EFFECTS OF NEXT-GENERATION VEHICLES ON TRAVEL DEMAND AND HIGHWAY CAPACITY

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JANUARY 2014

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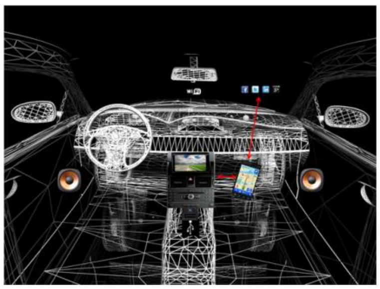
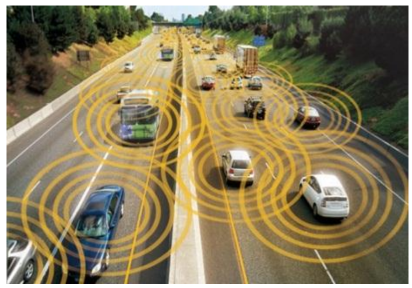
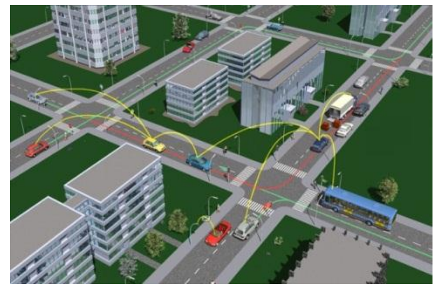
1. EXECUTIVE SUMMARY

Self-driving (autonomous) vehicles are already being road tested in several states and will be available for sale within five to ten years. They promise to make automobile travel safer and more efficient, and to dramatically change transportation planning and engineering. This paper assesses the most likely effects of autonomous vehicles (AVs) on traffic generation and highway capacity and congestion over time as AVs come to represent a greater percentage of the vehicles on the road.

RATE OF ADOPTION

Factors that will influence how rapidly AVs enter the fleet in large numbers include perfection of fail-safe technology, safety and licensing, legal issues and liability, privacy and security issues, personal preferences, cost and equity, and infrastructure implementation (at least until vehicles can communicate and cooperate with one another without embedded roadside equipment). By comparison, airbags, another substantially beneficial and much simpler technology, took 15 years to become standard on all new cars.

Two pivotal AV issues are:

- When and to what degree the NHTSA permits, and then ultimately requires, the use of AV capabilities
- When automakers will begin to operate under a subscription-based car possession model, replacing the current ownership and leasing models

We estimate that AVs will represent a high enough proportion of the fleet to affect the performance of different transportation network elements as follows:

Exclusive freeway lanes	2025-2030
Mixed freeway lanes and ramps	2030-2035
Auto-dominated arterials	2035-2040
Multi-modal streets and intersections	2040-2050
Vehicles operating without a legal driver aboard on:	
private streets and self-parking in private lots	2040-2050
public streets and lots	2050+

IMPACT ON VEHICLE MILES TRAVELLED

AVs offer the potential to free drivers' attention from the road, to chauffer people who are unable to drive and, ultimately, to drive robotically without anyone aboard. A number of factors will influence the AV driving experience and the degree to which it will affect VMT, including:

- Driver experience in terms of stress relief, comfort and ability to use travel time for other purposes
- Proportion of the network over which AVs are deemed safe enough to operate with high autonomy
- Quality of service offered by alternative modes of travel, which will vary by urban setting
- Vehicle costs and sharing or subscription opportunities
- Legality of use by those otherwise not qualified to drive

These unknowns make it difficult to assign specific dates, but we can say that, even at 50% market penetration AVs are likely to produce increases in VMT ranging from 5% to 20% depending on facility class. When fleet penetration reaches 95% and when non-drivers are permitted to travel in robotic cars, VMT increases may reach as high as 35% on portions of the transportation network.

EFFECT ON HIGHWAY CAPACITY

Initially, AVs will either have no impact, or at worst, they could degrade highway capacity as safety-conscious conservative programming of vehicle speeds and headways reduce vehicle densities and flow. In the very long term, when AVs reach almost full penetration of the fleet and when vehicles are able to cooperate with one another to negotiate merging and intersection right-of-way, operating efficiencies will begin to improve. Some researchers estimate that per-lane freeway capacities could increase to 4,000 vehicles per hour or more.

Until that time, our own VISSIM simulation analysis suggests capacity benefits are likely to occur only on freeways when the fleet mix is at least 75% autonomous and assuming performance is programmed at intermediate levels between conservative and aggressive. At that point, likely post-2035, the AV fleet mix is likely to achieve traffic flow benefits of 25-35%. Beyond that, when regulations, liability concerns and driver comfort allow much more aggressive car-following algorithms, vehicle delays may be reduced by 45% or more.

IN CONCLUSION

Favorable effects on the efficiency of the roadway network will vary by facility type, will take several decades to arise, and will be little more than about a 45% increase at that time. Concurrently, improved driver experience and the availability of robo-chauffeuring for those who would otherwise not be permitted to drive may increase VMT per capita by as much as 35%, off-setting much of the efficiency gain. Although the net operational improvements to streets and highways would not significantly reduce the need to expand infrastructure to keep pace with population growth, the bottom-line benefits of AVs on the road are most likely to take the form of improved mobility for all, increased safety, reduced incident-related congestion and reduced environmental and social costs.

2. BACKGROUND AND CORE QUESTION

Automated vehicle technologies promise to transform traveler experience and traffic operation. Technologies already undergoing on-road testing include adaptive cruise control, traffic incident and lane departure warnings, driver attentiveness detection, vehicle route navigation and congestion avoidance, eco-driving optimization and self-parking capabilities. They offer the ability to maintain safe and efficient vehicle spacing and flow, and will ultimately drive fully autonomously without requiring driver attention with, some forecast, significant reductions in collisions and much more efficient use of road capacity.

Recognizing the potentially dramatic changes to the transportation planning and engineering profession, the FP Think working group prepared this white paper in order to:

1. Clarify the operating characteristics and driver experience likely to become available in next gen vehicles
2. Determine how soon such vehicles will be in common use
3. Predict their effects on traffic generation, including whether they will increase or reduce the number of vehicle miles traveled
4. Estimate their effects on traffic capacity and congestion

In the future, the group would also like to undertake research on the safety benefits of autonomous vehicles and the potential reduction in accidents and incident-related congestion.

These factors will clearly influence our long- and short-range travel behavior forecasting, traffic impact assessments, traffic simulations and operations analyses, and transportation system planning and engineering. The interactions among automated vehicles and pedestrians and bicyclists will also affect our planning and design integrated modal networks and complete streets. Some experts project there may soon be a legal requirement to consider vehicle automation in EIRs and EISs .

In the following chapters, we consider the implications of next-generation vehicles on the four factors listed above. We recognize all five levels of automation defined by the industry:

- **Level 0** – No Automation: Current non-automated vehicles. The diver is in complete control. Warning devices, such as blind spot monitoring, may be included. Vehicle-to-vehicle (V2V) warning technology may be included as well.
- **Level 1** – Functional-specific automation: Moderate level of automation for a specific function like stability control or braking that assists the driver.
- **Level 2** – Combined-function automation: Ability to address two specific functions such as traffic jam assist where the vehicle could maintain both speed and lane position in a severely congested environment.
- **Level 3** – Limited self-driving automation: Driver is not expected to constantly monitor the roadway while driving and can cede control of the vehicle in selected environments. Does require the driver to maintain full vigilance and ability to take over operation of the vehicle as needed.
- **Level 4** – Full self-driving automation: Driver needs only provide destination or navigation input.
- **Level 5** – Automated taxis/”electronic chauffer” service and cooperative vehicles capable of negotiating rights-of-way with one another.

While we address the market penetration, operating characteristics and driver experience likely to become available in all five stages, we focus most attention on the transformative potential within levels 3 and 4 of next gen evolution.

