

**MODELING AND UNDERSTANDING THE IMPLICATIONS OF
FUTURE TRUCK TECHNOLOGY SCENARIOS FOR
PERFORMANCE-BASED FREIGHT CORRIDOR PLANNING**

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Presented to
The Academic Faculty

by

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Dedicated to Katie Haynes, Mary Caldwell, Sterling Caldwell, Randolph Haynes, Symes Haynes Jr., Louis Haynes, & Elizabeth Gordon, who started this journey with me.

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LIST OF ABBREVIATIONS

AHS	automated highway system
ATP	autonomous truck platoon
AV	autonomous vehicle
CACC	cooperative adaptive cruise control
CD	tractor plus double trailer combinations
CO ₂ eq.	carbon dioxide equivalents
CS	tractor plus semitrailer combinations
CT	tractor plus triple trailer combinations
CV	connected vehicle
DATP	driver assistive truck platooning
FAST Act	Fixing America's Surface Transportation Act
FAF	Freight Analysis Framework
GHG	greenhouse gas emissions
MAP-21 Act	Moving Ahead for Progress in the 21 st Century Act
MPO	metropolitan planning organization
NO _x	nitrogen oxide
OD	origin-destination
OUE	origin user equilibrium
PCE	passenger car equivalents
PM	performance measurement
PM _{2.5}	particulate matter less than or equal to 2.5 microns
SU	single unit trucks
TT	truck plus trailer combinations
TTI	travel time index
V2I	vehicle-to-infrastructure
V2V	vehicle-to-vehicle
v/c ratio	volume to capacity ratio
VHT	vehicle hours traveled
VMT	vehicle miles traveled

SUMMARY

Autonomous highway vehicles are coming. The question regarding this technology has shifted from “if” to “when”. Many advocates predict that autonomous trucks, in particular, will be commercially available within the next decade, and perhaps even before autonomous passenger vehicles. This includes the emergence of autonomous and connected multi-vehicle truck platoons. Unfortunately, this technology is developing more rapidly than the public sector is preparing for it; the situation is exacerbated by the fact that the time-frame for which the technology is expected to make up a substantial portion of the motor vehicle fleet is within the current planning horizon of most transportation planning agencies. Thus, there is an immediate need to explore the implications of this technology for public agency planning purposes; exploring these implications will in turn require the development of tools to quantify the potential costs and benefits involved. With these needs in mind, the objectives of this dissertation were to (1) develop a simulation modeling and performance measurement tool that incorporates autonomous and connected truck platooning technology into the long-range planning process, (2) demonstrate how this tool can be applied to a selected interstate corridor in Georgia (I-85 and I-285), and (3) develop a scenario planning framework that uses the results from the tool to guide policy development. The model consists of an iteratively linked, supply-demand equilibrium based multi-commodity and multi-vehicle class truck trip distribution and a highway traffic assignment model, requiring changes be made to the typical travel demand modeling process to capture the characteristics of platooning technology. The results from an empirical application of this model were then used to assess the safety-, economic-, congestion-, and emissions-related impacts of platooning technology.

The model developed is flexible enough to allow for a number of variations in platooning details, and was supported by a multi-variable sensitivity analysis of key input variables. This sensitivity analysis showed a range of costs and benefits of the technology, with the greatest benefits seen when labor costs were cut by allowing some of the trucks to be driverless (which would also help to alleviate a currently significant shortage of experienced truck drivers). Allowing the autonomous trucks to operate on a dedicated lane was found to tremendously reduce travel time and congestion for those trucks. However,

the magnitude of cost savings depends on a variety of factors, including the deployment of platoons of different sizes, the potential for platoon-supported fuel savings, and the level of corridor traffic congestion. In some scenarios, these congestion benefits came at the expense of the convenience of other vehicles, while in other scenarios, these vehicles experienced modest congestion-reduction benefits. The emissions impacts varied; the benefits for fuel consumption and emissions for platoons were as much as 9.6% at optimal speeds. While these findings are insightful, it is important to note that they are based on a specific set of assumptions and do not consider infrastructure costs related to the implementation of the technology. Changing the assumptions in some cases could significantly change the results.

