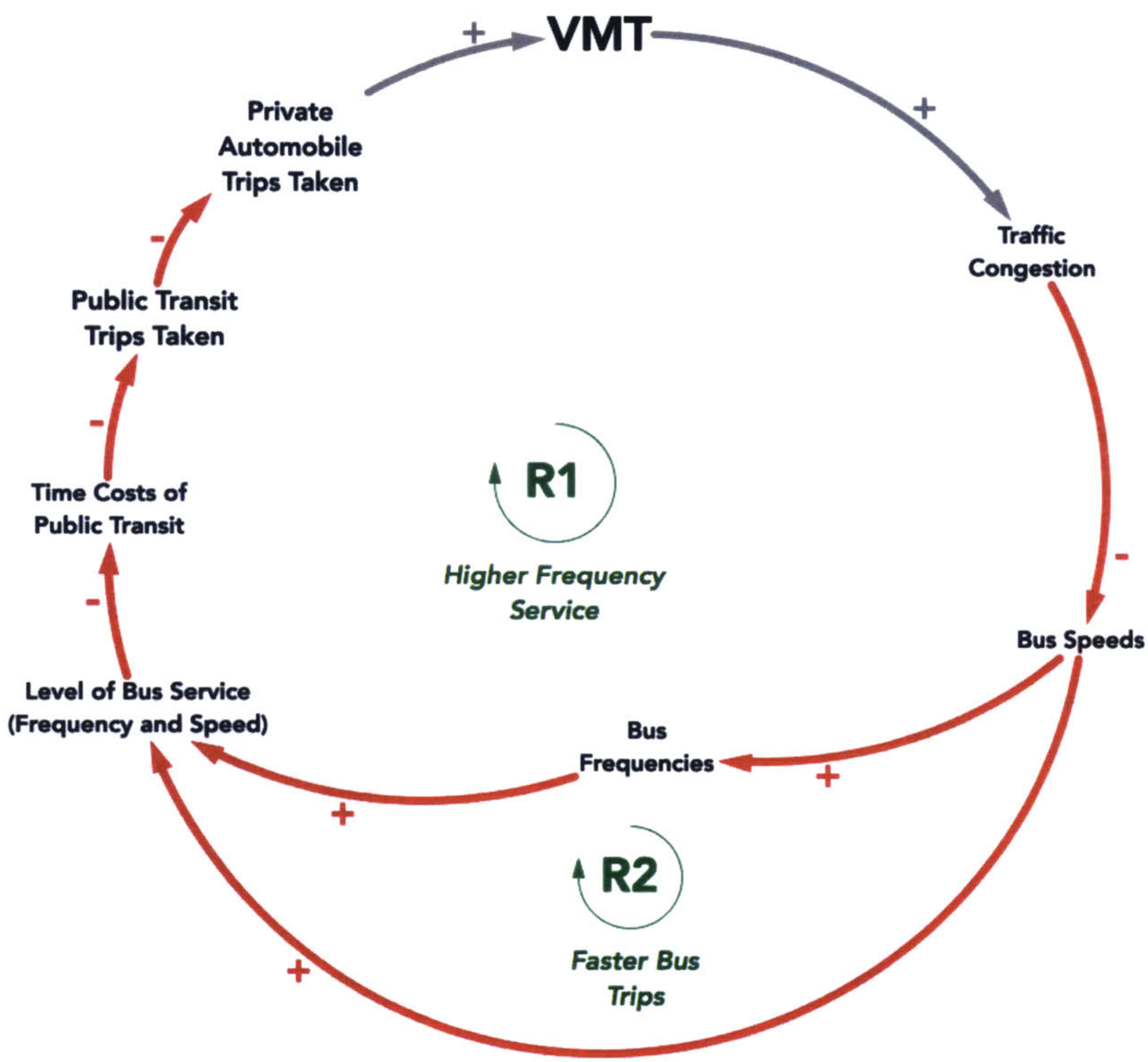


Figure 6.4. Some of the Key Dynamics Driving the Behavior of Public Transit Systems*, with particular focus on bus systems. (Red arrows indicate new relationships added in this section.)*

Figure 6.4 illustrates some of the structural dynamics of public bus transit systems, including two reinforcing loops.

- ***R-Loop, "Higher Frequency Service"***: as automobile traffic increases, traffic congestions increases, which reduces bus speeds, which reduces bus frequencies (as it takes longer to complete each cycle of a bus route), which reduces the level of service, which reduces the attractiveness of riding the bus, which drives more people away from buses and into cars, which increases traffic congestion, and so on.

- ***R-Loop, "Faster Bus Trips"***: as automobile traffic increases, traffic congestions increases, which reduces bus speeds, which reduces the level of service (by making it take longer to reach one's destination), which reduces the attractiveness of riding the bus. If we presume that a slow ride in a private car is more appealing than a slow ride in a bus (possibly crowded and uncomfortable), then this effect will drive more people away from buses and into cars, which increases traffic congestion, and so on.

Table 6.3, below, adds more variables, relating to the negative image that buses often have. This is based on the fact that as the appeal of any service diminishes, those who continue to use it are likely to be the ones who have no other choice. In the case of public transit, these are people who either cannot afford to live close to their desired destinations, cannot afford to own a car, or are too old to drive. As people exercise the option to drive instead of ride transit, the population of bus riders will increasingly appear to be the poor and elderly. This builds a social stigma that buses are for the poor or the elderly. Due to inherent social biases in favor of youth and wealth, this effect further drives down the attractiveness of riding a bus, which further drives people to exercise the option to drive instead.

Table 6.3

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Level of Bus Service	Attractiveness of Public Transit	+	Very Strong	By definition	Here, "Attractiveness of Public Transit" is defined as a function of the overall costs (broadly defined) of using transit and the quality of the service provided.
Attractiveness of Public Transit	Transit Trips by People Who Can Afford to Drive	+	Strong	Strong	It is reasonable to assume that as public transit improves, the costs and quality of service will be such that it will be more attractive than private automobiles, which suggests that some people who are able to drive will choose transit instead.
Transit Trips by People Who Can Afford to Drive	Economic & Demographic Diversity of Bus Riders	+	Moderate	Strong	This asserts that a key driver of the economic and demographic composition of bus riders is the fact that many people who ride buses do so because they can't afford to drive. This will depend largely on location, and if it holds true, then as more people who can afford to drive choose to ride transit, the economic diversity will increase, and the demographic diversity will increase as well, because it will add people to bus ridership who are not yet too old to drive.

Economic & Demographic Diversity of Bus Riders	Social Stigma of Buses	-	Strong	Strong	This asserts that there is a widespread notion that people who ride buses are either old or poor, and that as more people who are neither old nor poor ride buses, this perception will be reduced. Furthermore, this also asserts that, due to inherent social biases in favor of youth and wealth, the perception of buses as primarily for poor and elderly strengthens a social stigma against buses.
Social Stigma of Buses	Attractiveness of Public Transit	-	Moderate	Strong	It would be difficult to determine how much the social stigma of buses affects the overall "attractiveness" of riding buses. Here, the effect is assumed to be moderate.
Transit Trips by People Who Can Afford to Drive	Public Transit Trips Taken	+	Strong	By definition	
Transit Trips by People Who Can't Afford Cars or Can't Drive	Public Transit Trips Taken	+	Very Strong	By definition	

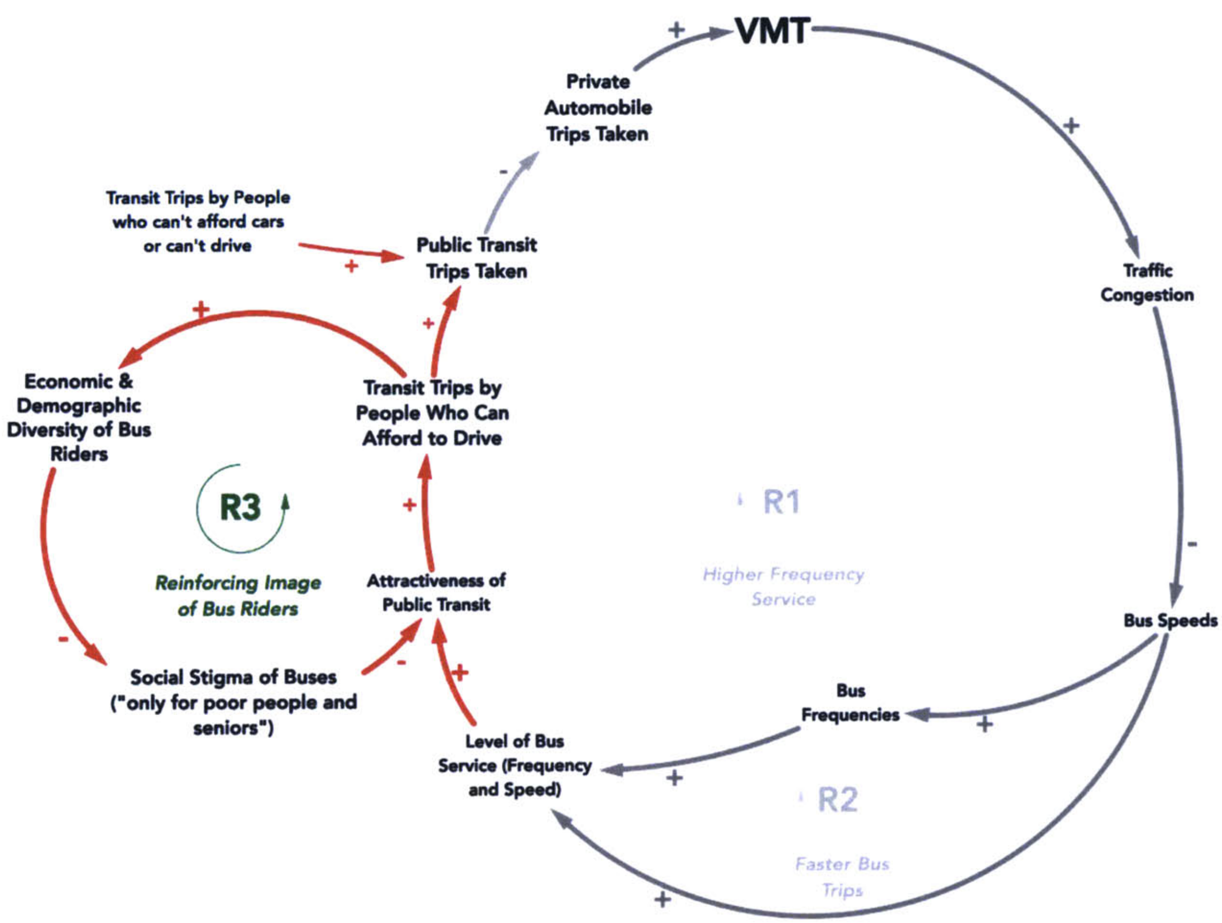


Figure 6.5 The Role of the Negative Image (or "Social Stigma") of Buses. *(Red arrows indicate new relationships added in this section.)*

Figure 6.5 shows that the factors identified in Table 6.3 produce a reinforcing loop, which will interact with the reinforcing loops in the rest of the model.

Table 6.4, below, shows causal relationships linking the effects of the scenario assumptions on vehicle sharing to the dynamics of public transit.

Table 6.4

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Attractiveness of Vehicle Sharing	Attractiveness of Using Shared-AVs to Access Transit ("FIRST MILE")	+	Very Strong	By definition	This just asserts that as vehicle sharing becomes more attractive in general, this specific application of vehicle sharing will also become more attractive.