I. MARKET ABSORPTION/FLEET CONVERSION

This chapter will address questions like, "When will autonomous and/or connected vehicles be available?" and "How fast will they be integrated into the vehicle fleet such that they will affect travel behavior and system performance?" First we will look at car manufacturer and technology producer projections on when autonomous vehicles will be ready for the market. Once they are available there will still be barriers to fleet conversion, and we will spend some time addressing those factors. Next, we will look at available projections from people who have been studying this topic for some time. All of this information will be synthesized and we will develop our own projections.

A. WHEN WILL AUTONOMOUS VEHICLES BE AVAILABLE?

Vehicles with Level 1 automation (functional-specific automation) are available now. These features include adaptive cruise control, vehicle spacing monitoring with speed adjustments, lane assist (which monitors the vehicle's position in the lane and warns the driver when the vehicle is leaving its lane), and parking assist, which assists the driver in parallel parking.

Predictions from major automobile manufacturers and technology companies regarding increased levels of automation include:

<u>2013</u>

- The 2014 Mercedes S-Class comes with options for autonomous steering, lane keeping, acceleration/braking, parking, accident avoidance, and driver fatigue detection.
- The 2014 BMW i3 can autonomously steer, accelerate, and brake in traffic jams at up to 25 miles per hour.

<u>2014</u>

- Israeli company Mobileye expects to release semi-autonomous car technology.

<u>2015</u>

- Audi plans to market vehicles that can autonomously steer, accelerate, and brake at lower speeds such as in traffic jams.
- Cadillac plans vehicles with "super cruise" that will allow autonomous steering, braking and lane guidance.
- Nissan expects to sell vehicles with autonomous steering, braking, lane guidance, throttle, gear shifting, and, as permitted by law, unoccupied self-parking after passengers exit.
- Toyota plans to roll out near-autonomous vehicles dubbed Automated Highway Driving Assist with Lane Trace Control and Cooperative-adaptive Cruise Control.

<u>2016</u>

- Tesla expects to develop technology to allow their vehicles be autonomous for 90 percent of distance driven.
- Mobileye expects to release fully autonomous car technology.

2018

- Google expects to have autonomous cars on the market.

2020

- GM, Mercedes-Benz, Audi, Nissan, Volvo, and BMW all expect to sell autonomous cars.

B. WHAT ARE THE BARRIERS TO FLEET CONVERSION?

Even after fully autonomous vehicles are available, it will take some time before they represent a majority of the vehicle fleet since vehicle owners will not just go out and immediately dispose of their old vehicles and buy new ones. Plus, the first autonomous vehicles will be expensive and it will take time for manufacturers to ramp up production to meet the demand. In addition to these economic (financial and supply/demand) constraints, there are other legal, social, and technological barriers that will affect the pace of fleet conversion.

1. TECHNOLOGY

The birth of autonomous vehicle technology is hard to pinpoint. One point of reference is the 1980s when German engineer Ernst Dickmanns equipped a Mercedes sedan with video cameras and processors and programmed it to follow lane lines. Google's team started developing their autonomous vehicle (AV) in 2008 and they are continually testing and perfecting the technology. But more testing and fine tuning are needed before Google's AVs are ready for public consumption, estimated to be in 2018. Therefore, one barrier is that the technology, while moving rapidly toward the needed functionality, is not yet available. Once it is, universally-adopted platform/software compatibility among manufacturers would need to be created to reap the benefit of V2V communication, and that could take more time.

2. COST/SOCIAL EQUITY

Like most new technology, the fist AVs will be expensive and the vehicles will only be affordable to those with high incomes. The added cost will eventually decrease but it could take 20 years for them to be "affordable."

3. SAFETY AND LICENSING

A major barrier will be licensing the vehicles to determine when they are ready for the road. One of the benefits of autonomous vehicles is enhanced safety since human factors (lack of visibility, slow reaction times, inattention, influences of alcohol and drugs, etc.) are removed. However, drivers encounter a great number of circumstances when judgment is needed and it would be difficult to ensure that autonomous vehicles can operate safely in all of those circumstances. For example, if there is an object in the road, what are the appropriate responses? Change lanes, but only if the lane is clear. Go off the road, but only is there is a shoulder. What if the object is only a cardboard box? AVs must be tested to prove they are safer than current technology for a variety of circumstances. The extent of the testing needed to assuage concerns of regulators and consumers has not yet been determined but will likely be very high at a "six sigma level" meaning three defects per million.

4. INFRASTRUCTURE

Infrastructure will be needed to accommodate AV on the roadways. Initially they will likely require separate lanes or separate facilities so they are not mixed with traditional vehicles.

5. LEGAL ISSUES AND LIABILITY

Another barrier is liability in case of an accident. Human drivers are provided leeway in accidents that occur because of situations beyond their control. But the sensors and software in AVs are expected to make more-informed decisions; there is, therefore, a higher expectation of accident avoidance. But what happens if an accident occurs? Who is liable? The vehicle's owner? The manufacturer for faulty software? What if the only option is to hit another vehicle? Does (or should) the AV prioritize the safety of the people in its vehicle versus other crash-involved parties? These questions (and others) will need to be answered prior to AVs entering the vehicle fleet.

6. PRIVACY

AVs gather, share, and store a lot of data to operate. There will be questions regarding how much data should be stored, who owns the data, and who has access to the data. There are many beneficial applications for the data such as traffic signal optimization and better planning/improved transportation infrastructure funding decisions. However, there are also concerns such as using it to assess liability when a person is driving an AV during an accident. But what about government agencies having access to travel data? (Think of the recent NSA spying scandal.) What about commercial applications of this data, such as targeted advertising?

7. SECURITY

A potential limitation for AVs is the security of their computer systems from either a software glitch or intentional sabotage. A car's computer could potentially be compromised, as could a communication system between cars.

8. PERSONAL PREFERENCES

Another barrier is people's acceptance of AVs because they might be resistant to forfeit control of their cars or their enjoyment of driving.

C. AVAILABLE PROJECTIONS

One of the most commonly touted predictions is from the Institute of Electrical and Electronics Engineers (IEEE) where a team of expert members estimate up to 75% of all vehicles will be autonomous by 2040.

Todd Litman of the Victoria Transport Policy Institute predicts that in the 2050s half of the vehicle fleet will be autonomous and a fleet mix of 75% will not occur until the 2060s. These predictions are based on the deployment cycles, costs, and adoption rate of other automotive technologies. For example, automatic transmissions were developed in the 1930s but did not become reliable and efficient until the 1980s. Now, decades later about 90% of U.S. vehicles have automatic transmissions. But not all new technology has a cycle that long. Air bags were first developed in 1973 and took 15 years to become standard in some vehicles. But by 1998 they were in 100% of new vehicles due to Federal mandates.

D. OUR PROJECTIONS

The Victoria Transport Policy Institute makes a strong case it will take decades for AVs to reach a large enough proportion of the vehicle fleet to cause a substantial change to travel behavior and to require wholesale transportation infrastructure changes. Their prediction of 2050/2060 before AVs achieve a 50 to 75% share of the vehicle fleet is plausible. This prediction is based on an entry date of 2018/2020 and that it will take another 20 years (2040) for them to be affordable, historic vehicle purchasing/turnover rates (estimated to be eight years), and the numerous barriers described above.

Government regulators will also require time to become comfortable with the concept. The National Highway Traffic Safety Administration (NHTSA) is engaged in a several-year review and testing process, but some states are moving even more quickly. California plans to have draft regulations for Level 4 automated vehicles in place by January 2015.