This research is one of the first efforts to modify a traditional travel demand model to simulate autonomous truck platoons. One of the key components of this contribution is the use of an origin user equilibrium (OUE) traffic assignment, a relatively new path-based assignment which allows the user to specify vehicle class and origin specific traffic flows, and assign them to the network simultaneously. The OUE assignment has yet to be explored in depth with respect to multiple truck class-based, notably platoon-inclusive freight movements. Additionally, the research presents a new application of the Freight Analysis Framework, which is a widely used freight database within the United States.

Given the uncertainty associated with platooning technology, there are a number of limitations associated with this research, and the final chapter of this dissertation discusses such limitations and presents opportunities for future work. As the details of platooning technology become clearer, tools such as the one developed here can assist transportation planners with incorporating such technological advances into their planning processes.

CHAPTER 1: INTRODUCTION

1.1 Research Motivation

The topic of autonomous vehicles has been discussed for some time now. While the question in the past has focused on “if”, as in “if this technology will become a reality”, the question has now shifted to “when”. There are a number of projections and timelines that shed light on this question. Some projections suggest that we will see fully automated vehicles on the road within the next decade, while others more conservatively provide projections for 15 to 25 years out. In particular, the potential application of using this technology in the context of platooning trucks on public roadways for more efficient freight movement is presently being tested. Furthermore, there are views that this is the “most realistic starting point of the commercial adoption of the technology. The long-haul vehicles have the most to gain, both in terms of safety and economic benefits. The fuel savings witnessed by trucks in a platoon [have] a significant impact on the operating profits of the operator, not to mention the environmental impact of reduced CO₂ and emissions”¹. There are a number of additional reasons that have been offered to explain why this particular application of the technology is so attractive when compared to other applications:

- The benefits afforded by the technology will likely result in more direct costs-savings for trucks;
- The cost of the technology is less of an impedance for the trucking industry;
- The use of the technology by the trucking industry may be able to assuage the issues of driver retention and driver shortage;
- Purchasing cycles for commercial vehicles are relatively quick, so reaching market saturation of the truck technology may take less time as compared to passenger vehicles;

¹ Quote by Mike Baker, the chief engineer at Ricardo UK Ltd, a firm that is a part of Safe Road Trains for the Environment (SARTRE)

- Commercial trucking is regulated and involves professionally trained drivers operating professionally maintained trucks. This may allow the technologies to be used more safely as compared to the case of personal vehicles being driven by individuals; and,
- The trucking industry already has sophisticated freight logistic infrastructure. Such infrastructure can be used as the foundation for autonomous and connected vehicle technologies.

1.2 Research Objectives

Considering the points above, the business case for autonomous truck platoons is compelling. For this reason, this dissertation seeks to explore the potential safety-, economic-, congestion-, and emissions-related benefits of autonomous truck platoons and how such benefits can be estimated. The next chapter begins by briefly exploring the benefits and costs of the technology as well as development and deployment projections. Of significant note is that many state and regional transportation plans have planning horizons that extend through 2040 and after, within which time-frame some projections even suggest that full automation may be achieved. Accordingly, given the coming of this potentially disruptive technology and the overlapping of this technology with the current planning horizon, it is essential that states begin to seriously consider its implications. In particular, emphasis is placed in this dissertation on the implications of the technology in the modeling and performance measurement aspects of transportation planning. Accordingly, the three *objectives* of this dissertation are as follows:

1. Develop a modeling and performance measurement tool that incorporates autonomous truck platoon (ATP) technology;
2. Demonstrate how this tool can be applied to a selected interstate corridor in Georgia (I-85 and I-285); and,
3. Develop a framework that incorporates this tool in the planning process

Elaborating more on the third objective, the significance of this dissertation is tied to how the modeling and performance measurement tool that is developed can be used in the transportation planning process. There are a number of factors that will shape the future

of truck freight – technology being one of them. Given the uncertainty of the future of autonomous and connected truck technology, scenario planning is used as a tool, not to predict the future, but to develop plausible alternatives that can be used to help transportation planning agencies prepare for the future. The planning context in this dissertation, then, is centered on carrying out performance-based freight corridor planning using scenario planning.