Attractiveness of Vehicle Sharing	Attractiveness of Using Shared-AVs to Access Destinations FROM Transit ("LAST MILE")	+	Very Strong	By definition	This just asserts that as vehicle sharing becomes more attractive in general, this specific application of vehicle sharing will also become more attractive.
Attractiveness of Using Shared-AVs to Access Transit	Attractiveness of Public Transit	+	Very Strong	Very Strong	This asserts that the overall attractiveness of transit will be greatly improved by providing attractive alternatives for using shared-AVs to access transit.
Attractiveness of Using Shared-AVs to Access Destinations FROM Transit	Attractiveness of Public Transit	+	Very Strong	Very Strong	This asserts that the overall attractiveness of transit will be greatly improved by providing attractive alternatives for using shared-AVs to access destinations from transit.

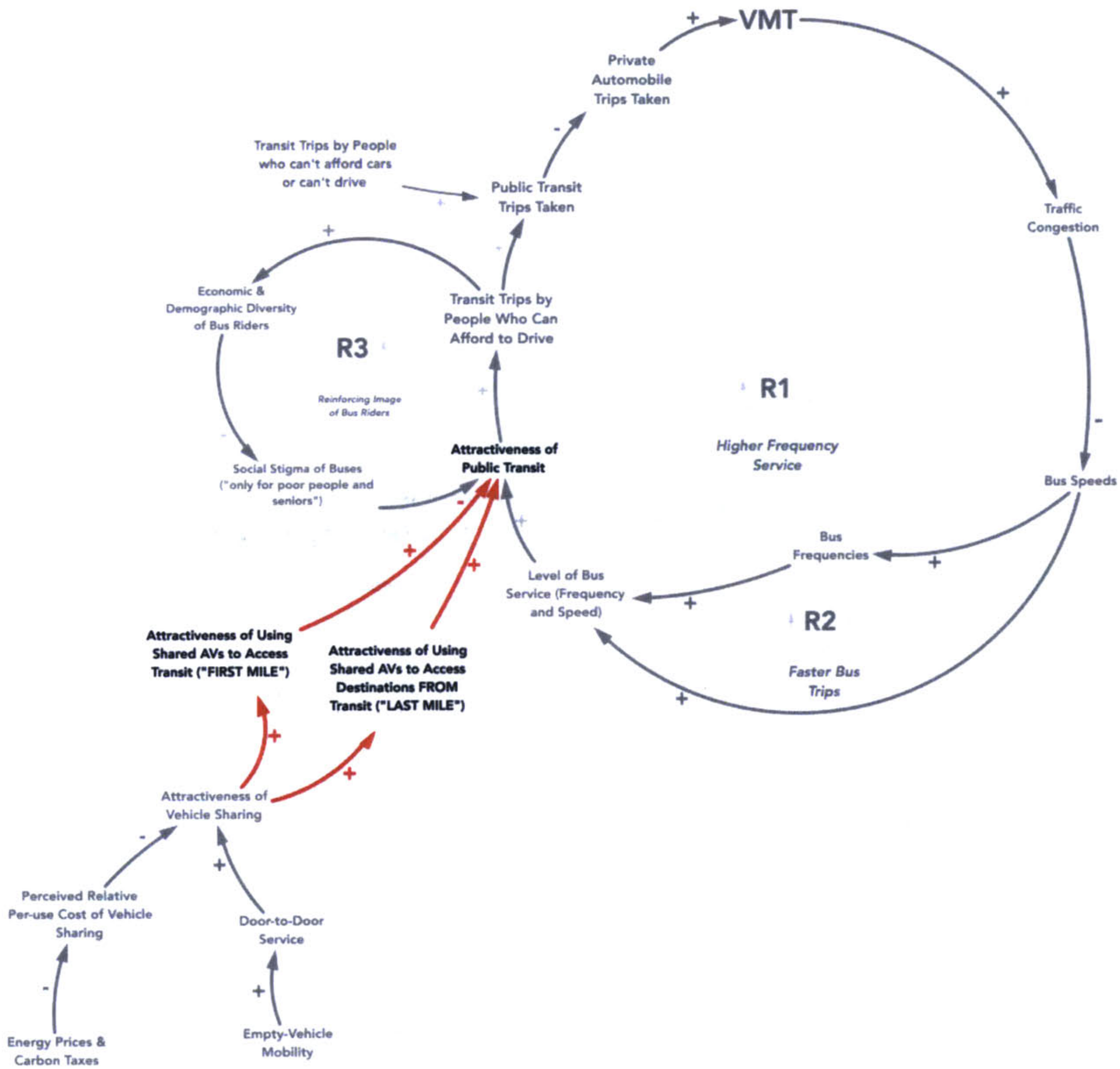


Figure 6.6. One effect of vehicle sharing on public transit. *(Red arrows indicate new relationships added in this section.)*

The structure of Figure 6.6 suggests that the effect of improved vehicle sharing systems on the public transit system could be quite substantial. The lack of "First Mile" and "Last Mile" connectivity is one of the main limiting factors to the attractiveness of public transit, and most attempts to increase connectivity by expanding transit networks can be very expensive and very inefficient. Current car-services would generally be too expensive to fill this role, especially for daily commuting trips (a 1-mile Uber fare in Cambridge, MA, starts at \$5-\$6, and possibly more with surge pricing). And, current car-sharing programs simply cannot help make these connections, as one-way trips are usually not an option, and when they are, their utility will be limited by the availability of parking. However, by enabling car-sharing services to provide door-to-door (in this case "door-to-transit") service, it appears that AVs could finally provide a viable solution to the "first mile/last mile" connectivity problem. If successful, the ultimate outcome could be a substantial reduction in VMT.

To expand our understanding of the dynamics of the transportation system—broadly defined—the dynamics in Figure 6.6 can be combined with the balancing loop developed in section 6.3.1. Additional causal relationships to connect these two sub-systems are shown in Table 6.5.

Table 6.5

Causal Link: Independent Variable	Causal Link: Dependent Variable	+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Attractiveness of AV Sharing	Shared-AV Trips Replacing Non-Motorized Trips	+	Moderate	Strong	With the increased convenience of vehicle sharing (which, as stated earlier, could also be seen as a very large reduction in the cost of car-services, like Uber), it should be expected that some people would prefer to pay to use a shared-AV for some trips they had previously done by foot or on a bicycle.
Attractiveness of AV Sharing	Shared-AV Trips Replacing Transit Trips	+	Moderate	Strong	With the increased convenience of vehicle sharing, it should be expected that some people would prefer to pay extra use a shared-AV for some trips they had previously made on transit. This effect may be weaker than the one above this one, because transit trips are usually longer than those taken by non-motorized modes. Furthermore, the improved attractiveness of public transit would reduce this effect even more.
Shared-AV Trips Replacing Non-Motorized Trips	VMT	+	Very Strong	By definition	
Shared-AV Trips Replacing Transit Trips	VMT	+	Very Strong	By definition	
Traffic Congestion	Attractiveness of AV Sharing	-	Strong	Very Strong	Due to the higher utility of time in an AV, people may be less concerned by traffic, but some negative effect can be expected.
Energy Prices & Carbon Taxes	Attractiveness of Private Automobile Use	-	Strong	Very Strong	This relationship is somewhat simplified, leaving out the intermediate variable *monetary cost of automobile use*.

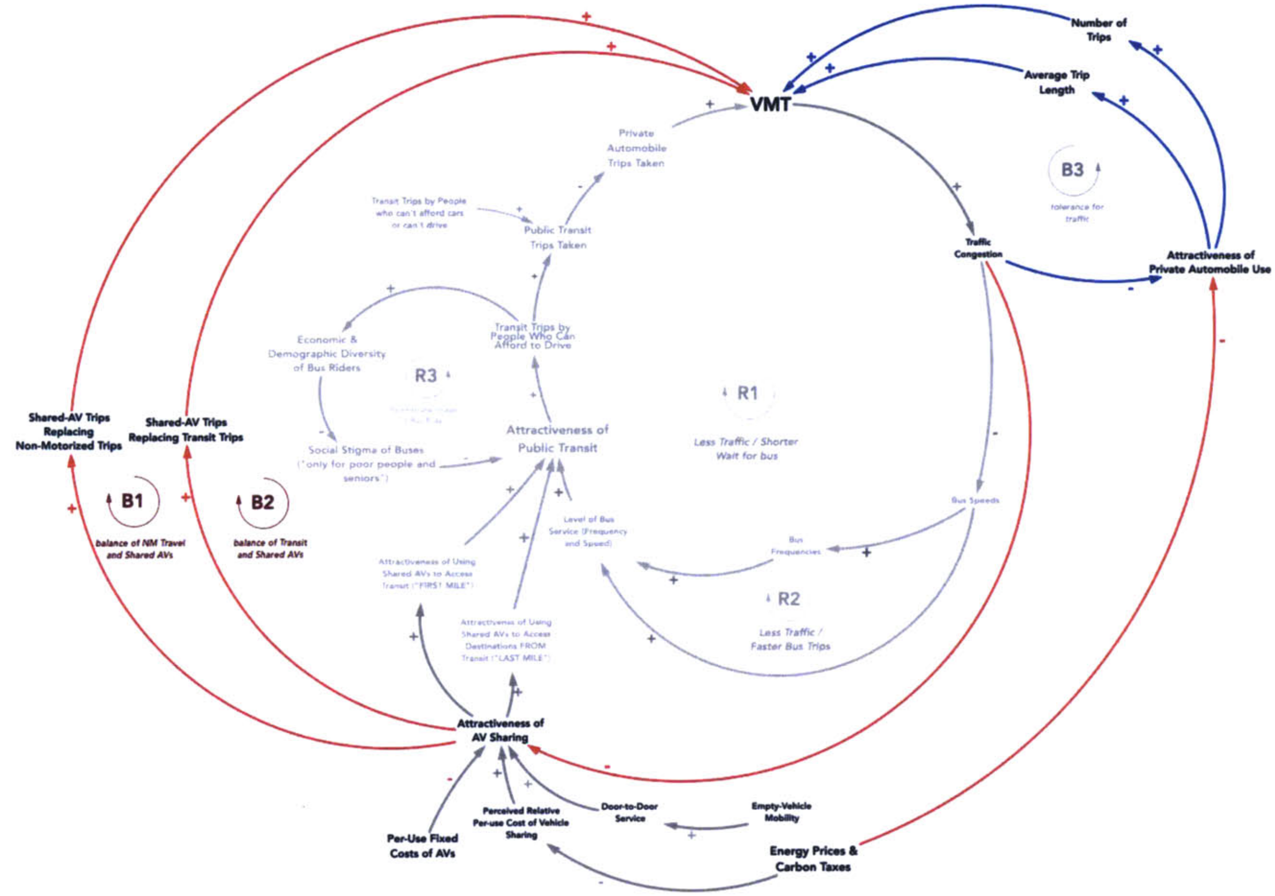


Figure 6.7. Expected Interactions Among Public Transit, Vehicle Sharing, and Private Vehicles. *(Red arrows indicate new relationships added in this section; blue arrows indicate previously identified dynamics newly incorporated into this model.)*

Figure 6.7 introduces three balancing loops. B3, which expresses the self-limiting behavior of traffic, provides a moderating effect between *Traffic Congestion* and *VMT*. This balancing loop will have a dampening effect on the benefits of AV sharing discussed above. The way this loop connects with the rest of the system structure suggests that as public transit bus services improve, VMT will go down, and traffic congestion will diminish. But this reduction in traffic will be likely to encourage more people to drive, thereby ultimately adding upward pressure to VMT and limiting how much effect the reinforcing loops in the bus system can have. The link between *Energy Prices and Carbon Taxes* and *attractiveness of private automobile use*, however, will weaken the effect of B3, as it will apply downward pressure to VMT.