On the other hand, there are high stakes and substantial momentum behind bringing intelligent vehicles to market. On the private side, the financial benefits to the insurance and other industries will be huge if, as projected, 80% to 90% of collisions can be eliminated. Consumer desire for convenience and gadgetry along with the business-model benefits of the massive data inflow and a captive audience for outflow of sponsored content and promotions have already captured the vigorous enthusiasm and R&D investment of all of the major automakers. With similar incentives, Google and other tech companies and universities are ambitiously refining the technology and machine-learning algorithms to speed the capabilities to market. Morgan Stanley predicts that autonomous vehicles can contribute $1.3 trillion in annual savings to the U.S. economy. Resistance to increasing vehicle cost will be considerably less than was encountered with airbags.

One significant wild card will be a possible paradigm shift away from the car ownership economy. Cars presently remain in use an average of over ten years. The auto industry is examining moving their products to a subscription model, similar to the cell phone market, which will speed up the fleet replacement and the introduction of new technologies. Another wild card could be that NHTSA, once it's fully comfortable with the technology and initial deployment, could require it to become standard on all new cars. Under the right circumstances, we could reach a 50 to 75% autonomous fleet mix between 2035 and 2045 rather than the VTPI forecast of 2050 to 2060.

Either way, there will be significant intermediate steps. Based on our research and judgment, we project:

- 25% of the vehicles on the road will be autonomous with vehicle-to-vehicle cooperation by 2035
- 50% of the vehicles on the road will be autonomous V2V in 2035-2050
- 75% beyond 2035 when federally mandated or when subscription "ownership" model prevails
- 95% beyond 2040 when federally mandated or when subscription "ownership" model prevails

Presence in the vehicle fleet does not necessarily mean all elements of the transportation network will be affected similarly. There will be operational challenges affecting vehicle capabilities and the fact that, at any stage, they will be less than ubiquitous. There are also unanswered questions on risk tolerance of the regulators and the public. Under the circumstances, we believe the deployment will affect different system elements as follows:

- exclusive freeway lanes in 2025-2030
- mixed freeway lanes and ramps in 2030-2035
- auto-dominated arterials in 2035-2040
- all multi-modal streets and intersections in 2040-2050
- without a legal driver aboard (including completely unoccupied):
    - private streets and self-parking in private lots 2040-2050
    - public streets and lots 2050+

However, given the stated uncertainties with respect to private industry R&D, government approval, and public acceptance, please consider these no more than educated guesses.

II. WHAT EFFECT WILL THEY HAVE ON VMT?

A number of complex factors with varying levels of interaction will affect changes to travel behavior patterns, resulting in either an increase or decrease in overall vehicle-miles traveled (VMT). In order to understand the uncertain nature of these elements, it is relevant to describe the range of possible outcomes related to each factor to ultimately determine the reasons that driving will reduce or increase with the adoption of autonomous vehicles.

A. DRIVER EXPERIENCE

If autonomous vehicles significantly enhance the user experience for drivers, then autonomous vehicles owners may travel more than they currently do. However, if autonomous vehicles provide a similar user experience as traditional vehicles, any change in travel behavior with their deployment will be limited. To understand the effect of autonomous vehicles on the user experience, one must first understand how driving is currently perceived. The research is replete with stories about the negative impacts of driving such as:

- A team of researchers from MIT concluded in June 2013 that driving in urban areas may actually be more stressful to some persons than skydiving[1].
- Just sitting in the driving position for long periods of time can cause muscle cramps, back pain and lead to long-term spinal disc degradation.[2]
- Long-distance commuters are more likely to divorce or separate from their partners.[3]

Given all of the negatives above, one can conclude the current experience for many drivers using their existing vehicles is negative. Some specific complaints are often voiced include:

- Need to maintain constant vigilance while driving

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[1] http://www.autonews.com/article/20130612/OEM11/130619945/for-some-driving-is-more-stressful-than-skydiving#

[2] http://www.safetyservicescompany.com/topic/equipment-and-vehicles/ergonomics-and-vehicle-safety-beating-the-unhealthy-effects-of-frequent-driving/

[3] http://www.samfak.umu.se/english/about-the-faculty/news/newsdetailpage/long-distance-commuters-get-divorced-more-often.cid160978

- Repetitive nature of driving
- Frustrations related to congesting
- Wayfinding
- Physical position required for driving

One unique aspect of driving is that the layout of vehicles has not changed significantly since their invention. Driving has provided significant advantages that will remain present in AVs, including door-to-door mobility, trip scheduling freedom and (under the right circumstances) enjoyment. However, similar to 100 years ago, a driver of today must sit erect in his seat, facing forward, hands on the wheel, feet on the pedals. Even with the technological change in cars over this time, drivers still must remain attentive to the roadway conditions and maintain hands on the wheel, ideally at all times.

While autonomous vehicles hold the promise of improving the user experience, the change in user experience is likely to be gradual with a significant change occurring only at the highest levels of automation.

One method to examine the change in user experience is to review the NHTSA autonomous vehicle hierarchy, offered on page 5.

We anticipate the change in user experience will be moderate until one reaches Level 3 or even Level 4.

Level 1 vehicles are currently deployed on the market in the United States as of 2013 and limited deployment of Level 2 vehicles is anticipated in 2014. However; these vehicles provide limited change in the user experience for the following reasons:

- Drivers still must maintain constant vigilance of the roadway and other vehicles
- Drivers must still maintain the forward, erect position

There may be some marginal benefits to Level 2 automation, particularly for drivers making longer-distance commutes in congested urban areas. For example, a Level 2 vehicle with traffic jam assist could be highly beneficial to a driver commuting in a location such as Los Angeles or Silicon Valley, where commutes of one hour in each direction are not uncommon. In this instance, a driver's stress level might be slightly reduced if they are able to cede a moderate level of control, similar to how drivers currently use cruise control in uncongested environments.

Level 3 presents the minimal threshold at which there is a tangible change in the driver experience. One significant change is that drivers could be free to divert their attention from the roadways for extended periods of time. As currently occurs, drivers currently attempt to multi-task while driving, particularly while on congested roadways. Anecdotal evidence suggests drivers will often engage in other activities while driving including eating, drinking, speaking on their cellphones, checking email, or texting. A recent survey indicated that ¼ of drivers in the United States may be accessing the internet while driving. With the implementation of Level 3 automation, drivers may be able to further engage in these activities while driving. California, Florida and Nevada currently allow on-road testing of Level 3 autonomy, including assessing whether to allow drivers to engage in distracting activities while in charge of the vehicle. If not, a limitation on behavior change will occur in the regulatory environment, such as California's current laws which exact significant monetary penalties for talking on a cell phone without using a hands-free device while driving.

Another factor related to Level 3 automation is the physical position of the driver. Level 3 vehicles will very likely be designed similar to the cars of today, requiring the driver to maintain the same erect, forward-facing posture as drivers have historically done. Therefore, we could expect to see many of the same physiological challenges that drivers currently experience.

Level 4 automation has the potential to significantly improve the user experience for drivers, based on a number of factors. The one key change is there may not be a need for a designated driver compartment as with the vehicles of today. In a sense, all persons in the car would be able to operate as passengers instead of driver operators. For example, occupants could be seated in a back passenger compartment, recline on couches, or even rest. Many of the activities drivers already engage in while driving such as talking on the phone, texting, emailing, or checking the internet could be done easily.

A Level 4 autonomous vehicle could also significantly reduce the amount of stress which drivers currently experience. A recent study in the United Kingdom indicated riding a bus reduces stress levels as compared to driving on the same route by a significant margin[4]:

The author of the study stated the following:

> *Three main factors that make driving a car stressful: heavy traffic causes the brain to work harder, traffic congestions causes a build-up of anger and there is a sense of frustration that a person is "wasting one's life" because few things can be done at the same time as driving.*

With improved user experience, persons may be encouraged to travel more than they currently do; thereby increasing VMT.