To set the stage for this dissertation, let's consider an approach that includes corridor selection, scenario development and evaluation, and integration of the results into long-range transportation plans. This approach would begin with a selection of key freight corridors based on a number of criteria that have been set. Future conditions along those corridors would be considered, along with the details of autonomous truck platoons, to develop a number of plausible scenarios. Once developed, these scenarios would be evaluated against a set of performance measures that reflect the goals of the agency. The results of the evaluation would then be used to develop insight on how the different scenarios could impact the performance of the transportation system and on how best to prioritize projects and invest resources to maximize benefits. The results from the scenarios, along with proposed future year projects and policy recommendations, would then be included as a part of an update to a long-range transportation plan. As more information becomes available, the scenarios would be adjusted and the results would be updated. And while this approach is anticipated to be used for future year projects, the information also provides a basis on how to invest today to meet both current and future needs.

The three objectives of this dissertation lead to the following *research questions*:

- How can an existing travel demand model be modified to represent the characteristics of autonomous truck platoon technology?
- How can the model results be used to measure safety-, economic-, congestion-, and emissions-related impacts of the technology?
- How do changes in the truck technology scenarios alter the performance of truck freight? How do operational and infrastructural details impact the benefits of the technology?
- How can the technology be incorporated into the freight corridor planning process?

There are three distinct phases of this dissertation: (1) modeling, (2) performance measurement, and (3) planning. These research questions are answered through the tasks laid out in each phase, leading to three separate contributions to the field. These *contributions* include the following:

1. A modeling and performance measurement tool that simulates and quantifies the impacts of autonomous truck platoons;
2. New performance measures that are specific to autonomous truck platooning on public roadways;
3. A set of policy recommendations, which are linked to the results from the modeling and performance measurement tool, to address autonomous truck platoon technology

1.3 Organization of the Dissertation

The following chapter, Chapter 2, presents the findings of a literature review, which covers details of autonomous and connected vehicle technology and related policy, modeling and performance measurement efforts, and performance-based freight corridor planning. These three areas are explored separately as well as in relation to each other. The intersection of these three areas is used to identify the gaps in the literature, and subsequently determine where contributions will be made in this dissertation. Those contributions, as briefly discussed above, are described in more detail at the end of Chapter 2. The methodology applied is discussed in Chapter 3. The chapter, which is organized into the three phases, explains: (1) the steps taken to develop a traditional four-step truck freight model and adapt it to incorporate autonomous truck platoon technology; (2) the series of calculations applied to the results from the model runs to measure the performance of each scenario; and (3) the process of developing a planning framework that places the modeling and performance measurement tool in a planning context. Chapter 4 then presents the results and findings for each of these phases. The final chapter, Chapter 5, provides a discussion on the contributions of this dissertation, limitations associated with the modeling and performance measurement tool, and opportunities for future research.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

Three areas are explored in this dissertation: (1) technology characteristics and related policy, (2) modeling and performance measurement, and (3) performance-based freight corridor planning. There is a growing literature in each of these areas. Accordingly, the following three sections are dedicated to discussing this literature as it pertains to the dissertation objectives. The fourth and final section of this literature review provides a discussion of the intersection of these three areas, the literature that exists in that intersection, and the gaps that remain. This discussion provides the basis for this dissertation.

2.1 Technology Characteristics and Related Policy

This section provides technical details, future projections, and posited benefits and costs of autonomous truck platoon technology. Additionally, existing and future policy related to the technology is explored. The discussion on policy further defines the technology in terms of the boundaries within which autonomous truck platoons are likely to be operated.

2.1.1 Autonomous Truck Platoon Technology

An appropriate starting point for this topic is the recognition that the discussion on autonomous truck platoons involves two burgeoning technologies: (1) autonomous vehicle technology and (2) connected vehicle technology. While the two are closely related, the details of the technologies differ. Autonomous vehicle technology makes use of sensors and cameras which gather information about the driving environment in order for the vehicle's computer system to use that data to control steering, accelerating, and braking. Connected vehicle technology, on the other hand, uses dedicated short range communication (DSRC) in order to allow for wireless communication, or data exchange, between vehicles (vehicle-to-vehicle or V2V) and between vehicles and infrastructure (vehicle-to-infrastructure or V2I). Using the technology, the vehicle can, for example, alert the driver on real-time safety- and mobility-related information. Autonomous truck platoon technology combines the two technologies so that the "driverless" (whether partially or

fully) trucks can travel at the same speed and brake at the same time (see Figure 2.1).