The addition of AV sharing to the system is not all positive for improving public transit and reducing VMT. As loops B1 and B2 indicate, there is also the potential for people to use shared-AVs not to *access* public transit, but as a *replacement for* non-motorized travel or public transit. Most of the public transit trips that would be replaced by shared-AVs are likely to be shorter ones, due to the higher per-mile cost. However, the appeal of a "one-seat," door-to-door trip may be strong enough to justify significant added cost. This will especially be true if two or more people are traveling together and can share the cost of an AV trip.

6.3.2A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

The structure that emerges in Figure 6.6 and 6.7 shows that there will be three reinforcing feedback loops that will further reinforce each other. In other words, if a variable on any of these loops changes for any reason, all three of these loops will work to reinforce and accelerate further change in that direction. In the case of VMT, this means that any reduction in VMT is likely to spur further reductions that will accelerate each other unless counteracted by an opposing force. From an initial glance at Figure 6.6, it might appear that the new causal links from the introduction of shared-AVs could have a powerfully transformative effect on the system, as they will clearly play a role in improving the *attractiveness of public transit*, which should spur further self-reinforcing improvements throughout the system. However, with the addition of the balancing loops in Figure 6.7, it is apparent that these reinforcing effects will be limited to some degree. The interaction of these balancing and reinforcing loops raises further issues and questions:

- How strong will the effect of *Shared-AV Trips Replacing Transit Trips* be? If this effect is very strong, it could drive up congestion to the point where it would offset the benefits of AVs providing access to public transit (and the resulting activation of three reinforcing loops, R1, R2, and R3). A sample narrative interpretation of this dynamic is: *I used to ride in a shared-AV to get to the bus, but I figured out it was easier to just take the AV all the way to work. For a little more money, I got a one-seat ride with no waiting. And I get there faster than the bus, because we're all fighting the same traffic congestion, but I don't have any stops to make.*
- How strong will the effect of *Shared-AV Trips Replacing Non-Motorized Trips* be? This could cause severe localized congestion, as there are often a large number of NM trips concentrated at single locations, like subway or rail stations. It could also be a major factor in inclement weather, when people will be disinclined to walk or ride a bicycle.
- The strength of loops B1 and B2 will largely be determined by the exogenous variables, *per-use fixed costs of AVs* and *Energy Prices and Carbon Taxes*. In other words, if the cost of using a shared-AV is high enough, people will use them minimally, and for purposes that highly leverage the benefits they provide, like gaining convenient, comfortable access to mass transit. If the cost is low, however, their appeal could outweigh the appeal of transit, and they could have the opposite effect of driving up VMT.

6.4 Potential Macro-System Responses

6.4.1 Delayed Macro-System Reactions for Public Transit

Figures 6.4 and 6.5 explored some of the structure of a generic public transit system and analyzed some of the ways that the system might respond to the deployment and use of AVs in this scenario. In this section, I expand that analysis to consider a key macro-system response, which involves changes that might occur within the public transportation system. Table 6.6 shows a few causal relationships that can be expected to play a role in responding to changes in VMT.

Table 6.6

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Traffic Congestion	Cost of Bus Operation	+	Strong	Very Strong	Congestion increases fuel consumption and wear and tear on buses.
Cost of Bus Operation	Number of Buses in Service	-	Very Strong	Very Strong	
Number of Buses in Service	Bus Frequencies	+	Very Strong	Very Strong	
Public Transit Trips Taken	Farebox Revenues	+	Very Strong	Very Strong	
Farebox Revenues	Number of Buses in Service	+	Moderate	Very Strong	The number of buses in service will also be strongly determined by service policies regarding crowding (i.e., service policies will set maximum crowding levels, and a certain number of buses will be required to meet these policies)

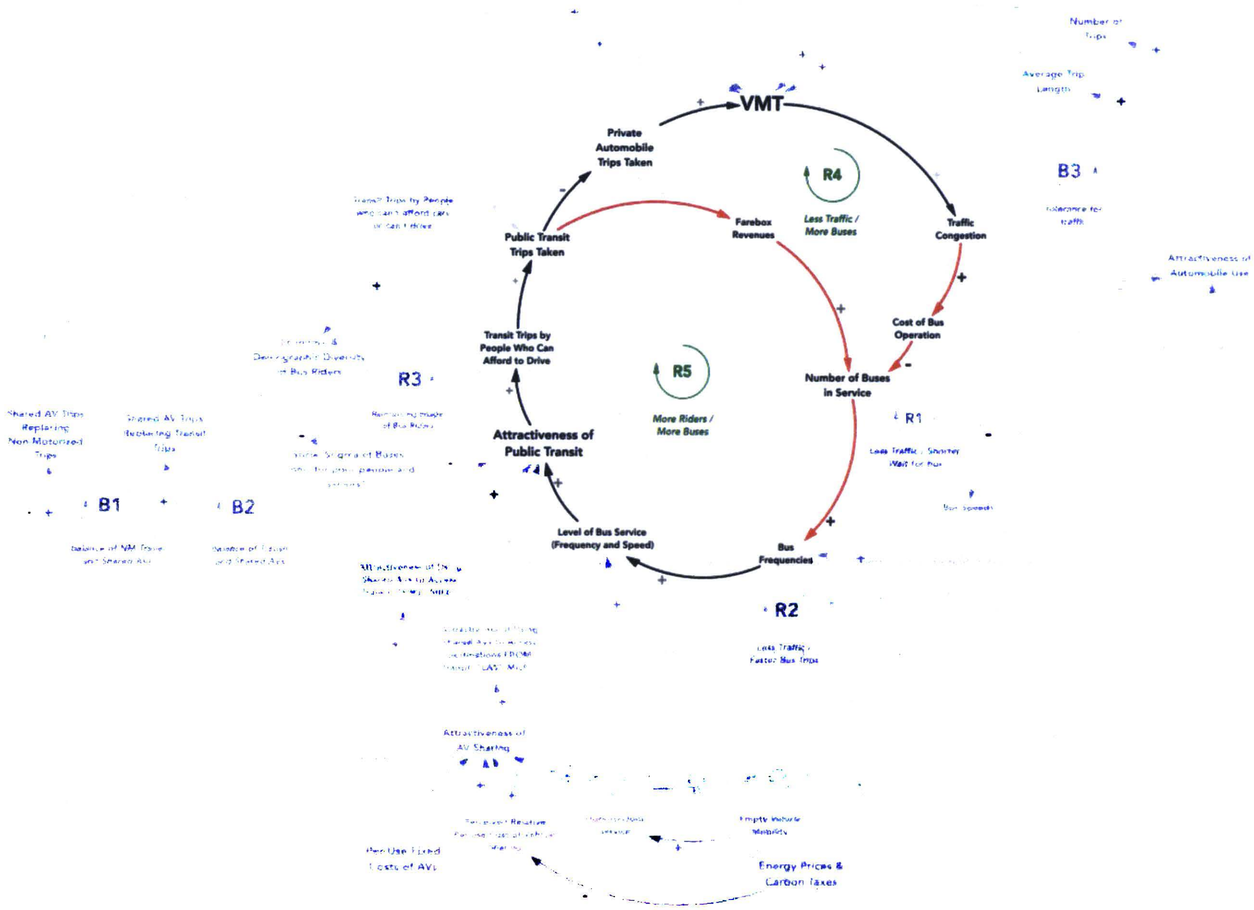


Figure 6.8. Macro-system relationships that may affect the public transit system in response to changes in VMT. *(Red arrows indicate new relationships added in this section.)*

After integrating these relationships into the CLD (Figure 6.8), two new reinforcing loops appear:

- ***R4, "Less Traffic, More Buses"***: ***If VMT increases,*** traffic congestion increases, which increases the cost of bus operation (increased fuel consumption and wear due to stop-and-go movements and more operator hours to complete a route), which reduces the number of buses that agencies can keep in service, which reduces bus frequencies, which reduces the attractiveness of public transit, which drives more people away from buses and into cars, which increases traffic congestion, and so on. ***If VMT decreases***, the cycle runs the opposite way, ultimately increasing the number of buses and driving further reductions in VMT.
- ***R5, "More Riders, More Buses"***: In this case, VMT is actually outside of this loop, but because the changes in variables in this loop will affect those in R4, the effects are closely related. ***If VMT increases***, the *cost of bus operation* increases and *bus speeds* decrease, which both ultimately reduce the *level of bus service*, which reduces the attractiveness of public transit, which reduces the number of public transit trips taken, which reduces fare-box revenues, which further reduces the number of buses in service.

Note that there are important delays in the system here: as the cost of bus operation changes, the number of buses in service will not respond immediately. The transit agency will likely go through an extensive review process before determining where and how to increase or reduce service.

6.4.2 Combined Reactions of Public Transit and Vehicle Sharing Systems

One of the key effects in Scenario 3 is the positive effect that AVs could have on vehicle sharing, due to their ability to make empty-vehicle trips. This section considers dynamics related to vehicle sharing and examines how they interact with the public transportation system. Table 6.7 shows additional variables and causal relationships relevant to vehicle sharing.

Table 6.7

Causal Link		+/-	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**	**(polarity)**			
Attractiveness of Vehicle Sharing	Customers' Use of Vehicle Sharing Programs	+	Very Strong	Very Strong	Other factors may come into play, but the overall "attractiveness," the way the term is used here, will play a large role.
Customers' Use of Vehicle Sharing Programs	Revenues	+	Very Strong	Very Strong	
Revenues	Capacity Expansion	+	Strong	Very Strong	It is expected that this will be very non-linear relationship.
Capacity Expansion	Access to Shared Vehicles	+	Very Strong	Very Strong	This is also expected to be very non-linear and also location-dependent.
Access to Shared Vehicles	Attractiveness of AV Sharing	+	Very Strong	Very Strong	This asserts that easy access to vehicles is essential to of the convenience of using shared vehicles, and that convenience plays a major role in their overall "attractiveness."