B. MODE SPLIT VARIATION

The relation and effect of autonomous vehicles on other modes is one element that has a multitude of outcomes on travel behavior and VMT changes. A substantial amount of research has looked at the notion of travel time utility and how users of various modes perceive that travel time. Is travel truly a derived demand and how does it vary between bicycling, walking, transit and automobile travel? Researchers in New Zealand evaluated this concept and found that walkers and cyclists were most likely to enjoy their time commuting as opposed to drivers or transit users[5]. All told, 89% of the drivers in the study said they would switch to public transport or walking if the travel time and cost was equal. This element is the big unknown in the case of autonomous vehicle impacts on travel behavior. Mode choice is largely an economic equation, in which time-value and costs are weighed against the general utility of the travel itself. Due to the previously discussed variations in potential costs with autonomous vehicle travel, it is extremely difficult to accurately predict mode shift outcomes. That said, it is possible to evaluate shifts in time-valuation as a result of vehicle automation. Research has estimated bicyclists and pedestrians' valuation of time during travel is equal to that of passengers in vehicles and transit (roughly 25% of

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[4] http://www.telegraph.co.uk/motoring/news/8010735/Driving-a-car-is-more-stressful-than-going-by-bus-says-new-research.html

[5] http://www.nzta.govt.nz/resources/research/reports/469/docs/469.pdf

the wage rate)[6]. Drivers' value of time ranges from 25% to 50% depending on conditions and this variability is present in transit users depending on vehicle crowding. As stated in the previous section, the change in the driver experience may align the value of time of drivers to that of transit users in an un-crowded environment. Therefore, given a constant per-mile cost, a certain percentage of transit users and/or pedestrians and bicyclists may switch to autonomous vehicles for a portion of their travel, thereby increasing VMT.

C. SAFETY

A report by KPMG stated up to 90% of all vehicle accidents could be eliminated with the use of autonomous vehicles. A major reduction in accident rates could have a significant effect on safety features such as frame design, airbag provision and overall vehicle weight. The true degree of vehicle weight reduction hinges on the actual degree of change in the accident rate. Initial expectations in accident reduction may be overstated based upon prior experience with vehicle safety improvements. Research by Sam Peltzman of the University of Chicago found the 20% reduction in highway traffic fatalities from government regulations in the 1950s and 1960s was offset by an increase in accidents as a result of drivers feeling "safer"[7]. This included an increase in pedestrian and bicyclist fatalities as a result of higher speeds allowed due to safety regulations. The difference in this case is the safety improvement provided by autonomous vehicle technology is mostly dependent on non-human factors and thus may not suffer from the same offsetting effect. That said, automakers and consumers may demand that the underlying algorithms within the safety features allow for closer following distances and higher speeds due to the increased perception of safety, a concept known as

Next Generation Vehicles – An Active Transportation Perspective (by Matt Benjamin)

From the active transportation perspective, increased roadway safety is the greatest potential benefit of next generation vehicles. Safe passing of bicyclists and yielding to crossing pedestrians are exactly the types of driver behavior that active transportation planners would like to program into the minds of human drivers. To date, the primary focus has been on safety, which could have important benefits when the vehicles are fully integrated into the consumer market.

There are also some reasons for concern. While the ability of self-driving vehicles to operate safely will undoubtedly be the primary criteria for their initial acceptance by regulators and consumers, various other expectations that they will increase roadway capacity have the potential to undermine the safety benefits. Safety and capacity are often at odds under current conditions, forcing traffic engineers and policy makers into difficult decisions as they attempt to strike the appropriate balance.

The demands of the public often skew this balance in favor of capacity rather than safety. Traffic collisions are typically viewed by the public as a sad but unavoidable byproduct of human mobility, while congestion is seen as correctable malfunction that needs to be resolved. Examples include traffic engineering decisions to restrict pedestrian movements at some intersections, allowance of permissive left turns and reluctance to implement automated traffic enforcement technologies.

Autonomous vehicles will have sophisticated built-in capabilities to sense pedestrian and bicycle movements and to avoid conflicts and collisions regardless of the effect on traffic capacity. However, in practice, we will need to thoroughly evaluate the abilities of system planning and vehicle operations to remain within the limits of their technological abilities and to operate safely rather than to squeeze more capacity out of our limited roadway space. This is especially the case in dense urban settings where pre-programmed 100% yielding vehicle compliance become a source of driver frustration and increased street congestion.

While humans may no longer be "behind the wheel" in the literal sense, we will still be driving these important decisions.

[6] http://www.vtpi.org/tca/tca0502.pdf

[7] The Effects of Automobile Safety Regulation. Peltzman, Sam. University of Chicago. 1975.

"risk compensation." Users of vehicles may increase their miles-traveled as the perception of safety increases relative to other modes, especially for long distance travel such as air and rail.

Additionally, this notion of risk compensation may be evident in levels of autonomy up to Level 3 in which a user's perception of safety results in less attention to monitoring the vehicle, even though the capability of the vehicle's autonomy does not warrant that level of control. Issues of shared liability at autonomy Level 3 may necessitate enhanced safety features rather than a reduction due to the varying nature of driver control. Vehicles operating at high speeds may still require significant safety features due to uncontrollable events such as weather, debris or other accident-related factors as the frequency of accidents would never reduce to zero.

While "risk compensation" and other offsetting effects may lead to a decrease or a stabilization of vehicle-miles-traveled, the general improvement in safety most likely will lead to an increase in vehicle travel. With a lower accident rate, incidental congestion will realize a dramatic decrease, with estimates that 25% of all congestion is incident related[8]. The resulting decrease in congestion would allow for expanded mobility and a reduced cost of travel for existing and future drivers which may result in additional induced travel.

D. VEHICLE COSTS AND CAR SHARING

The extent to which autonomous vehicle technology will increase vehicle cost has a range of possibilities. If the safety feature reduction described above allows for a reduction in vehicle size and materials required, those savings could partially offset the added cost of the new technology. Additional, improvements in safety could yield a dramatic decrease in insurance premiums for vehicle ownership. The KPMG report stated that the Google Car currently utilizes roughly $100,000 in technology, but that added cost is predicted to dramatically decrease with economies of scale present in mass-production. Assuming that costs are still higher than current vehicles, what will this mean for vehicle ownership trends? While the image of roaming shared autonomous vehicle is typical for Autonomy Level 4, car-sharing will take on an expanded role for levels of autonomy 1 through 3 due to the added costs and current shifts in ownership trends[9]. Studies have shown that car-sharing service provision substantially reduces overall vehicle ownership [10] which in turn reduces user VMT[11]. In a study by Cervero, 29% of the car-sharing members had gotten rid of a car while also reducing their overall VMT. The VMT decrease was partially due to users' increased perception of the true transactional cost of vehicle usage, which affected the number of trips taken and the total length of each trip. Based on the expectation that the expansion of autonomous vehicle technology will coincide with an increase in car-sharing due to the added costs of the technology, VMT on a system-wide level may in fact decrease. However, if vehicle costs are reduced due to a decrease in size and materials required and/or reductions in insurance premiums, then ownership may increase which could lead to an increase in VMT.

E. PREVIOUS NON-DRIVERS

[8] http://newsroom.aaa.com/wp-content/uploads/2011/11/2011_AAA_CrashvCongUpd.pdf

[9] http://www.vtpi.org/future.pdf

[10] http://transweb.sjsu.edu/MTIportal/research/publications/documents/Carsharing%20and%20Co2%20(6.23.2010).pdf

[11] http://trb.metapress.com/content/j81w2542q372x2p5/

A major factor in the potential change to overall VMT is the introduction of drivers who previously could not or chose not to own and operate a vehicle. This includes older and disabled populations, low-income households (especially with car sharing) and children. Much of the discussion of this effect centers on the previously discussed elements, including vehicle costs and mode split variations. If current vehicles are priced too high for low-income households, then autonomous vehicles will certainly be out of reach for those individuals and they will continue to travel via their current modes. More affluent older and disabled persons may realize the most benefit from autonomous vehicle technology and may in fact travel more. This could result in both an increase in vehicle trips and in trip length due to a switch from other modes of travel and induced demand. Again, as with the previously discussed elements, this change is contingent upon overall vehicle operating and ownership cost reductions. Assuming that costs remain competitive, it's fair to assume the introduction of a population of new drivers will most likely yield an increase in VMT.