A significant component of autonomous vehicle technology is the United States' Global Position System, better known as GPS. Autonomous vehicles require high quality maps of the driving environment to be accurate and reliable. The high precision GPS technology, which is able to provide tracking to the decimeter, helps the vehicle drive by maintaining its position in its lane and staying a safe distance away from other vehicles. In addition to this, the live, second-by-second data from the GPS can alert the drivers of the equipped vehicles with information about accidents, traffic, and lane closures (Miller 2014). This has implications for route choice, which is especially useful for the trucking industry with regard to increased reliability and the on-time arrival of shipments. As it pertains to platooning, the GPS technology, along with radar and Wi-Fi, allows the trucks to communicate with each other. Another area in which GPS is relevant is the growing use of truck GPS data for freight performance measurement and planning. In particular, the American Transportation Research Institute (ATRI) has worked closely with the Federal Highway Administration since 2002, leading to the Freight Performance Measures Program (American Transportation Research Institute 2012). The performance measures in this program make use of "ATRI's real-time anonymized freight truck data sourced through unique industry partnerships" (American Transportation Research Institute 2012). The data, which include time, location, and speed, are used to produce the following measures: average speed, travel time, and reliability of truck movement; quantification and ranking of bottlenecks and other congested and deficient areas on the highway; border crossing time and delay; demand for truck routes and highways; and data that can assist in the development of origin-destination truck models. The arrival of autonomous and connected trucks could likely enhance such efforts.

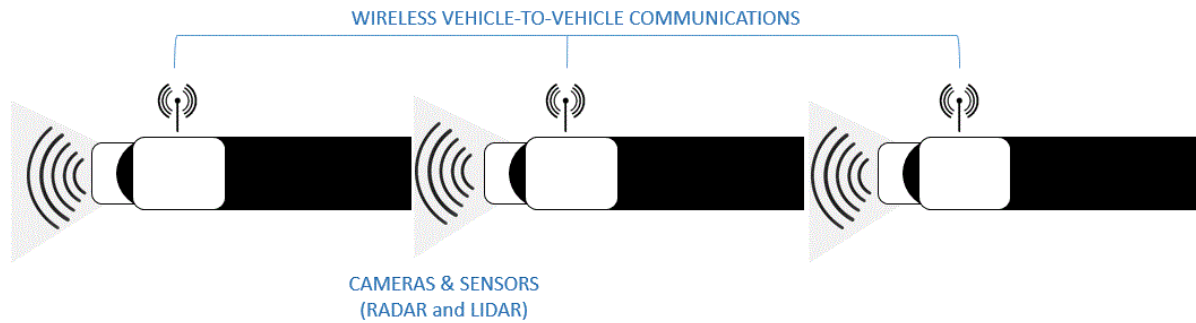


Figure 2.1: Diagram of a Three-Truck Autonomous Truck Platoon

A number of testing efforts that focus on truck platooning on public roadways have been or are currently being carried out (such testing is discussed in more detail later in this section). Early development and proof of concept programs date back to the 1990s with the United States Department of Transportation’s (USDOT’s) Automated Highway System program and Europe’s CHAUFFEUR I and II projects (ATA Technology & Maintenance Council 2015). European efforts continued into the 2000s with Safe Road Trains for the Environment (SARTRE) and KONVOI. The Energy ITS Project, a Japanese effort, also emerged in the 2000s. Despite these programs and prior work, autonomous truck platoons have not yet become a reality at a commercial scale. The details of the arrival of these platoons are uncertain, especially given the other factors that will influence future transportation demand as well as the development of other competing technologies. Nevertheless, in order to effectively plan for the future, transportation professionals will need to have a reasonable idea of the implementation timeline of the technology. While the projections for autonomous vehicle technology vary widely, the literature recognizes the need to consider the deployment of the technology by the level of automation. The National Highway Traffic Safety Administration (NHTSA) defines five different levels (National Highway Traffic Safety Administration 2013).

- **Level 0 – No-Automation:** At all times, the driver is in complete control of the primary vehicle functions (i.e., braking, steering, throttle, and motive power).
- **Level 1 – Function-Specific Automation:** This level of automation involves one or more specific control functions. The driver has complete authority but yields

limited control of certain functions to the vehicle. Some examples include adaptive cruise control, automatic braking, and electronic stability control. Driver assistive truck platooning (DATP) is another example of Level 1 automation. DATP uses V2V communications so that two or more trucks can “electronically couple”. The lead truck is driven either manually or in normal adaptive cruise control mode. While longitudinal movement is automated, both drivers remain responsible for steering.