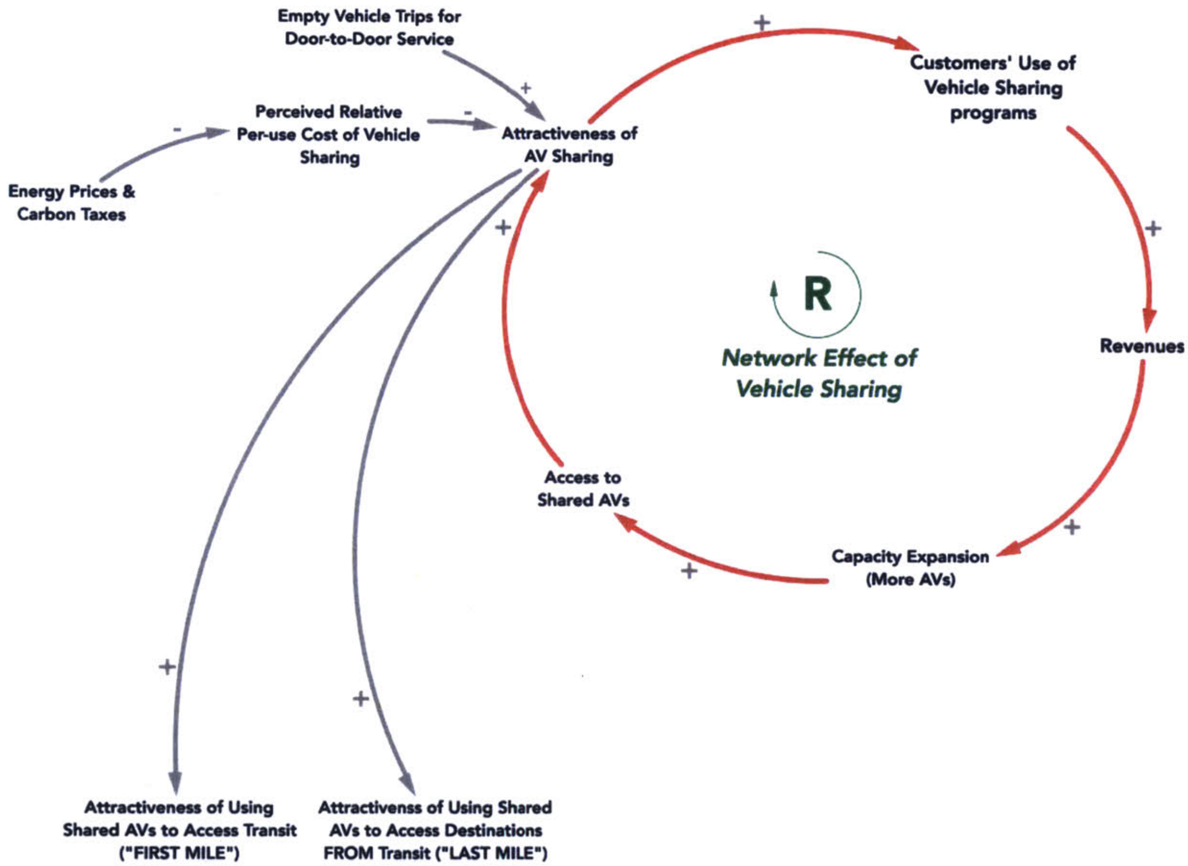
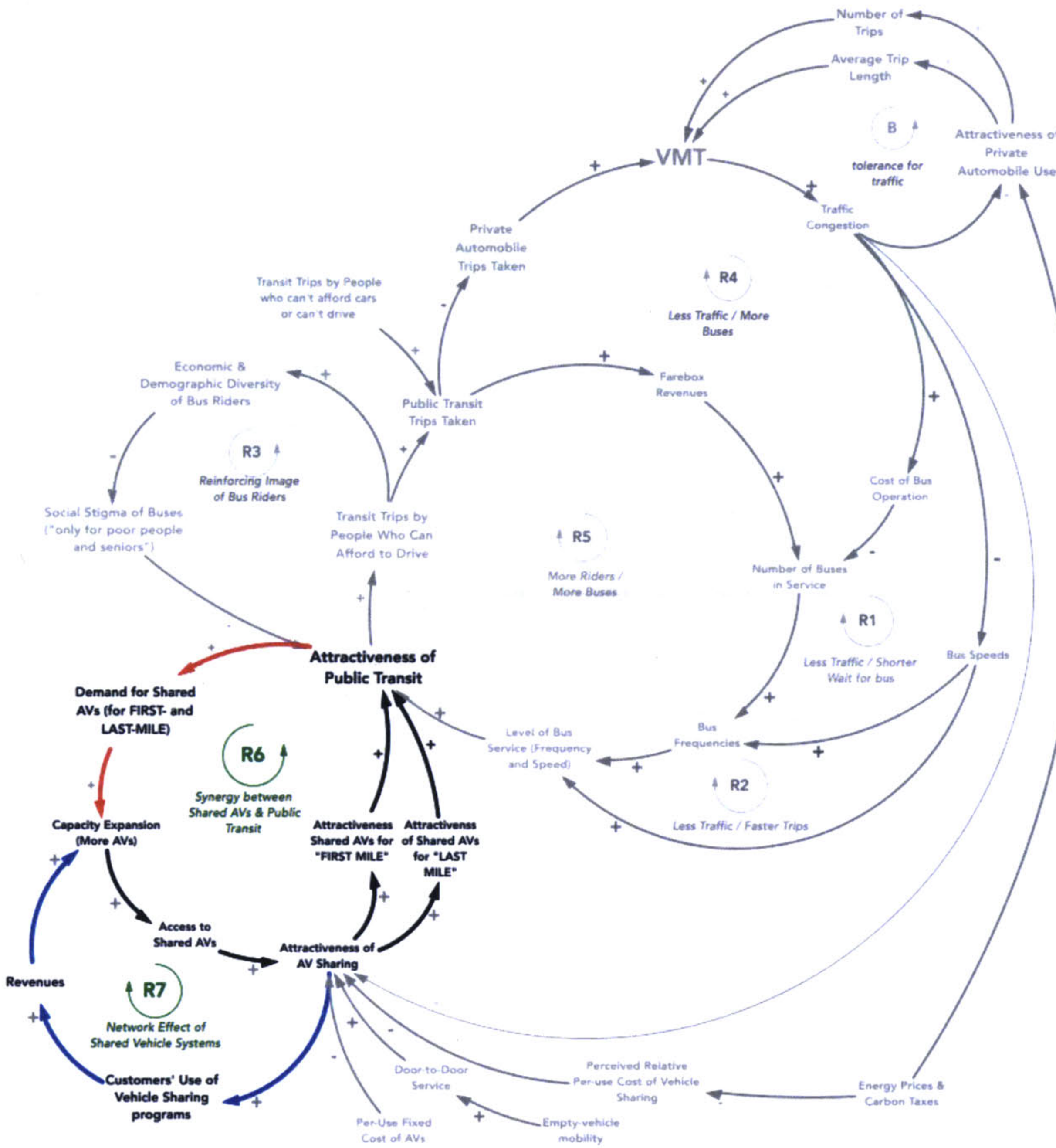


Figure 6.9. Network Effect on Vehicle Sharing. *(Red arrows indicate new relationships added in this section.)*

The key dynamic that emerges in Figure 6.9 is the *Network Effect*, a reinforcing loop. In this scenario, there are two exogenous variables driving this loop: (1) the ability of AVs to make empty vehicle trips and (2) high energy prices and carbon prices. The resulting effect is an increase in the attractiveness of vehicle sharing, which increases customers' use of vehicle sharing programs, which increases revenues and leads to capacity expansion. Unlike in the case of public transit, there should not be significant delays in the system here, as a vehicle-sharing operator can very quickly add AVs to the fleet in response to increased demand. This increased capacity increases access to shared-AVs, which in turn increases the attractiveness of vehicle sharing, and so on.

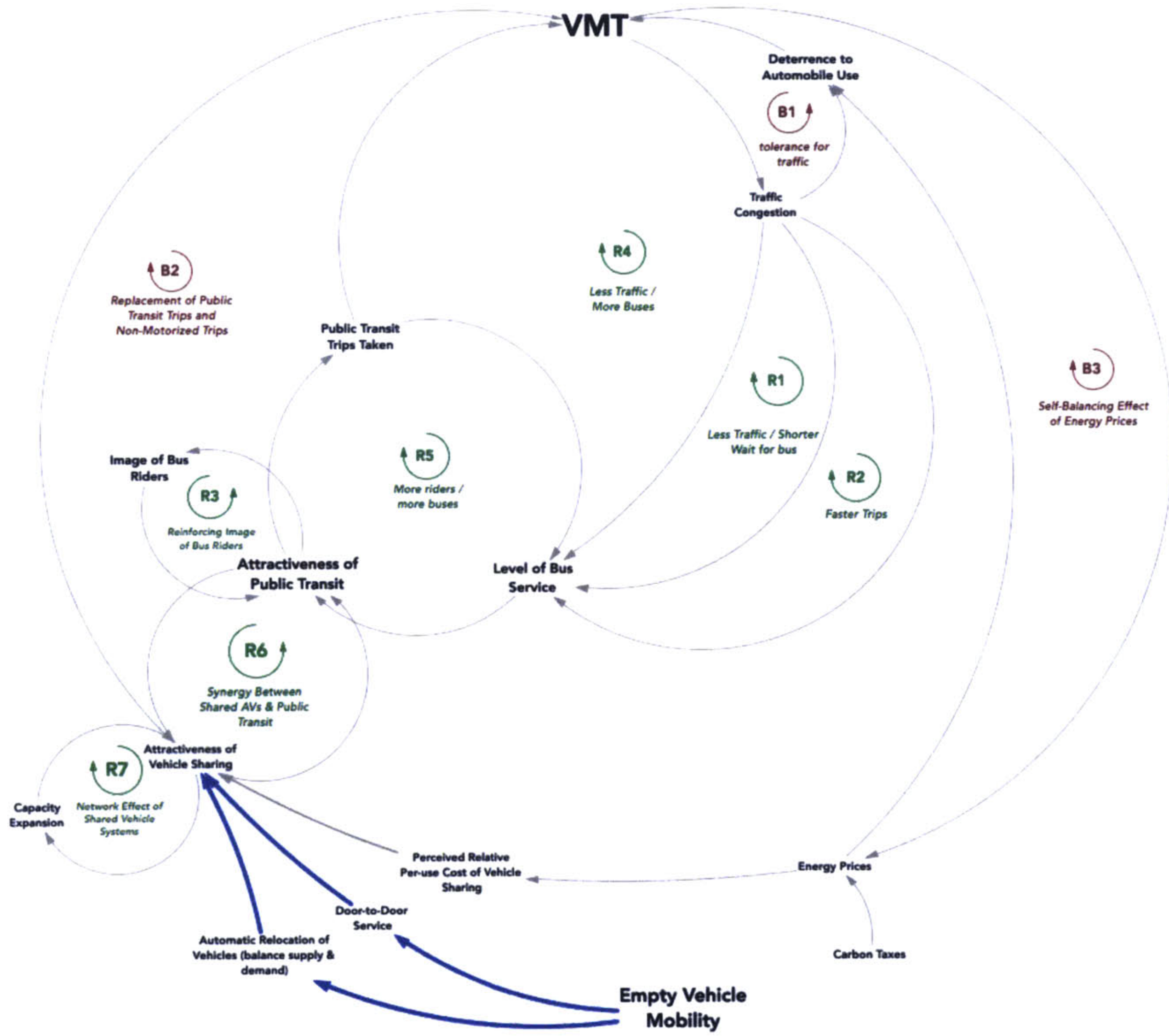
Table 6.8 shows two additional causal relationships that will complete the connections between the vehicle sharing system and the public transit system.

Table 6.8					
Causal Link					
Independent Variable	**Dependent Variable**	**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Attractiveness of Public Transit	Demand for Shared-AVs (for FIRST- and LAST-MILE)	+	Strong	Strong	Part of the assertion involved here is that as other aspects of public transit become more appealing, the "first- and last-mile" problem will loom larger. More people will want to use transit, but find that this issue is a primary impediment. This will increase demand for first- and last-mile solutions, of which shared-AVs could be a very effective approach.
Demand for Shared-AVs (for FIRST- and LAST-MILE)	Capacity Expansion (More Shared-AVs)	+	Strong	Very Strong	There may be other factors that impede capacity expansion, but the underlying connection between demand and expansion will remain.



6.10 Combined CLDs showing multiple interactions of vehicle-sharing system and public transit system. *(Red arrows indicate new relationships added in this section; blue arrows indicate previously identified dynamics newly incorporated into this model.)*

Adding the causal links from Table 6.8 shows that the public transit system and the vehicle-sharing system are linked in a reinforcing loop ("R6: Synergy between Shared-AVs and Public Transit"). The most central variable in this diagram is *Attractiveness of Public Transit*: changes in this variable will drive changes in the reinforcing loops throughout the public transit system and the shared-AV system.



6.11 Simplified CLD, with Energy Effect included. *Note that to simplify the diagram and focus on the key dynamics, several variables have been removed, and the polarities have been removed from the arrows (the dynamics can be understood by the name and orientation of the loop-labels).*

Figure 6.11 is a simplified diagram that summarizes the effects discussed in this chapter. It also includes an additional loop (B3), showing the balancing effect of energy prices: If VMT drops significantly, energy prices may fall, reducing the relative advantage of vehicle sharing, which will reduce the attractiveness of vehicle sharing (compelling more people to drive their own cars) and therefore reducing the effect of all the connected reinforcing loops in the model, thereby putting upward pressure on VMT.