F. REGIONAL VARIATIONS

The varying effect on VMT can also be attributed regional differences in which multi-modal provision or geography yields an opposing outcome. A more urban area with a robust transit network may in fact realize a decrease in VMT. This is due to autonomous vehicles' ability to potentially solve the "last-mile" problem that faces many transit agencies. A historical problem in cities has been the fact that drivers remain in their cars because of the difficulty of connecting to a main transit station from their house or place of work[12]. The underlying rapid network is in place but is unable to provide a competitive service to all areas of the city. An area in Singapore is already testing the ability of shared autonomous vehicles to solve this problem[13]. If successfully implemented in coordination with transit service, urban areas may realize an overall decrease in VMT due to travelers shifting the longest part of their journey to transit while utilizing autonomous vehicles for the shortest segment of the trip. However, for trips outside of the core transit network, drivers within urban areas may realize an increase in VMT due to a modal shift for inter-regional travel from airplane or rail to personal vehicles. This shift is primarily contingent upon changes in operating costs for the various modes and the travel time variations.

Contrast this scenario with that of a rural area or less urbanized city without a definitive transit network. Without any other options for travel, drivers in these areas may realize an overall increase in VMT due to the previously described improvements in the driver experience. The low amounts of congestion coupled with expected increase in operating speeds will drastically increase the travel shed of drivers in these areas, and only the cost of fuel and land use constraints will limit the extent of this growth.

G. SUMMARY

A summary of the elements and their varying effects on VMT is presented in Table 1 below. Additionally, with the assumption that many of these elements will lead to an increase in VMT, tables 2 and 3 present the range of change in VMT dependent on regional variation as well as the range of VMT changes associated with varying locations of permitted use.

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[12] http://m.theatlanticcities.com/commute/2012/03/bike-will-fix-public-transits-biggest-problem/1572/

[13] http://www.sciencedaily.com/releases/2013/08/130816094643.htm

TABLE 1.
ELEMENT VARIATIONS ON VMT IMPACTS

Element	Reasons for VMT increase	Reasons for VMT decrease
Driver Experience	Levels 3 and 4 allow for multi-tasking and improved riding position Change in passenger layout and seating configuration Reduced level of stress for "driver"	Change in driver experience is not significant at Level 3, and stress levels remain constant due to continued congestion
Mode Split Variation	Cost per mile rivals transit and time-value equation shifts toward autonomous vehicle instead of transit/bike/walking	Cost per mile increases significantly, placing more value on transit and other modes
Safety	Safety improvements reduce need for added vehicle weight, reducing fuel need and cost of driving Safety improvements improve roadway operation with reduction in incidental congestion Increased perception of safety relative to other modes results in higher vehicle usage	Risk compensation leads to offsetting increase in other accidents Shared liability in Level 3 requires vehicle to operate "too safely", negating improved roadway operational benefits Uncontrollable factors such as debris or weather place a limit on improvements to safety and reductions in vehicle safety features for high-speed operation
Vehicle Cost of Ownership	Decreased vehicle size due to safety improvements decrease vehicle cost Reduction in insurance premiums	Costs for technology increase, leading to continued downward trend in ownership rates
Previous Non-Drivers	Added population of new drivers who can afford the technology (elderly, disabled)	Technology is still out of reach for low-income and many current non-drivers
Regional Variations	Rural and smaller urban areas provide no alternative to autonomous vehicle travel	Robust transit network works in conjunction with autonomous vehicle technology to solve "last-mile" problem

TABLE 2.
INCREASE IN VMT PER CAPITA IN AUTO-DEPENDENT REGIONS

Locations where Use Permitted	Market Penetration			
	25%	50%	75%	95%
Exclusive freeway lanes	+10%	+20%	+30%	+35%
Mixed freeway lanes and ramps	+5%	+10%	+20%	+30%
Auto-dominated arterials		+5%	+10%	+20%
All multi-modal streets			+5%	+10%
Without a legal driver aboard			+35%	+35%

TABLE 3.
INCREASE IN VMT PER CAPITA IN MULTI-MODAL REGIONS

Locations where Use Permitted	Market Penetration			
	25%	50%	75%	95%
Exclusive freeway lanes	+5%	+10%	+15%	+20%
Mixed freeway lanes and ramps	+0%	+5%	+10%	+15%
Auto-dominated arterials		+0%	+5%	+10%
All multi-modal streets			+0%	+5%
Without a legal driver aboard			+25%	+35%

III. AUTONOMOUS VEHICLE IMPACT ON FREEWAY OPERATIONS

In this section we examine some potential impacts of Automated Vehicles on the capacity and efficiency of roadways. For the purposes of this white paper, the focus is on *freeways.* To be sure, Automated and/or Connected (V2V) Vehicles will change the way all vehicles interact with local roadways. It appears, however, that automated functions are being developed for freeways first; thus we will focus on that application.[14]

A. MEASURING CAPACITY

Traditionally, freeway capacity is measured according to the following criteria:

- *Hourly traffic volume, measured in vehicles per hour per lane (vphpl).* Typically under ideal conditions, freeways have an hourly traffic volume capacity (i.e., "maximum throughput") of 2,000 vphpl. If the demand volume exceeds the maximum throughput a bottleneck is formed creating a queue of vehicles.
- *Delay, measured in vehicle-hours per day or person-hours per day for a particular segment.* Delay occurs at bottlenecks because the desired throughput (i.e., "arrival rate") is greater than the maximum throughput (i.e., "departure rate"), causing vehicles to slow. Vehicle-hours of delay is determined by the area between the curves for cumulative vehicle arrivals and departures over time. Person-hours of delay is determined by multiplying this value by the average occupancy per vehicle.
- *Travel time, measured in minutes and seconds.* Travel time through a segment increases as speed decreases. Speed decreases for a given segment with increasing traffic demand, particularly once the demand exceeds the maximum throughput (see Figure 1).
- *Travel time variability, measured in standard deviation of travel time for a sample of trips*. Travel time variability is an estimate of the reliability, or consistency, of travel times. A normalized version of the travel time variability is sometimes reported by dividing the standard deviation by the average travel time. This normalization ensures that a given standard deviation of travel time has a larger impact on the variability metric as its percentage of the average travel time increases (e.g., a five minute standard deviation has a greater impact on variability when the average travel time is twenty minutes versus one hour).

Additionally, each freeway segment can exhibit its own relationship (unique from other segments) between traffic volume (vphpl) and traffic density (vehicles per mile per lane). Traffic volume on a freeway segment increases from zero to the maximum throughput at the optimal density. Beyond the optimal density, the traffic volume begins to decrease and eventually