- **Level 2 – Combined Function Automation:** This level involves automation of at least two primary control functions designed to work together to relieve the driver of control of those functions. An example of combined functions is adaptive cruise control and lane centering. The driver is still responsible for the safe operation of the vehicle.
- **Level 3 – Limited Self-Driving Automation:** Vehicles with this level of automation enable the driver to cede full control of all safety-critical functions, but only in certain environments and traffic conditions. The vehicle is expected to monitor changes in those conditions in order to alert the driver as to allow for a sufficient amount of transition time so the driver can take control.
- **Level 4 – Full Self-Driving Automation:** The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. At this level, the driver would provide destination or navigation input, but is not expected to be available for control at any time during the trip. This level of automation is for both occupied and unoccupied vehicles.

A report by the Victoria Transport Policy Institute (VTPI) lists different phases of development and deployment for autonomous vehicles, making note that many new vehicles already have some level 1 automation features, that level 2 is the current state of art and currently available on some new vehicles, that level 3 is currently being tested, and that significant technological development and technical improvement is necessary before full self-driving automation (level 4) will be possible (Litman 2015). Based on information about past vehicle technology deployment cycles (i.e., time from first commercial availability to market saturation), the typical cost premium, and the market saturation share,

the VTPI report provides implementation projections for autonomous vehicles. The projections assume that fully-autonomous vehicles will be available for sale and legal to drive on public roadways by 2020. It also takes into consideration the initial imperfections and high prices of the technology. Therefore, starting in 2020, the technology will only represent a small portion of total vehicle sales. Then, as time progresses, performance improves, costs decrease, and benefits become more apparent, autonomous vehicle market share will increase and then ultimately total vehicle fleets will increase. As demonstrated with this and other projections, there is recognition that highly-automated driving will enter the market gradually. IHS Automotive, an automotive industry research firm, predicts that self-driving cars with driver assistance will be available by 2025 and fully-automated cars will be available around 2030 (IHS Automotive 2014). The study forecasts that all vehicles are likely to be self-driving cars and commercial vehicles soon after 2050.

Focusing more specifically on commercial vehicles, there are a number of experts in the field that provide estimates for the deployment of autonomous trucks. Those trucks with lower levels of automation are expected to be available over the next decade while fully autonomous trucks are expected to be rolled out around 2025 or later (Cullen 2014). Another, more detailed estimate says that the technologies being released over the next five to ten years will mainly be adaptive cruise control technology and platooning. Then, between 2020 and 2025, the focus will shift to level 3 technology. And once level 4 technology is available, it may be used for specific applications, such as driving over dedicated routes (Cullen 2014). The American Trucking Associations' Technology and Maintenance Council (TMC) recognizes that there are two primary truck platooning approaches that are currently under system development: (1) truck platooning (level 1) and (2) highly automated trucks (levels 2 and 3). The TMC projected that level 1 will start being implemented between 2016 and 2018 and level 2 and above will start being implemented between 2020 and 2022 (ATA Technology & Maintenance Council 2015). In Europe, where autonomous trucks seem likely to be deployed first, there are already requirements for new truck models to be equipped with advanced emergency braking systems and lane departure warning systems (Transport Business 2014). A principal analyst at ABI Research suggested that the introduction of partially autonomous commercial vehicles in Europe will come by about 2020, while truck trains may be possible

by 2025 (Transport Business 2014). Truck manufacturers also have hopes for when they would like, or when they expect, their trucks to be road-ready. Daimler, for example, is hoping to have its Mercedes-Benz Future Truck operating regularly on the road by 2025 (Strange 2014).

As previously noted, there are viewpoints that suggest autonomous trucks will come before autonomous passenger vehicles. A report by University of California PATH Program (Shladover 2004) offers several reasons why cooperative vehicle-highway automation systems (CVHAS) are likely to be applied to heavy vehicles first:

- The technologies can be used more safely on professionally maintained vehicles operated by professional drivers than on personal vehicles driven by members of the general public.
- The cost of the technologies is not as much of an impedance for truck operators.
- CVHAS technologies can be introduced into the production process faster for small lot production as opposed to mass production.
- Heavy vehicles are already equipped with more onboard electronic infrastructure, which can be used as the foundation for the autonomous technologies.
- Benefits such as travel-time reduction, increased safety, and improved trip reliability can result in more direct costs-savings for heavy vehicles.