6.4.2A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

From a cursory examination of Figure 6.11, it would be easy to conclude that the system is dominated by several potentially powerful reinforcing loops. This would suggest a largely unstable system, prone to gravitating toward extremes. If one were interested in reducing VMT, an optimistic interpretation would be that the introduction of shared-AVs could have a profoundly positive effect, especially if it coincided with other factors making cars less appealing (such as high energy costs). The combination of these factors might push the system past a tipping point, which would have cascading effects throughout the system, ultimately reversing the reinforcing loops that have marginalized public transit in most of the country—turning them into virtuous cycles and ushering in a new age of transportation, dominated by public transit systems that would vastly improve the efficiency (in terms of space and energy) and greatly reduce many of the harmful effects of our transportation system.

A pessimistic interpretation for public transit interests would be that the availability of shared-AVs in would be a very attractive alternative to public transit, even in denser urban areas. Shared-AVs would also allow more people to experience very convenient (door-to-door) travel by automobile who otherwise would not be able to own a car, and many more trips would be possible that weren't in the past because there would no longer be a need to park at the destination. By pulling a number of riders out of the public transit system who can afford to pay slightly more for shared-AV rides, a number of reinforcing loops would be activated in the opposite direction, potentially undermining the public transit system.

Evidence of extreme behavior. The suggestion of instability by these reinforcing loops is actually borne out to some degree by history. For example, in most places in America, the dynamic interplay of public transit and automobiles has not resolved in a "moderate" equilibrium state that reflects the inherent advantages and disadvantages of each mode. If it had, one would expect a more balanced mix between use of transit and private cars across the country, varying somewhat in proportion to population density (with more transit use as density increases and more car use as it decreases). Instead, historically, the initial tension between cars and public transit systems (usually in the form of streetcars) was resolved in the near-total collapse of the streetcar system, which was completely overwhelmed by the vicious cycles driving their demise and the virtuous cycles driving the adoption of automobiles. What remains in most cities and towns in the United States is a shell of public transit, often limited to the bare amount necessary to ensure mobility for those too poor or infirm to use automobiles. The cities where public transit plays a dominant role are in the slender minority, and public transit's presence is often maintained only through proactive policies or in areas where population densities impose severe limits on the amount of roads that can be built and the number of cars that can be parked.

Sources of stability. There are also sources of stability in the system, including balancing loops B1 and B3. B1 provides an inherent deterrent to driving, which will also apply to AV use, and should provide some limit on VMT. Then, in loop B3, as VMT increases, energy use will increase, which should drive up prices. However, this is an unreliable effect, as oil prices are determined by many other factors beyond VMT in a given area. There are also a number of effects that may stabilize the system, which aren't shown in this diagram but are likely to arise after the dynamics in the system have some time to play out. For example, the reinforcing loop that shows the "network effect" only indicates the strong reinforcing relationships present in the early stages of a network's growth. Of course, as a network grows, eventually it reaches a size where there are diminishing returns to continued growth and the market eventually becomes saturated. The important question from such a loop, then, is: What is that saturation point? Which, in this case, translates to: How big will the capacity of AV-sharing systems be?

Other resistance to change—threshold effects. Many if not all of these reinforcing loops have certain thresholds that must be crossed before the loop truly becomes "activated." In a more detailed model, other variables would be included to show these forces. For example, increasing the number of people who ride public transit does not guarantee a direct system response that will improve the level of service. Nor does a small improvement in the level of service guarantee an immediate response in the form of increased ridership. The changes must be noticeable enough to affect the behavior of the users of the system or they must reach a level that compels system operators to respond. Therefore, to understand and predict which way these feedback effects are likely to work, it will be necessary to answer the following questions:

1. Will exogenous effects on the model assumed in this scenario (the increasing energy prices and carbon pricing) reduce the attractiveness of automobile use enough to cause a reduction in traffic that will noticeably improve the level of service of bus operations?
2. How strong will the impact of empty vehicle trips be on the attractiveness of vehicle sharing? Will it be enough to drive significant expansion of the network? Will this expansion be enough to improve the attractiveness of public transit and drive further expansion of public transit systems?
3. How quickly or slowly will transit operators respond to growth in demand and fare-box revenues to expand bus fleets? If this reaction is too slow, will there be another feedback effect, where riders are discouraged by overcrowding and some revert to driving?

Ultimately, if the goal were to reduce VMT, foremost among the concerns would be the possible effect of switching from public transit and non-motorized modes to shared-AVs (loop B2) and the cost of energy. Such a goal might compel policy-makers to consider VMT charges, or to develop ways to ensure that the effect of loop B2 is limited and that there remains a floor on energy prices (so that no matter how low demand for oil drops, the price will not fall low enough to attract drivers back onto the roads).

Integration of Shared-AVs and Public Transit—Taken One Step Further

While it is not essential to this scenario, the dynamics in this model suggest another sub-scenario that could evolve, where public transit operators and "last-mile providers" (shared-AV operators) form partnerships. In these partnerships, the shared-AV operators would provide services to cover under-utilized bus routes, which can be very inefficient and expensive to run. In return, transit operators would subsidize the AV trips to make them affordable—either as a part of a linked, single-fare route, or with only a small premium. Costs could be even further reduced through implementation of a shared-ride system, which might result in slightly longer trips and slightly longer wait-times, but surely a vast improvement over the current service on underperforming feeder bus-routes. To understand the scale of the impact such an arrangement could have, it's worth considering that the 15 busiest bus routes in the Boston Area's transit system (the MBTA) carry approximately 40% of all bus passengers in the system. It takes roughly 150 more routes to carry the remaining 60% of bus riders. Furthermore, as of 2012, there were 18 routes in the MBTA system that had a net cost to the MBTA of more than $5 per passenger-trip (MBTA 2014). In addition, some of these routes are relatively short—e.g., the #217 (Wollaston Station - Ashmont Station), which is no more than three miles from the Red Line subway at any point on the route—so the entire bus line could be replaced by on-call shared-AV services that would reduce costs for even the most isolated passengers. Given the scale of the inefficiency of providing regular bus services on certain routes, it's possible that significant funds could be saved, and resources re-allocated to improve service on the trunk lines.

6.4.3 Infrastructure Effects

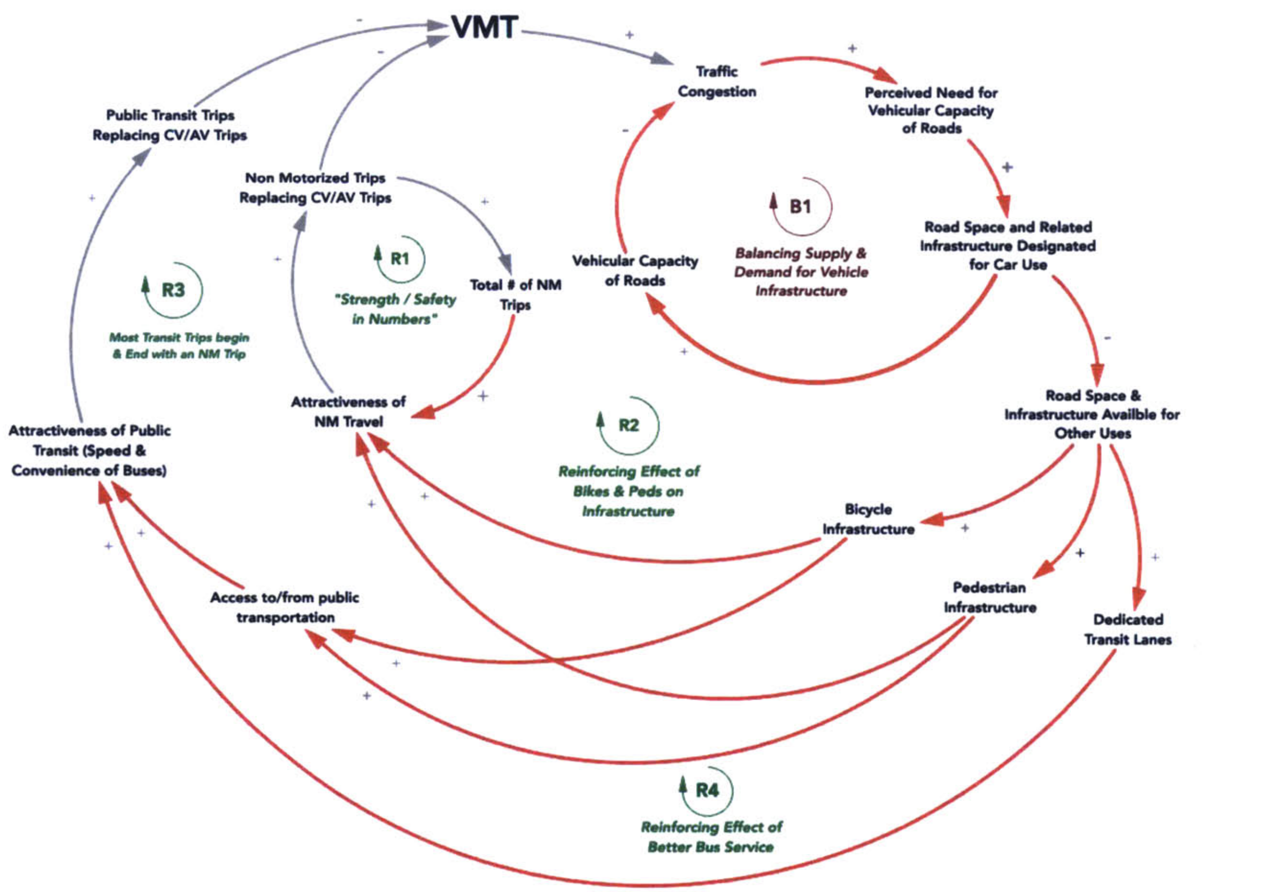
This section examines some of the potential macro-system responses that will affect the transportation infrastructure. Since they involve physical alteration of the existing infrastructure, some delay can be reasonable expected between the initial wave of adoption of AVs, the observation of the effects on the transportation system, and the effects on the infrastructure. Table 6.9 lists some of the key relationships that can be expected to influence changes to the infrastructure.

Table 6.9

Causal Link		+/- (polarity)	Hypothetical Strength of Causal Relationship	Strength of Hypothesis that Causality Exists	Notes
Independent Variable	**Dependent Variable**				
Traffic Congestion	Perceived Need for Vehicular Capacity of Roads	+	Very Strong	Very Strong	This relationship represents the most direct reaction to congestion—the notion that because congestion arises when the number of cars exceeds a road's intended capacity, the solution is to increase capacity.
Perceived Need for Vehicular Capacity of Roads	Road Space and Related Infrastructure Designated for Car Use	+	Strong	Very Strong	While traffic engineers have long recognized the potential role of induced demand and the possibility of unintended consequences from expanding road space designated for car use, I assume there is still a strong relationship here.
Road Space and Related Infrastructure Designated for Car Use	Vehicular Capacity of Roads	+	Very strong	Very strong	It should be noted here, that road space is not the only factor, and AVs in particular, may play a strong role in increasing road capacity, through more-efficient driving and routing. This effect has been discussed in other sections of this thesis.