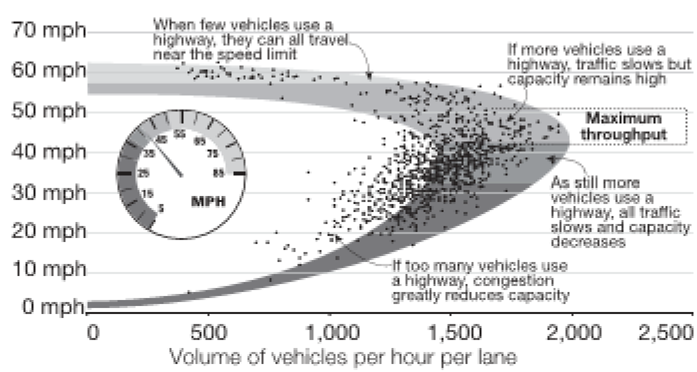
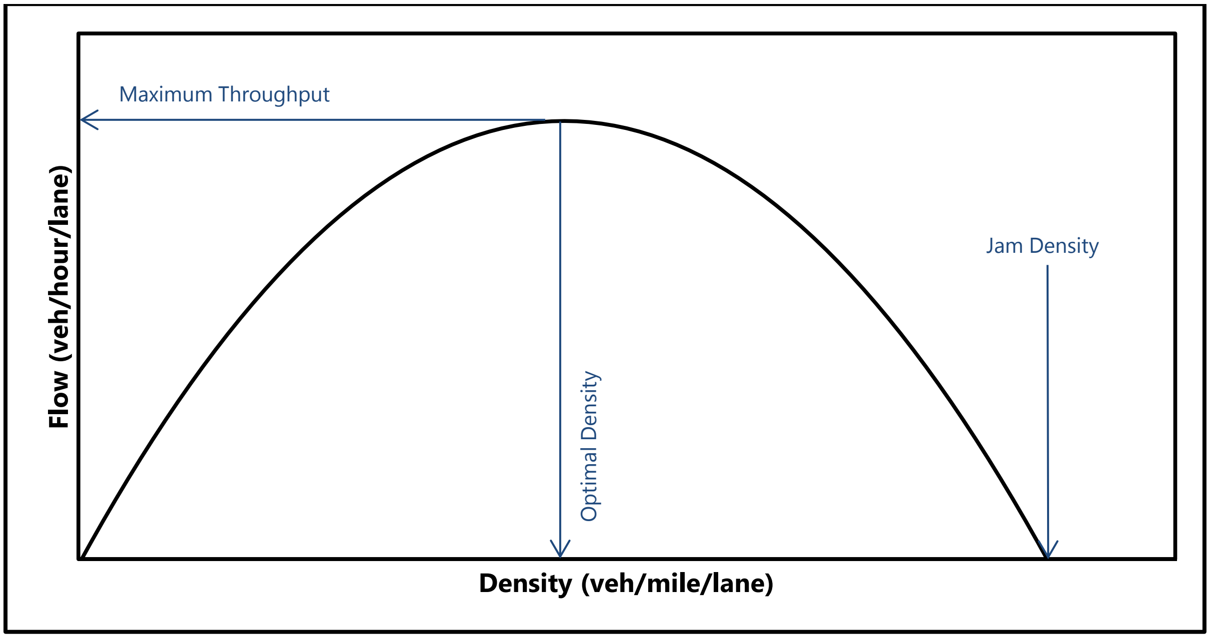


FIGURE 1. SPEED VS. VOLUME (WSDOT, 2013)

[14] While we focus on freeways in this white paper, autonomous vehicles have the potential to improve capacities at intersections through similar operating improvements as described below and through vehicle-to-infrastructure (V2I) communication.

approach the jam density, at which both flow and speed become zero (Figure 2)[15].

FIGURE 2. TYPICAL TRAFFIC DENSITY – VEHICLE FLOW RELATIONSHIP



B. HOW AUTOMATED VEHICLES AFFECT CAPACITY

Automated and connected vehicles will have a net effect on freeway operations and capacity, depending upon their share of the fleet mix, their operating parameters (acceleration, deceleration, headway, etc.) and their ability to react to traffic conditions beyond the vehicles immediately adjacent to them.

1. FLEET MIX

Chapter 2 of this paper discusses the prospective timeline by which automated vehicles will enter the fleet, suggesting the high market penetration among vehicles on freeways is not expected until at least 2030 and high use on other facilities is not likely until beyond 2035.

Based on our review of literature there are relevant findings with respect to fleet mix. van Arem et al. [1] find that the penetration rate needs to exceed 40% before significant impacts are noticed. Similarly, Jones and Philips [2] reviewed simulations and established a summary conclusion that positive impacts on flow stability and capacity are achieved only when fleet penetration rate of vehicles with Cooperative Adaptive Cruise Control (CACC) exceeds 40%. Davis [3] found that 50% penetration rate was effective. Tientrakool [4] finds that capacity improves little until the CACC penetration rate exceeds 85%. Shladover [5] reports that capacity improves linearly from 2,000 to 2,300 vphpl at 50% CACC, but then increases non-linearly and reaches nearly 4,000 vphpl at 100% CACC.

[15] We recognize this is a very generalized curve; many argue against a continuous q-k relationship.

In summary, based on simulation to-date Adaptive Cruise Control by itself does not appear to have significant impacts on capacity, however, when the vehicles are allowed to communicate and cooperate with each other, there are significant impacts when the fleet mix exceeds 50% CACC.

2. OPERATING PARAMETERS

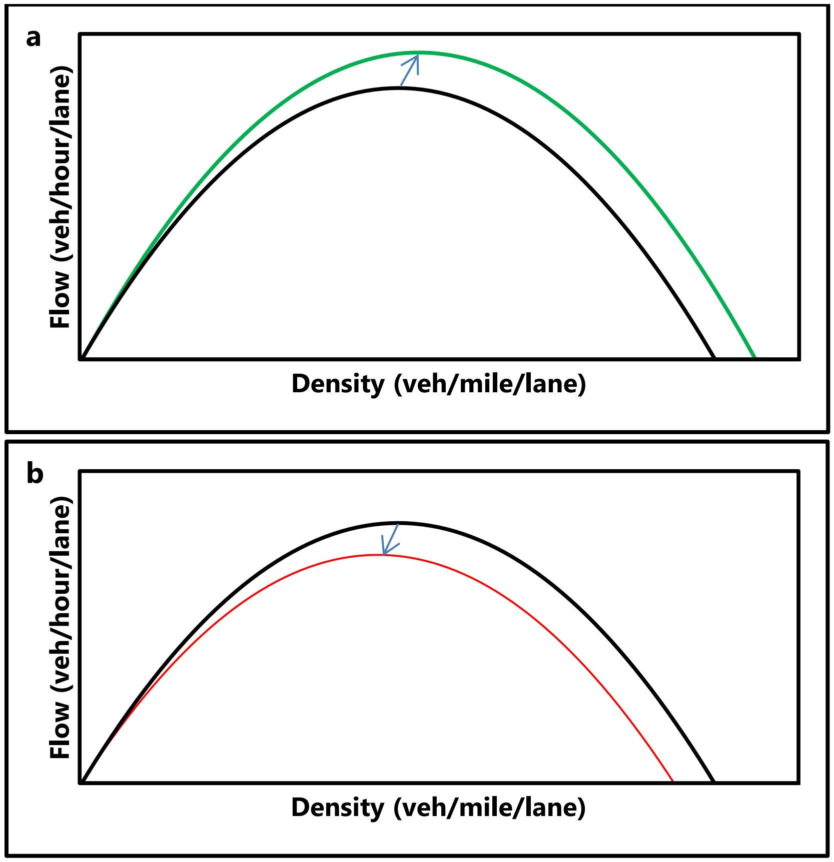
Human drivers tend to vary their acceleration, deceleration and following distance in a way that makes each human driver unique. Drivers tend to accelerate more slowly than they decelerate, which is one of the reasons bottlenecks occur. They also have preferences with respect to car following, and those preferences can change daily. As well, drivers vary in how quickly they react to vehicles slowing down ahead of them. Autonomous vehicles can improve traffic flow and freeway capacity by (1) keeping these parameters *constant*, and (2) allowing for faster, more tightly spaced vehicles.

Most practitioners are aware of the classic relationship between traffic flow and density shown in Figure 2. As the traffic volume increases, headway tends to decrease and become more constant (i.e., the distribution has a smaller standard deviation). At some point, headways reach a minimum, density reaches a critical maximum (aka "optimal density"), drivers slow down and a traffic jam occurs, greatly reducing the capacity of a segment.