Nevertheless, there are still a number of issues that must be considered before these trucks and truck platoons are deployed. These issues, which are summarized in Table 2.1, represent different aspects of truck platooning that need to be addressed in order to solidify the feasibility of the application. Regarding first and last mile travel, if the autonomous operation mode is limited to highway travel, there exists the issue of figuring out how the trucks get to and from the highway. One option is for drivers to remain in the vehicle for the entire trip. But if a truck is operated by a human driver for the first and last mile and unmanned on the highway portion of the trip, what happens to the driver once they get to the highway? Answering this question may involve the mentioning of staging areas near on- and off-ramps and/or distribution centers near the Interstate. Trucking industry logistics may be adjusted to accommodate the technology by designating drivers that only drive from the distribution centers to the staging areas. Getting back to the distribution center

Table 2.1: Summary of Issues Related to Autonomous Truck Platoons

Issues	Related Questions	References
Platoon partner selection	How will drivers and carriers decide who to platoon with? How will competition influence who is willing to travel together? Will truck fleets choose to platoon within their own company or be open to platooning with other fleets?	(Auburn University et al. 2015)
Platoon scheduling	Will platoons be scheduled in advance or will trucks search for platoon partners in real time? How will schedules for different trucks in a platoon be coordinated? How long will drivers and carriers be willing to wait for platoon partners?	(Zhang et al. 2016)
Platoon formation	How and where will trucks form platoons? Will there be staging areas for platoon formation or will trucks form platoons as they are driving?	(Liang 2014)
Driving considerations	What training requirements and certification will drivers need to have? What will driver responsibilities be? How will hours of service regulations be impacted by the technology?	(ATA Technology & Maintenance Council 2015)
Insurance and liability	Who will be at fault when the equipped trucks are involved in a crash? The driver? The manufacturers and suppliers?	
First and last mile travel	In the case that drivers are not required in all trucks, what are the logistics associated with traveling to/from platoon merging/splitting points on roads that would likely require a driver in each truck?	
Unequipped vehicle cut-ins	How will the technology deal with vehicles that cut in the platoon? Is there a safe spacing between platooning trucks that can be achieved in order to eliminate cut-ins? How will this problem be addressed at highway on-ramps and off-ramps in particular?	(Auburn University et al. 2015)
Infrastructure requirements	Will the technology require infrastructure other than clear road markings and signs? Will policy require the separation of equipped and unequipped vehicles?	
Safety and security	Is the technology just as safe, if not safer, than current technology? How robust is the technology with regard to dealing with cybersecurity threats?	

may be a matter of implementing a shuttle system or developing an advanced scheduling system so that a truck drop-off coincides with a truck pick-up at the same staging area location. Seemingly contradictory to this notion of automation being restricted to highway facilities, is the increasing focus on using self-driving trucks specifically for the purpose of last mile delivery. Google, for example, has patented an unmanned, self-driving delivery truck which would make deliveries between distribution centers and residential houses (Myllymaki 2016). There are even views that, despite the complexity and dynamic nature of congested urban environments, such environments may be ideal for today's autonomous vehicle technology which functions best at lower speeds (DHL Trend Research 2014). Still, this particular application of last mile does not address the part of the trip from the highway to the distribution centers.

Addressing these issues effectively will help to maximize the benefits of the technology. In addition to travel-time reduction, increased safety, and improved trip reliability, there are a host of other benefits which may be seen as a result of the implementation of autonomous trucks. These include: reduced fuel consumption along with the associated costs savings and emissions reductions; increased operational efficiency; enhanced line-haul capacity and reduced congestion given that the trucks can travel more closely together, thus taking up less road space; the potential for reduced lane width or eliminated need to build new roads altogether since more trucks can make use of the existing road space; elimination of human error along with reduced number of crashes given the autonomous trucks' ability to avoid or lessen the impact of crashes; and reduced number of truck drivers leading to decreased cost of transporting goods (helping to stimulate economic growth) (Piesing 2014; Shladover 2004). To elaborate on this last point, truck platoons have the potential to bring reductions in labor cost given the nature of the technology; while the lead vehicle may be driven by a human, the trucks that follow may not be.