Vehicular Capacity of Roads	Traffic Congestion	-	Very Strong	Very Strong	This is a very strong relationship, and—***all other things being equal***—changes in road capacity will have a direct effect on congestion.
Road Space and Related Infrastructure Designated for Car Use	Road Space & Infrastructure Available for Non-Car Purposes	-	Very Strong	Very Strong	Assuming some limits on how much total space is available for all transportation modes, there will be some direct tradeoff between the space available for cars and the space available for other modes.
Road Space & Infrastructure Available for Non-Car Purposes	Bicycle Infrastructure	+	Very Strong	By definition	
Road Space & Infrastructure Available for Non-Car Purposes	Pedestrian Infrastructure	+	Very Strong	By definition	
Road Space & Infrastructure Available for Non-Car Purposes	Dedicated Bus Lanes	+	Very Strong	By definition	
Bicycle Infrastructure & Pedestrian Infrastructure	Attractiveness of Non-Motorized (NM) Travel	+	Very Strong	Very Strong	This asserts a very strong relationship between the adequacy of infrastructure and the attractiveness of a given mode of travel. This may be especially strong for non-motorized (NM) travel, as inadequate infrastructure may make greatly amplify concerns about safety.
Bicycle Infrastructure & Pedestrian Infrastructure	Access To/From Public Transportation	+	Very Strong	Very Strong	This reflects the fact that most public transit trips involve NM travel at the beginning and end.
Access To/From Public Transportation	Attractiveness of Public Transit (speed & convenience)	+	Very Strong	Very Strong	It stands to reason that if it is difficult to access a service, no matter how good that service is, it will remain unappealing to use.
Dedicated Bus Lanes	Attractiveness of Public Transit (speed & convenience)	+	Very Strong	Very Strong	Dedicated bus lanes could dramatically reduce or eliminate the effect of traffic congestion on bus operations, thereby improving speeds, frequencies, etc.

Total # of NM Trips	Attractiveness of NM Travel	+	Strong	Strong	This asserts that as more people walk or travel by bicycle in a given area, the level of comfort with those modes of travel increases. E.g., this presumes that people will feel safer walking on a path when there are more people around them than if they are alone; and, similarly, cyclists may feel safer in a pack of bicycles, which will be more visible than a lone cyclist, and will demand more attention from drivers, and possibly even slow down traffic speeds.



6.12 Potential Macro-system responses affecting transportation infrastructure. *(Red arrows indicate new relationships added in this section.)*

In Figure 6.12, the balancing loop, B1, represents a fairly straightforward effect, illustrating the common (if uninformed) notion that the proper response to congestion is to provide more road space for cars. And, if demand remains constant and VMT is unchanged, this would be successful, with road capacity expanding to reduce congestion enough to diminish the demand for additional capacity. However, if VMT initially falls instead (as we might expect from the behavior of the rest of the system in this scenario), and there is a reduction in demand for road capacity for cars, this may make road space available for other uses, which could trigger any of the four reinforcing loops, all in ways that will further reduce VMT:

- **R1 "Strength/Safety in numbers":** If the available road space were repurposed for bicycle or pedestrian infrastructure, this would increase the *attractiveness of non-motorized (NM) travel*, which will result in more bicycle or pedestrian trips replacing automobile trips, which will increase the *total number of NM trips*, which can also be expected to increase the *attractiveness of non-motorized travel*. As explained in table 6.9, they underlying hypothesis of this causality is that cyclists and pedestrians feel safer in larger groups, in part because they are more visible, they have a calming effect on overall traffic speeds, and they have a psychologically reinforcing effect of showing other potential cyclists or pedestrians that the area is safe.
- **R2 "Reinforcing Effect of Bikes/Peds on Infrastructure":** If the available road space were repurposed for bicycle or pedestrian infrastructure, this would increase the *attractiveness of non-motorized travel*, which will result in more bicycle or pedestrian trips replacing automobile trips, which will further reduce VMT, leading to even more available road space.
- **R3 "Most transit trips begin and end with an NM Trip":** If the available road space were repurposed for bicycle or pedestrian infrastructure, this would increase *access to/from public transportation*, which will result in more transit trips replacing automobile trips, which will further reduce VMT, leading to even more available road space.
- **R4 "Reinforcing Effect of Better Bus Service":** If the available road space were repurposed for dedicated transit lanes, this would increase *attractiveness of public transportation*, which will result in more transit trips replacing automobile trips, which will further reduce VMT, leading to even more available road space to be converted into more transit lanes.

6.4.3A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

One particularly interesting aspect of Figure 6.12 is that it appears very likely that the behavior of the system may get "worse before it gets better." If planners attempt to stimulate the reinforcing loops in a direction that will reduce VMT by building bike lanes and bus lanes and expanding sidewalks, first, there will be a delay during construction, where users of the street will have to endure reduced capacity for vehicles without even having the benefits of the expanded infrastructure for non-automotive modes. Then, even after construction is finished, there will be another delay, while behavior adapts to the new infrastructure: people who used to drive will not simply all switch to non-automotive modes overnight. Such delays may be a significant source of apprehension about undertaking such efforts. However, if VMT were to fall initially and provide a surplus of road capacity, then that would be an opportune moment for infrastructure changes to be made, before new demands can emerge to fill the road's capacity for automobiles.

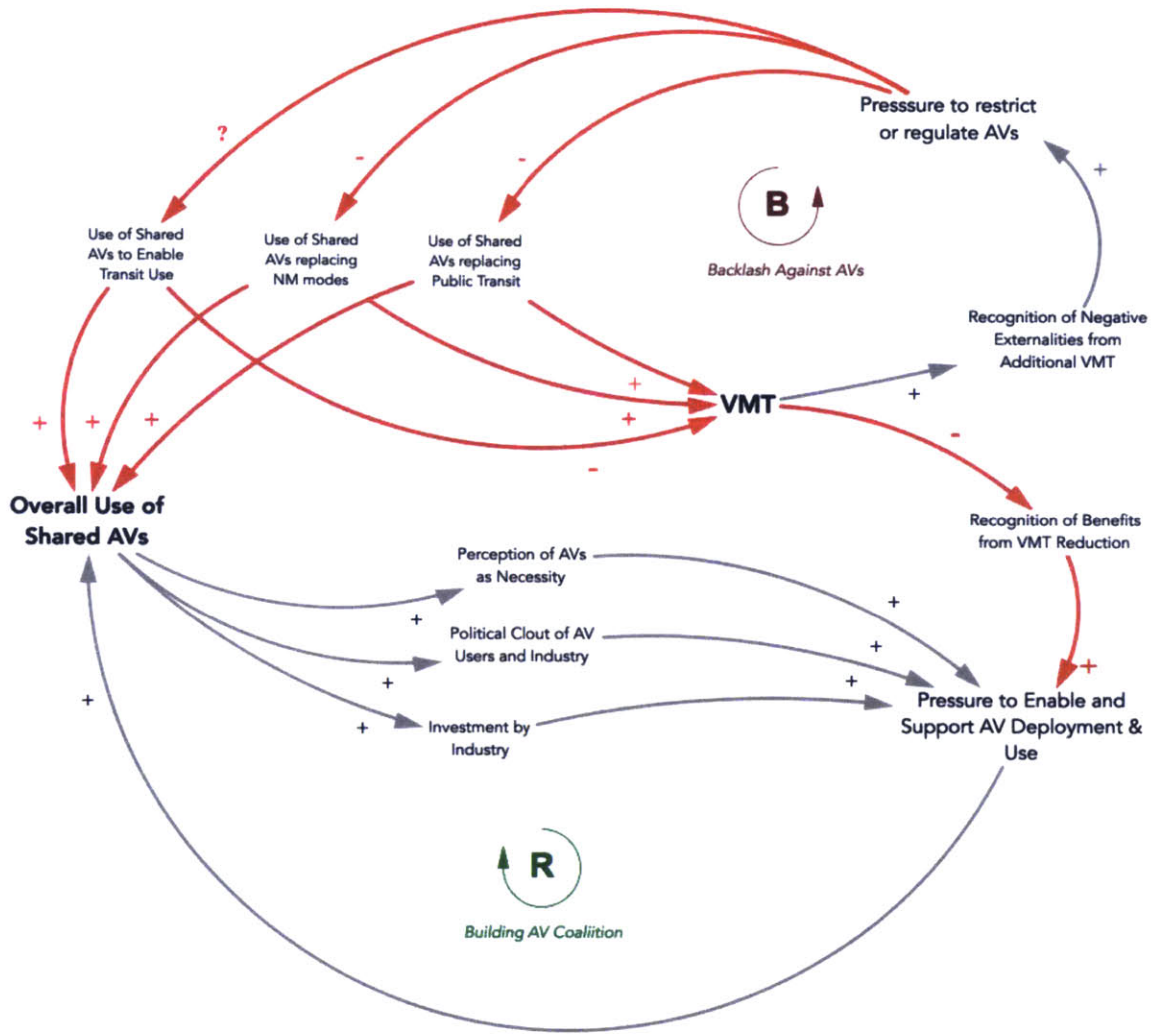
6.4.4 Stakeholder/Policy Reactions

Similar to section 5.4.5, this section addresses potential reactions by stakeholders and their policy implications. Some of the relevant causal relationships are shown in Table 6.10.

Table 6.10					
Causal Link		**+/- (polarity)**	**Hypothetical Strength of Causal Relationship**	**Strength of Hypothesis that Causality Exists**	**Notes**
Independent Variable	**Dependent Variable**				
Pressure to Restrict or Regulate AVs	Use of Shared-AVs to Enable Transit Use	?	--	--	I have declined to assign polarity here, due to the total uncertainty of the effects of the reaction to restrict or regulate AVs. If key stakeholders determine that AVs are beneficial only as enablers of transit use, then policies may be crafted to restrict all other uses and promote that one. However, it may also occur that stakeholders simply decide that *all* AVs need to be restricted.
Pressure to Restrict or Regulate AVs	Use of Shared-AVs replacing NM Modes and Public Transit	-	Weak	Strong	If regulations were put in place to reduce VMT from AVs, it would be expected that the primary aim would be to prevent or discourage people from switching to AV use when they could use NM modes or public transit.
Use of Shared-AVs to Enable Transit Use	Overall Use of Shared-AVs	+	Strong	By definition	
Use of Shared-AVs replacing NM Modes and Transit	Overall Use of Shared-AVs	+	Strong	By definition	
Use of Shared-AVs to Enable Transit Use	VMT	-	Strong	By definition	
Use of Shared-AVs replacing NM Modes and Transit	VMT	+	Strong	By definition	
VMT	Recognition of Benefits from VMT Reduction	-	Moderate	Strong	This asserts the connection between the emergence of the benefit and its recognition, which we can reasonably assume will involve a certain time delay. This delay may also somewhat diminish the strength of this relationship.
Recognition of Benefits from VMT Reduction	Pressure to Enable & Support AV Deployment & Use	+	Weak	Strong	This relationship is considered weak, to reflect the difficulty some people may have understanding that adding a new and appealing vehicle technology could actually reduce overall VMT.