If automated vehicles operate at lower headways, then maximum throughputs could generally increase (Figure 3a). Conversely, a more conservative headway would result in the opposite impact on capacity (Figure 3b). In fact, some experiments (e.g., Kerner, 2003[10]) have noted that if these vehicles operate at lower speeds in order to achieve a more stable flow, they could reduce the capacity of a bottleneck and increase delay and travel time.

In addition to headway and speed benefits, autonomous vehicle response can reduce disruption effects and improve laminar flow. If vehicles are programmed to optimize at least two of the three factors (speed, headway, uniformity) within the parameter ranges currently being tested, they're likely to achieve capacity benefits.

FIGURE 3. THEORETICAL IMPACTS OF A) LOWER HEADWAY AND B) HIGHER HEADWAY ON TRAFFIC FLOW



While the exact operating characteristics of automated vehicle technologies are proprietary and unknown, we expect both automakers and the consumer market to initially prefer automated vehicles with adaptive cruise control that favors headways comfortable to the vast majority of drivers. They will also implement the technology conservatively, due in part to potential liability (the 2009 Toyota recall that resulted in over a billion dollars in lawsuits due to a series of accidents that were ultimately determined to be mostly unrelated to technical issues [6]) and uncertainty with which owners will base their purchases on implementation results. For example, it is not clear how buyers will react to recent IIHS tests that exposed “crash avoidance” technology on several vehicles that did not avoid the crash [9]. Even the Google car, with more autonomous miles that any other vehicle, is currently programmed to drive less aggressively than people, at headways generally higher than two seconds [6]. On the consumer side, Shladover et al. [7] found that when commuters were given vehicles with autonomous technology and asked to choose from several headway options, they chose the headway that most closely matched their own driving behavior. When applied to a freeway simulation, those headways showed no freeway capacity benefit.

Perhaps as consumers become more accustomed to the vehicle dynamics and less in control of the driving task, vehicle headways can be reduced, and speed can increase. Part of the reason that the huge capacity benefit with CACC vehicles is plausible is they can safely travel with very low headways (0.5 seconds or lower) and higher speeds. Shladover et al. [7] found that drivers, when convinced their vehicles were in a safe platoon, were content to allow substantially lower headways than those of manual operation, and that when those choices were applied to their freeway simulation model, freeway capacity increased significantly.

3. DURATION AND SIZE OF RECURRING AND NON-RECURRING CONGESTION

Autonomous vehicles *could* increase segment capacity though lower headways and thus reduce duration and size of recurring congestion. Connected vehicles could hold much greater benefits. For starters the vehicle headway could be much less, and secondly, they could greatly improve the efficiency of weaving at ramp junctions, and greatly increase the capacity of segments adjacent to ramps.

Connected vehicles could similarly reduce the duration and size of non-recurring congestion resulting from an incident by reducing the frequency of disruptions from collision clearance and "rubbernecking." However, there is still some uncertainty on the degree to which fully autonomous vehicles will reduce the possibility of incidents altogether.[16]

4. COOPERATIVE AUTOMATION

We have noted that literature suggests a high fleet mix of connected vehicles is required to achieve substantial freeway capacity improvements. The capacity benefits come from improved operating parameters, and from the fact that these vehicles could be programmed for the benefit of system performance rather than purely for the perceived good of the individual. The benefits to system performance would be particularly large at weaving segments, where autonomous technology alone has limited benefits. However, a high fleet mix of cooperative vehicles is needed largely because the vehicles need to be in relatively close proximity, and the chance that any two vehicles are connected is the fleet mix squared. Autonomous vehicles alone may provide limited capacity benefits in the future through their operating parameters, but the evidence suggests that conservative parameter programming and low fleet penetration of cooperative V2V vehicles could actually reduce capacity initially. Similar conclusions could be made about impacts on the actual duration and size of congestion, although there are additional important considerations of how connected vehicles could potentially influence the frequency and impact of non-recurring events.

C. OUR EXPERIMENT

Fehr & Peers conducted a series of freeway simulations in VISSIM to get an initial estimate of the impacts of adaptive cruise control (ACC) on capacity. The simulation case represents the performance of individual vehicle technologies, capable of sensing the situation several cars ahead and alongside, but not connected V2V technology, or cooperative adaptive cruise control (CACC).

A simple congested freeway network was developed. A corridor was developed with seven segments, including basic (mainline), diverge (off-ramp), and merge (on-ramp) types. Rather than create an ACC vehicle from scratch,

[16] It is worth noting that levels of autonomy below 4 could result in "cockpit automation," in which reliance on automation to perform a set of tasks limits pilot experience and erodes skills when manual control is required, as has happened in the airline industry [8]. Cockpit automation may somewhat offset otherwise expected reductions in incidents due to automated vehicles.

we modified the existing Wiedemann model that exists within VISSIM. Because the operating characteristics of ACC systems are proprietary, we opted to initially develop conservative and aggressive scenarios that represent a wide range of possible ACC characteristics. The conservative scenario is characterized by higher headways and lower acceleration/deceleration rates than the base assumptions for manual operation, whereas the aggressive scenario is characterized by the opposite set of assumptions (additional details on simulation assumptions are in Appendix B). In both cases, we tested scenarios with 50% of the fleet assumed to be operating with ACC.

The results on freeway efficiency are shown in Table . As expected, the conservative scenario results in an increase in both delay and travel time, while the aggressive scenario results in the opposite outcome relative to the base scenario. Additional details are in Appendix B.

TABLE 4
PRELIMINARY VISSIM SIMULATION RESULTS – FREEWAY PERFORMANCE WITH CONSERVATIVE AND AGGRESSIVE ACC SCENARIOS

Performance	Base	50% Conservative	50% Aggressive
Total Delay [hours]	39	80	21
Average Delay per Vehicle [seconds]	16	34	9
Total Travel Time [hours]	331	370	312

After validating the direction of capacity changes associated with adjustments to the car following model parameters, we then simulated an intermediate ACC scenario at different fleet penetrations (Table). At a 10% fleet penetration, no change is observed. At a 50% fleet penetration, some improvements are observed but they are marginal. Even at a 75% fleet penetration, the improvements are minor.

TABLE 5
PRELIMINARY VISSIM SIMULATION RESULTS – FREEWAY PERFORMANCE WITH INTERMEDIATE ACC

Performance	Base	10% Intermediate	50% Intermediate	75% Intermediate
Total Delay [hours]	39	39	37	27
Average Delay per Vehicle [seconds]	16	16	16	12
Total Travel Time [hours]	331	331	328	317

On a Level of Service (LOS) basis, the overall impacts of any ACC scenario are also marginal. The most noticeable impact on LOS occurs in the segment upstream of a bottleneck, in which there is substantially more congestion in the 50% conservative case but substantially less congestion in the 50% aggressive and 75% intermediate scenarios. This finding is consistent with the impacts of headways described in the previous section on maximum throughput at bottlenecks and queue lengths behind the bottleneck. See Appendix B for LOS results.

Given the uncertainty surrounding actual operations of automated vehicle technology, these results are not meant to represent our predictions but are rather meant to illustrate the range of possible outcomes and a general lack of improvement in freeway capacity associated with ACC alone. Since only the car following model was adjusted in this preliminary analysis and most freeway congestion is caused by lane changing at on-ramps or weaving segments, larger impacts to capacity could be captured in future simulations that account for potential improvements in lane changing. For example, a simulation conducted by Kesting et al. [11] found that ACC vehicles could significantly reduce congestion at an on-ramp bottleneck, even at low fleet penetrations. More dramatic improvements would be expected with a high penetration of connected vehicles that could both platoon at extremely low headways and communicate/anticipate speed changes.