In addition to the potential savings in driver costs, the platoons could also address future qualified driver shortage issues. Driver shortage and qualified and experienced driver retention are two of the top concerns within the trucking industry (ATRI 2014). Even in the case that drivers have to remain in the trucks, which is very likely for the foreseeable future, the industry may be able to attract and retain more drivers through the technology

benefits of reduced driving stress and fatigue. A study by Daimler found that autonomous driving can ease truck driver workload, increase driver attentiveness, and reduce drowsiness by 25% (Daimler AG 2015). Doing other tasks, which is possible with the technology, relieves drivers of the monotonous task of driving, especially over long distances, improving the quality of their work time and allowing them to perform better. With regard to enhanced line-haul capacity and reduced congestion, there are claims that suggest that platooning will allow for more efficient use of existing roadway. A study by Dutch Company TNO found that compared to two trucks driving 80 km/h with a 2 second-gap, two trucks platooning at a 0.3 second gap would decrease the length of those two trucks by 46 percent, from 82 to 44 meters, essentially halving the amount of road space taken up (Janssen et al. 2015a). Other benefits that may be less direct, but just as relevant, are related to reduced health and community impacts.

Moving forward, some critical questions to consider are, once on the road, how will these equipped vehicles interact with unequipped vehicles, to what extent will potential benefits be realized when only a portion of vehicles are autonomous, and once market saturation is reached, will the technology increase or decrease total vehicular travel demand, offsetting the congestion reducing, and perhaps also some safety, benefits.

There are also various costs that will come with autonomous vehicles, as they will require special equipment: automatic transmissions; cameras and sensors; wireless networks; navigation systems; automated controls; and servers, software, and power supplies. In addition to the initial cost of the equipment, the components may be expensive to manufacture, install, maintain, and repair. VTPI suggests that when mature, the technology will add several thousand dollars to the purchase price of the vehicle, as well as a few hundred dollars in annual maintenance and service costs (Litman 2015). A forecast by IHS Automotive predicts that the price premium for the self-driving electronics technology will add between \$7,000 and \$10,000 to the price of a car in 2025, and then drop to around \$5,000 in 2030 and \$3,000 in 2035 (IHS Automotive 2014). The Boston Consulting Group speculates that AV technology will range from \$2,000 for partial automation to \$10,000 for full automation and then decline by about 4 to 10 percent (on a compound annual basis) in the first ten years (Boston Consulting Group 2015). The costs associated with the truck technologies include up-front engineering and development costs,

additional vehicle equipment and installation, operation, and maintenance (Shladover 2004). A study carried out by strategy consulting firm Ronald Berger analyzes the potential cost of automated trucks in particular (Ronald Berger 2016). The findings show that the incremental costs of a level 5 (fully automated as defined by the Society of Automotive Engineers) truck will range from \$1,800 to \$6,200 per truck totaling \$23,400. In addition to the costs associated with the vehicle equipment, up-front construction costs for truck-only facilities and right-of-way costs may come into play in the case that the equipped vehicles, especially at higher levels of automation, are required to operate on a separate right-of-way than unequipped vehicles.

Under the FHWA Exploratory Advanced Research Project, a survey of trucking industry players was carried out to get an outlook on the financial expectations associated with DATP technology from a trucking industry perspective (Auburn University et al. 2015). Willingness to pay (WTP) for initial purchase costs and maintenance, as well as break even period (in number of months), were assessed. Owner-operators' average WTP per truck for the initial payment was about \$1,511 while the average WTP per truck per year for maintenance was \$497. For carriers, WTP varied by fleet size (i.e., an average of \$833 for initial purchase costs and an average of \$410 for maintenance costs for smaller carriers; an average of \$1,500 for initial purchase cost and an average of \$250 for maintenance costs for larger fleets). The expected average payback period was 10 months for owner-operators and 18 months for fleet respondents. While the respondents of the survey did not have much insight into the costs and benefits of the technology at the time of the survey, and these expectations may change as more information becomes available to them, the responses do provide a range of realistic costs. It is suggested in this same paper, that because of the trucking industry having relatively slim operating margins, investment costs, payback periods and net return-on-investment (ROI) are more important than the benefits from the technology. A Federal Motor Carrier Safety Administration (FMCSA)-sponsored benefit-cost analysis for onboard systems showed that technology investments are expected to pay for themselves in a one to one and a half-year time period. Aside from the monetary costs associated with the technology, there are non-monetary costs to consider as well, including cyber-security issues and privacy concerns, increased external costs, and social equity concerns. On this last point, there is the question of who