These relationships are shown in Figure 6.13. Similar to Figure 5.11, this CLD can be understood as essentially two feedback loops:

- The balancing loop, "Backlash Against AVs," could be triggered in the "backlash" direction if VMT grows, in which case there is likely to be some recognition that AVs are part of the cause, which would increase pressure to regulate them. From here, it seems fairly clear that the desired regulations would seek to decrease *Use of Shared-AVs Replacing Public Transit* and decrease *Use of Shared-AVs Replacing NM Modes*. However, it is not clear if these restrictions would blindly reduce the use of all AVs, which would also mean reductions in the *Use of Shared-AVs to enable Transit Use* (hence the question mark shown over the causal link leading to this variable). One could easily imagine that policymakers might make no distinction between uses of AVs that increase VMT and those that reduce it, and just enact across the board restrictions on all AVs. Or, it may simply be too difficult to craft policies that selectively limit specific uses.
- The reinforcing loop, "Building AV Coalition," would be triggered by the very existence of AV users and industry players invested in the technology. It is then likely that it would be strengthened if VMT were to fall and cause an increase in *Recognition of the Benefits from VMT Reduction*, which would further build *Pressure to enable and support AV Deployment and Use.*



6.13 Factors Involved in Potential Stakeholder and Policy Reactions. *(Red arrows indicate new relationships added in this section.)*

6.4.4A COMMENTARY, KEY ISSUES, AND QUESTIONS RAISED

One significant difference between this model and the one in Figure 5.11 is that in this scenario there is an insignificant level of private ownership of AVs. Therefore, the role of the political clout of AV users and industry might be smaller. For one thing, if industry sells far fewer AVs, the overall size and importance of the industry will be less than in Scenario 2; and, if there are very few private owners of AVs, there will be fewer people who feel financially invested and committed to the technology and to realizing its full benefits. That is not to say, however, that passionate advocates who enjoy the technology will not still emerge.

Overall, the effect on VMT in scenario 3 is far less certain than in Scenario 2, and appears likely to be either a smaller increase, or a very large reduction, depending on the direction the reinforcing loops act in. It might also be expected that if Scenario 3 were to play out, it would be more difficult to observe and understand the changes taking place, which might create substantial delays in the system and the policy responses—e.g., delays after increases in VMT occur and before the resulting negative outcomes and their cause are recognized, or delays after decreases in VMT and before the resulting benefits and their cause are recognized.

Chapter 7. Reflections and Related Questions

7.1 Short-Term Questions

The analysis in Chapters 4-6 raises more questions than it answers—and that was the intended outcome. The following table summarizes the main questions.

Source Figure *(origin of question)*	**Strategic Questions that Emerge from the Scenarios**
4.3 Basic System Feedbacks	How much of a direct impact will automated driving have on the efficiency of the flow of vehicles? Similarly, how many more vehicles will the roads accommodate at the same level of congestion?
4.3 Basic System Feedbacks	How much safer will *all* automobile users feel due to the presence of AVs on the roads?
4.3 Basic System Feedbacks	How much will reductions in congestion increase travelers' tolerance for safety risks?
4.3 Basic System Feedbacks	How much will the perception of increased safety of traveling by car increase travelers' tolerance for traffic congestion?
4.3 Basic System Feedbacks	How many more people will be able to use a car, due to the elimination of driver's license requirements?
4.3 Basic System Feedbacks	And how much upward pressure will these new users add to VMT?
4.3 Basic System Feedbacks	What are the benefits of mobility in the region, and how will these benefits affect the equilibrium value of VMT?
4.3 Basic System Feedbacks	What are the relative costs of alternative travel modes in the region, and how will these compare with the costs of automobile use?
4.4 Effects on Adopters	If there is an effect of "diminishing advantage of AVs," as congestion decreases, how strong will this effect be?
4.4 Effects on Adopters	If behavior doesn't change substantially, while the direct benefits of AV technology may be partially offset by increased VMT, the resulting equilibrium value of traffic congestion and accidents should still be lower—but how much lower?
4.4 Effects on Adopters	Will improvements in traffic flow diminish the relative advantage of AVs enough to limit adoption? In other words, at what level of adoption will the traffic-flow-improvement of AVs be high enough that the relative advantage of an AV will not be enough to justify the cost for new adopters? (Or is there even such a point?)
4.4 Effects on Adopters	How much of a role does *Traffic congestion* play in *Total costs of AV use* compared to its effect on *Total costs of CV use*?

Source Figure *(origin of question)*	Strategic Questions that Emerge from the Scenarios
4.4 Effects on Adopters	How high will the level of AV adoption need to be to realize the benefits in terms of safety and congestion, and how strong will these effects have to be to improve market perceptions?
4.5 Macro-System Effects: Benefits, Policy Responses, and Adoption	Will the traffic-reducing characteristics of AVs be offset by the increase in VMT?
4.5 Macro-System Effects: Benefits, Policy Responses, and Adoption	Will the increase in overall energy efficiency of the auto fleet be offset by the increase in VMT?
4.5 Macro-System Effects: Benefits, Policy Responses, and Adoption	How much will people consider AVs as a "replacement" for CVs? That is, will they wait for their CV to reach the end of its useful life before replacing it with an AV? Or will they view AVs as offering entirely new value?
4.5 Macro-System Effects: Benefits, Policy Responses, and Adoption	If there are negative consequences from AVs that are substantial enough to be recognized (e.g., congestion and energy consumption noticeably increase), will key stakeholders recognize the introduction of AVs as the cause?
5.1-5.3 Effects Related to Empty-Vehicle Trips	Will the total monetary cost of automobile use (*Monetary Cost of Driving* plus *Cost of Parking*) be less or more overall with an AV?
5.1-5.3 Effects Related to Empty-Vehicle Trips	Will the savings from AV use (improved efficiency, fewer accidents, less wear and tear, lower cost of parking, less or no liability insurance) outweigh the higher per-mile capital cost?
5.1-5.3 Effects Related to Empty-Vehicle Trips	Will the reduction in VMT due to eliminating cruising for parking be outweighed by the extra driving to gain access to cheaper remote parking locations?
5.1-5.3 Effects Related to Empty-Vehicle Trips	Will the reduction in congestion due to eliminating cruising for parking be outweighed by the extra congestion generated by additional VMT from vehicle trips to remote parking locations?
5.5 Effects of Automated Driving on Basic Traffic Dynamics	How much will VMT increase due to the potential behavioral changes resulting from automated driving (as discussed in Scenario 2)?
5.5 Effects of Automated Driving on Basic Traffic Dynamics	How much will AVs' improvements (in comfort, risk, and utility of time) allow traffic to increase while still maintaining the same Total Costs of AV use? In everyday language, this could be: *How much more traffic am I willing to tolerate if I can get work done or sleep while I'm in the car?* Or it could be: *How much more traffic will I tolerate if my trip is more comfortable and safe?*

Source Figure *(origin of question)*	Strategic Questions that Emerge from the Scenarios
5.5 Effects of Automated Driving on Basic Traffic Dynamics	How comfortable will AV owners be with sending their AVs on empty trips? Will they use them to run errands? Will they be much more likely to use them for formerly one-way trips that were previously cheaper via public transit (e.g., trips to the airport or train station)?
5.5 Effects of Automated Driving on Basic Traffic Dynamics	Will people use their AVs to facilitate long-distance travel? Will they be willing to send their AV full of luggage to another destination and then travel much more quickly and conveniently via airplane and have their vehicle meet them at the destination? Would this have a substantial impact on car rentals?
5.5 Effects of Automated Driving on Basic Traffic Dynamics	If AV use indirectly drives up the disincentives ("costs") of CV use, how strong will the deterrent effect be on CV users?
5.6 (a-c) Effects of AVs on Travel-Mode Choice	What will be the relative utility of time spent in an AV, a CV, a bus or a subway? And how much will this affect the overall perceived "cost" of time spent traveling?
5.7 Causes and Effects of VMT	Will the harm of increased VMT outweigh the other benefits of AVs?
5.7 Causes and Effects of VMT	If the resulting harm from increased VMT does outweigh the benefits, will the benefits be recognized, acknowledged, and reacted to first, or will people recognize and react to VMT and all its related problems first?
5.9b Potential unintended effects of restrictions in response to increased traffic congestion	In one potential policy response, would restricting access to streets for non-motorized (NM) transport push enough people away from public transit and into cars or AVs that the restriction will actually have the perverse effect of making traffic worse? Or will a modest level of restriction cause enough of a drop in congestion (without pushing too many people away from transit) that the pressure to restrict access diminishes?
5.9b Potential unintended effects of restrictions ...	Would pro-AV policies have a stronger disincentive effect on CVs or non-motorized modes?
5.9b Potential unintended effects of restrictions ...	How will interests align over the use of streets, if there is significant pressure to change existing rules and access?
5.10b Potential unintended effects of regulations to attain full safety benefits of AVs	If restrictions against conventional vehicles are put in place, will these take hold first, improve overall safety enough to reduce regulatory pressure, and therefore limit any new restrictions on non-motorized transport? Or will restrictions on non-motorized transport take effect and begin to drive the reinforcing loops that force people away from transit and non-motorized travel?
5.10b Potential unintended effects of regulations ...	How strong will peoples' belief in the fundamental safety of AVs be? How much will this affect their choice of where to assign "blame" for traffic accidents?

Source Figure *(origin of question)*	**Strategic Questions that Emerge from the Scenarios**
5.10b Potential unintended effects of regulations ...	Even if AVs are safer on an individual basis, and if they achieve tremendous safety improvements when operating among other AVs, will the increase in VMT lead to more accidents involving pedestrians, cyclists, and conventional automobiles? In other words, will the increase in traffic volume increase the number of accidents more than they are reduced through safer operation of the individual AVs?
5.11 Delays in regulatory response	Which will be evident first, the negative externalities, or the societal benefits of AVs?
5.11 Delays in regulatory response	How strong will the effect of the political clout of the AV industry and AV users be on regulations and policies to support AV adoption? How much will the industry's investment in the technology drive this pressure?
6.7 Expected interactions among public transit, vehicle sharing, and private vehicles	How strong will the effect of *Attractiveness of AV sharing* be on the *Attractiveness of Public Transit*?
6.7 Expected interactions ...	How strong will the effect of *Shared-AV Trips Replacing Non-Motorized Trips* be?
6.7 Expected interactions ...	How strong will the effect of *Shared-AV Trips Replacing Non-Motorized Trips* be?
6.7 Expected interactions ...	Is there a viable strategy for pricing the use of shared-AVs that would encourage their use as a supplement for transit trips and non-motorized travel, but discourage their use as a replacement for those modes?
6.11 Multiple interactions of vehicle-sharing and public transit	Could high energy prices and carbon pricing reduce the attractiveness of automobile use enough to cause a reduction in traffic that will noticeably improve the level of service of bus operations?
6.11 Multiple interactions of vehicle-sharing and public transit	How strong will the impact of empty vehicle trips be on the attractiveness of vehicle sharing? Will it be enough to drive significant expansion of the network? Will this expansion be enough to improve the attractiveness of public transit and ultimately drive further expansion of public transit systems?
6.11 Multiple interactions of vehicle-sharing and public transit	How quickly or slowly will transit operators respond to growth in demand and fare-box revenues to expand bus fleets? If this reaction is too slow, will there be another feedback effect, where overcrowding discourages riders and some revert to driving?

7.2 Longer-Term Effects and Future Questions

Given practical limitations, the analysis in this thesis is limited to the loosely defined phase of "initial adoption" of AVs and the ensuing system responses. However, many additional and potentially powerful dynamics could be expected to emerge over the longer-term. A cursory list of some issues worth considering for a longer-term analysis follows:

- **Effects of Full Market Penetration of AVs**
    - Will there come a point when there are enough AVs on the roads to have AV-only lanes, or AV-only highways? What will be the effect on average trip-length? With AV-only highways, it's likely that speed could increase dramatically while maintaining safety; this would allow AV users to cover much more distance in less time.
- **Effects of Location-choice and Land-use**
    - If the time costs of travel by automobile decrease, will people be willing to commute greater distances? Coughlin and Yoquinto (2015) discuss potential scenarios involving 200-mile commutes.
    - Will such location-choices lock in these changes to the system? In other words, once enough people buy homes 200 miles from where they work, how much will this increase resistance to any attempts to curb VMT?
    - How long will it take for land-use patterns to begin to react to new location-choices? And once land uses begin to adapt to new location choices and travel patterns, how much will this further increase resistance to attempts to curb VMT? It is after all, one thing to tell a person he made a mistake by buying a house too far from where he works; it may be an entirely different matter to tell the developer of a multi-million dollar residential real estate project that his potential buyers will no longer be able to commute from that location.
    - What will be the effect on the overall dispersion of destinations—both in terms of the existing locations people will consider as destinations for automobile trips and in terms of the new destinations that may be established based on the expectation of a willingness to travel farther distances?
    - Will increased VMT result in increased space devoted to roads and automotive infrastructure?
    - What will be the effect on land used for parking? Will the need for public parking spaces decrease as a result of vehicle sharing? Or will many people choose to own private AVs, in which case public parking spaces would just move from expensive land to less-expensive locations?
    - Ultimately, what will be the feedback effects from these land-use changes? Will increased dispersion of destinations result in more VMT? Will this effect discourage use of public transit and therefore also increase VMT?