D. CONCLUSIONS

Our clients are asking if automated vehicles should be considered as an alternative in long range plans. Our answer, for the moment, is “maybe but probably not.” Long range transportation infrastructure plans are currently examining scenarios in 2035 or 2040. Even though the technologies and regulatory framework may be in place to allow autonomous operation on freeways in the early 2020s, significant market penetration of fully autonomous vehicles could take decades longer, as was the case with airbags. VTPI [12] predicts it will be 2050/2060 before automated vehicles achieve a 50 to 75% share of the vehicle fleet, which is the penetration rate at which capacity will be impacted by automated vehicles’ different driving behavior. However, as discussed in Chapter 2 above, under circumstances such as government mandated vehicle autonomy as a new vehicle safety feature, and an automobile industry shift away from the present auto ownership model to a subscription model, 50% market penetration may occur as early as 2035.

Will automated vehicles change freeway capacity? Our conclusion is “perhaps, but unlikely within the time frame of current long range plans.” Our initial tests indicate a high percentage of vehicles with Adaptive Cruise Control do not significantly change capacity of a freeway segment in one direction or another. Of course, this is our own car following model. Until automakers open the books on their own models, there is some uncertainty.

Others have demonstrated that with Autonomous and Connected Vehicles (so car X knows what is happening 10 cars ahead), you can have significant capacity increases. That is plausible; however, the "Connected" technology in autonomous vehicles is on a slower market penetration trajectory (all 10 cars need to have V2V technology), and we have little confidence it will play a significant role in mixed flow freeway traffic by 2035.

In summary, we project the following factors will dictate the effectiveness of autonomous vehicles in improving freeway capacity over the next 20 to 40 years.

EFFECTS OF AUTONOMOUS VEHICLES ON FREEWAY CAPACITY AND CONGESTION

	Reasons for Optimism	Reasons to Reign in Enthusiasm
Capacity Benefit Potential	When fleet mix approaches 100% (V2V*[17]), freeway lane capacity could reach 4,000 vphpl, double the present capacity	Capacity benefits are likely to occur only on freeways initially (pre-2030) and will only begin to be apparent when the fleet mix is at least 40% (V2V*[18]) autonomous
Driver Acceptance	Drivers will be convinced through experience that they are safe in closely spaced automated freeway platoons	Driver comfort with close vehicle following headways is a critical concern. In tests of ACC, most chose headways that closely matched their own driving behavior, resulting in little capacity benefit, though CCAC may change this
Early Wins	With high fleet penetration, efficiency and capacity of weaving at ramp junctions and adjacent freeway segments could be markedly improved, even before headway functions are perfected for line haul freeway segments.	On line-haul freeway segments, our VISSIM tests indicate that capacity of freeway segments would be significantly reduced with conservative AV parameter programming. Capacity benefits at locations other than freeways may be many decades away.
Speed of Adoption	Given the high stakes[19], interests including the automakers, Google and other tech companies and universities are ambitiously refining the technology and machine-learning algorithms. They may achieve our aggressive parameter capabilities and high fleet penetration sooner than our projected 2035+ time frame. Per our VISSIM tests, aggressive programming could reduce vehicle delays by about 45% once half the fleet is operating autonomously.	Even with higher-level technology capabilities vehicle occupants may not become comfortable with aggressive performance. Intermediate parameter settings require 75% autonomous fleet mix to achieve moderately high capacity benefit (25-30%).

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[17] Some of the literature suggests that this type of capacity improvement is theoretically possible without V2V technology, though a more common opinion is that V2V technology would be required given uncertainties related to the programming of autonomous vehicles.

[18] Ibid

[19] In addition to the business-sector incentive, public stakes are extremely high as well. Morgan Stanley's paper 'Self-Driving the New Auto Industry Paradigm' finds that autonomous cars can contribute $1.3 trillion in annual savings to the US economy.

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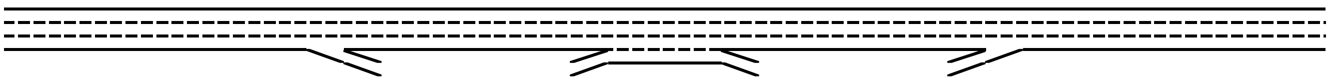
APPENDIX A: Simulation Analysis Assumptions

Project:	**LOS Videos**	**Alternative:**	**ACC Test**	*Data Entry Value*
Freeway Corridor:	**Eastbound**	**Time Period:**	**Peak Hour**	*Calculated Value*

Location	1	2	3	4	5	6	7



Key

<> Express Lane (HOV)

No Trucks

Name	Basic 1	Diverge	Basic 2	Weave	Basic 3	Merge	Basic 4
Define Freeway Segment							
Type	Basic	Diverge	Basic	Weave	Basic	Merge	Basic
Length (ft)	5,000	1,500	1,500	4,000	1,500	1,500	2,000
Accel Length						400	
Decel Length		150					
Mainline Volume	5,700	5,700	4,700	4,700	4,700	4,700	5,700
On Ramp Volume				1,000		1,000	
Off Ramp Volume		1,000		1,000			
PHF	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Terrain	Level	Level	Level	Level	Level	Level	Level
Truck & Bus %	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
FFS Curve	65	65	65	65	65	65	65
Summarize Segment Operations							
Segment v/c ratio	0.92	0.92	0.76	0.90	0.76	0.93	0.92
Segment Density	38.1	37.8	28.4	36.3	28.4	35.9	38.1
Segment LOS	E	E	D	E	D	E	E
Over Capacity							
Simulation Results							
Segment Density	34.6	35.5	27.6	25.9	27.8	38.8	33.3
Segment LOS	D	E	D	C	D	E	D

WEIDEMANN 99 CAR FOLLOWING MODEL PARAMETERS

Parameter		Default	ACC (Aggressive)	ACC (Intermediate)	ACC (Conservative)
CC0	standstill distance (ft)	4.92	3.28	4.1	4.92
CC1	headway time (sec)	0.9	0.5	0.8	1.2
CC2	following variation (ft)	13.12	6.56	9.84	13.12
CC3	threshold for entering following	-8	-8	-12	-16
CC4	negative following threshold	-0.35	-0.1	-0.35	-0.6
CC5	positive following threshold	0.35	0.1	0.35	0.6
CC6	speed dependency of oscillation	11.44	0	0	0
CC7	oscillation acceleration (ft/sec^2)	0.82	1.312	0.82	0.328
CC8	standstill acceleration (ft/sec^2)	11.48	13.12	11.48	9.84
CC9	acceleration at 50 mph (ft/sec^2)	4.92	6.56	4.92	3.28

DETAILED NETWORK PERFORMANCE (CONGESTED CONDITIONS)

Network Performance	Base	50% Aggr.	50% Cons.	50% Interm.	10% Interm.	75% Interm.
Number of Vehicles Served	8,202	8,195	8,170	8,193	8,186	8,192
Travel Distance [mi]	18,672	18,680	18,639	18,685	18,677	18,674
Travel Time [h]	331	312	370	328	331	317
Average Speed [mph]	56.5	60.0	50.5	56.9	56.5	58.9
Total Delay [h]	39	21	80	37	39	27
Average Delay per Vehicle [s]	16	9	34	16	16	12
VHD/VMT [min/mile]	0.12	0.07	0.26	0.12	0.12	0.09

LOS RESULTS (CONGESTED CONDITIONS)

Freeway Segment	Base	50% Aggr.	50% Cons.	50% Interm.	10% Interm.	75% Interm.
Basic 1	D / 35	D / 34	E / 36	D / 34	D / 34	D / 34
Diverge	E / 36	E / 37	E / 37	E / 37	E / 36	E / 36
Basic 2	D / 27	D / 28	D / 28	D / 28	D / 28	D / 28
Weave	C / 27	C / 27	E / 40	C / 27	C / 27	C / 27
Basic 3	F / 57	D / 31	F / 85	F / 50	F / 51	E / 37
Merge	F / 59	F / 50	F / 69	F / 65	F / 64	F / 59
Basic 4	E / 35	E / 36	E / 35	E / 36	E / 35	E / 36

Values shown as LOS Score / Density