- Or will the elimination of parking allow for denser land use that may actually be friendlier to public transit? will this effect be stronger or weaker than the other potential deterrents on NM transport and public transit?

- **Changes in Vehicle Architecture**
  - If AV users are not required to park at their destination, will they be able to use much larger vehicles, with more comfortable interiors?
  - If AVs dramatically improve safety, how might vehicle architecture change? Will it be possible to operate much lighter vehicles at higher speeds? Will the removal of some safety-related design constraints open up whole new architectures for automotive interiors? What will be the effects on utility of time spent in an AV? (For visualizations of a radically different new automobile architecture, see "The Future of Automobility" (Ideo 2015))
  - What will be the effects of these factors on roadway design and effective capacity?
- **Effects of Other Technology Improvements.**
  - What will be the effect of advances in "telepresence" and other communication technologies?
    - Will these technologies reduce demand for commuting enough to offset other increases in VMT?
    - Will they provide yet another opportunity for increasing the value of time spent in an automobile, further reducing disincentives to driving and probably causing an increase in VMT?
- **The role of AVs in Freight and Deliveries**
  - If vehicle automation dramatically reduces highway freight costs, how much freight movement will shift from marine and rail modes to trucks, and what will be the overall effect on available highway capacity?
- **General Effects of Passage of Time**
  - As people use AVs, they may make lifestyle choices that make them increasingly dependent on the unique capabilities of AVs. How would this growing dependency hinder efforts to curb or regulate VMT?
  - As time passes, people may tend to forget the conditions that existed prior to a change that has negative outcomes. A clear example is the way automobiles pushed out almost all other users of streets, and in less than a generation, people came to accept this as the new norm. If this happens with AVs, will this tendency for forgetfulness weaken efforts to restrict VMT?
- **Winner-Take-All Dynamic**
  - Will other uses of roads and highways remain compatible with AVs? Or, like the automobile, will they push out or radically restrict other users?

- **Social Equity**
  - If AVs evolve into the dominant mode of travel, what will be the effects on accessibility for lower-income citizens who can't afford an AV?
  - Will AVs transform the overall transportation system into one with fewer options for lower-income citizens? This could be seen as an extension of the effect of automobiles. Automobiles led to land-use patterns that made travel to many destinations only possible by automobile, eliminating access by public transit and non-motorized modes. Could AVs have a similar effect, putting more destinations out of reach of anyone who doesn't have access to an AV?

7.3 Underlying Questions: The Philosophical Challenge of AVs

7.3.1 What are the Limits to Demand?

In attempting to assess the impacts of a technology that might so radically reduce the costs and disincentives to driving, the question naturally arises: How much latent demand exists for mobility that might be released by the reduction in non-monetary costs of traveling by car and the increased access to traveling by car—effects that both directly result from AVs? We could probe this question a bit deeper as well, and put it in better context, by asking: What are the limits to demand? Or, put another way: How much would people travel if there were no cost?

This is by no means an easy question. In an article on latent demand in *Harvard Business Review*, Eddie Yoon articulates the challenge of assessing latent demand: "By definition unmet, unarticulated needs from unexpected consumers are hard to measure" (Yoon 2013). Considering latent demand in these terms, in the context of potentially radically reduced costs and disincentives, truly puts us in uncharted territory, with no analytical framework to proceed from. Just to gain a sense of the potential scale of the changes in demand, it may help to speculate through a thought experiment that frames the issue in terms of scenario questions. For example, we could ask:

- *How many people would visit their family in another state on a weeknight if it meant they had to drive three hours there and three hours back, arriving home in time for work the next day?* We could speculate that very few would do this, and the demand for such trips would be very low.

- *How many people would make this trip if they could (hypothetically, of course) make the trip instantaneously, for not much more cost than they would pay for gasoline in a conventional car?* We could reasonably speculate that many people would do this on a very regular basis, so demand for such trips might be very high.

- Then, for a potentially ***realistic*** AV scenario, we could ask: *How many people would make this 6-hour round trip, if they could watch a movie or catch up on emails on the way there and then go to sleep in comfortable bed in the AV on the way home?* We could reasonably speculate that there could be significant demand for such trips.

Taking this last example in a different direction, we might also expect additional demand for long-distance commuting, as mentioned in section 7.2. Not only might this allow people to live in much less expensive locations, or on much larger plots of land in the countryside, it might also allow spouses to hold jobs in different cities and still return to the same home every night.

Ultimately, the benefits of mobility ***for the individual*** may be virtually limitless. It may be argued that people will not desire to move around much more than they already do—that all the demand for mobility can somehow be satisfied. But that might be naïve—and naïve in the way that the first promoters of the "horseless carriage" failed to see how much latent demand the automobile would liberate. As with the AV today, even the most ardent promoters of the first automobiles focused on simple, direct benefits: automobiles would be safer and cleaner than horses and they would even solve the congestion problem that had arisen in cities (Morris 2015). And this may have been quite reasonable from the perspective based on a mental models of fixed travel demand: surely the horse-less carriage would not create as much manure, nor would it take up as much room as a carriage with a team of horses, and the human driver would surely be more predictable and better able to control the vehicle than a horse. However, they failed completely to predict or even imagine how much additional benefit people would gain from more mobility, and how much more demand for mobility would arise.

So, to look ahead from the present, the science-fiction concept of the "teleporter" may again be a useful conceptual tool to gain a sense of how far the benefits of mobility could extend. For example, if cost and time were not an issue, wouldn't many people enjoy the option of living on a tropical island and commuting to Manhattan every day? Or, in a more-realistic potential AV scenario, wouldn't many people enjoy the option of living on a beach house on Cape Cod and commuting to work in Manhattan? That may sound implausible, but it's almost within the range of the 200-mile commute discussed by Coughlin and Yoquinto. Ultimately, if technology continues to reduce the costs of mobility and the disincentives for travel, we cannot say with any real certainty how much more people will travel; and in the case of AVs, we cannot say with any certainty what the effect will be on VMT. The AV has the potential to reduce the costs and disincentives for traveling tremendously, perhaps the largest advance in personal travel since the advent of the automobile.

It would, therefore, be difficult to overstate the potential impact of allowing point-to-point, self-directed, self-scheduled travel, with low incremental monetary cost, no attention or effort required by a human occupant, potentially at higher speeds, greater comfort, and with improved safety (as explored in Scenario 2 of this thesis).

7.3.2 An opportunity to address deeper questions about mobility

Though we still cannot say with any certainty how much of an effect AVs will have, given all the uncertainties involved, the potential for system-wide transformation of personal mobility appears very real, and this provides an opportunity to consider mobility in the abstract, and consider the kind of world that could emerge after radical increases in mobility. Such a thought-exercise raises a number of interesting questions:

- If the total costs (and disincentives) of travel fall enough and people take advantage of this to travel significantly more than they do today, how will our individual and social constructions of space and location change?
- With enough easy mobility, can physical communities even exist as we know them today? Already the definition of towns and cities has been blurred by the movements enabled by the automobile, to the point where the boundaries and centers of many municipalities are virtually indistinguishable—this is one of the hallmarks of "sprawl."
- If the physical architecture of the automobile evolves with changing behaviors, one could imagine—as some industrial designers already have (Ideo 2015)—automobiles that serve as mobile workspaces or even bedrooms, blurring the distinction between homes, workspaces, and vehicles, and further altering constructions of space, location, community, and so on.

As humanity may be approaching a new age of personal mobility, it may be worth considering such questions, as the answers will have powerful implications for the shape and character of human habitation in the future.

7.3.3 *Framing Potential Outcomes*

The scenarios examined in this thesis can be used to frame a much wider range of potential outcomes, beyond what is examined here. In other words, these scenarios provide direct insights about what may plausibly happen to VMT under the assumptions considered, but they also identify key system structures and potential behaviors that can help predict different outcomes under different assumptions. Furthermore, the models developed can be used to help identify issues and questions to further hone our understanding of potential system reactions—for example, What are the most important uncertainties and which other uncertainties do they interact with? And which uncertain factors might play the biggest role in affecting VMT over the long run?

Furthermore, in developing models for analyzing effects on VMT, it was necessary to construct a fairly broad representation of many key aspects of the transportation system. The resulting models can also serve as a framework for future analysis, for potentially assessing other factors (not just VMT), a useful tool for identifying research needs and understanding the system implications of new facts and research outcomes.

7.3.4 *Potential Policy Interventions—from passive to active system control*

The most significant potential challenges of AVs appear to arise from their expected effect of reducing the costs and disincentives of automobile travel. It appears that the removal of these costs may amount to elimination of several key natural controls that have provided a certain amount of self-regulation to the transportation system over the past 100 years. Of course, over the entire history of the automobile, many of the outcomes of these inherent passive system controls have been far from ideal.

Interestingly, and perhaps a bit ironically, within the AV—the technology that threatens to break down these old controls and limiting factors—there may also lie the potential for new controls that are more active and responsive to desired ends for the overall behavior of the transportation system. For example, by replacing gasoline taxes (which have served as a proxy for road-use-charges for nearly 100 years) with computerized, dynamic pricing, a much more effective and potentially more equitable system of controlling (and charging for) road use could be developed. Such controls could also be viewed as tools for internalizing some of the external costs of transportation. For example, returning to the case of VMT, if a policy-making organization wished to reduce VMT (to reduce congestion or local air pollution) rather than applying a one-size-fits-all approach like a gasoline tax (which taxes users indiscriminately, whether they are driving in downtown Manhattan or in the wilderness of the Adirondacks), they could apply targeted congestion pricing to address specific trips, even pricing trips differently to encourage preferred routing that optimizes overall system performance. Similarly, rather than levying the same per-mile tax for the first mile a person drives in a given year as for the 9,999th mile driven, tiered pricing schemes could provide a much more equitable system, where costs for a baseline of "necessary" road use would be very low, or free, with costs increasing as road use becomes "excessive." This is similar to the tiered pricing schemes employed by some utilities in the United States. Adjustments could also be made to allow for different external costs of individual trips—e.g., the externalities of local air pollution and congestion are far greater in a dense urban area than they are on a country lane.

Over the last century, almost all the changes in the automotive experience—from highway building to cruise control, to air-conditioning, to surround-sound audio systems, heated seats, and video screens—have served to improve that experience and reduce the disincentives for driving. The AV presents a potential quantum leap on this path of progress, offering both the challenge of a transportation system unconstrained by many of the limits it has known for over 100 years, and the opportunity to take a more active role in determining the structure of that transportation system and how it is used. If this assessment is accurate, then the warning Coughlin and Yaquinto issue to conclude their article in *Slate* (Coughlin and Yaquinto 2015), would appear to aptly summarize the core of the challenge today: "We need to make a deliberate decision about how we will live in the future, before the self-driving car makes it for us."

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