benefits from the technology. One answer to this question is those who can afford the technology. In the application of autonomous truck platoons, this suggests that the technology, and the benefits it provides, may not be as easily accessible to smaller trucking companies. Moreover, competition and the issue of selecting platoon partners may exclude certain fleets from operating in platoons even if they can afford the technology. These equity issues are magnified if the platoons are required to operate on dedicated lanes. The passenger cars and unequipped trucks would not have the benefit of using the additional capacity, so the question of who pays for the lanes would need to be addressed. In addition to the equity issues, there is acknowledgement that autonomous and connected vehicles may introduce new risks such as system failures. Moreover, the benefits may be offset by risky behavior as a result of road users feeling safer and by rebound effects, specifically increased vehicle travel, as a result of a more convenient means of transportation. There are several studies that provide estimates for percent increase in travel as a result of the technology. For example, Fehr & Peers estimates that at 50% market penetration, AVs are likely to increase vehicle miles traveled by 5% to 20%, and at 95% market penetration, by up to 35% (Bierstedt et al. 2014). Freight modal share places 72% of tons (and a similar portion by value) on trucks and 11% of tons on rail (Cambridge Systematics Inc. 2013). Given that trucking is more labor intensive, and generally more expensive than rail, reducing costs for trucking through the use of the technology could make trucking more attractive in comparison to rail for moving commodities. Autonomous truck platoons could potentially lead to a mode shift from rail to truck due to faster and cheaper travel (Litman 2015). There is also speculation that rail movement, in response to ATPs, will be automated as well (Kuehn and Reiner 2015).

The estimated extent of the benefits and costs of vehicle automation vary significantly throughout the current literature. As suggested earlier, one thing that the literature is consistent on, though, is the recognition that the benefits and costs will depend on the level of automation. The energy savings benefits of automation will likely increase as the level of automation increases. Furthermore, it is posited that the full benefits of autonomous vehicle technology will be realized through “convergence”, or a combination of two technologies: sensor-based systems and connected-vehicle systems (Williams 2013). The extent of the benefits obtained will also vary by trip characteristics. In this

regard, it is likely that benefits will be most apparent at higher travel speeds and longer trips (given that the benefits accrue over time and distance). The literature also recognizes that the benefits will depend on the share of vehicles that have the technology, as the applicability of the technology is closely linked to the mixing between equipped and unequipped vehicles. Such mixing contributes to an already complex driving environment, in which autonomous systems would not be able to take over full responsibility for safe operation. As such, the impacts of autonomous vehicles will be more evident as the phases of development and deployment progress. Even without widespread adoption, some interim benefits may still be available when autonomous vehicles initially enter the market.

One of the main ways these benefits and costs are quantified is through testing. There have been a number of initiatives for testing platoons (CHAUFFEUR, Safe Road Trains for the Environment (SARTRE), Energy ITS Project, California Partners for Advanced Transportation Technology (PATH) Program, KONVOI, COMPANION, Connect and Drive, FHWA Exploratory Advanced Research Project (EARP), North American Council for Freight Efficiency, National Renewable Energy Laboratory, and NEXTCAR). The approaches to testing vary amongst these different initiatives. Many of the studies use both simulation modeling and experimental testing to analyze the fuel reduction potential of autonomous truck platooning. One such experiment and its results are described in a paper that investigates the fuel reduction potential of heavy duty vehicle platoons (Alam et al. 2010). The paper analyzed adaptive cruise control (ACC) in conjunction with a control system in order to achieve the requirements for platooning. The ACC is primarily designed to maintain a desired distance between trucks by sending information to the truck's engine and braking system. The control system architecture consists of feedback information regarding distance and velocity that is obtained through a radar sensor, information about surrounding vehicles, and decision information (e.g. route assigning, platoon formation, route topology) so that the ACC can make strategic decisions. These technologies were tested on a Swedish highway with a two-truck platoon. The two trucks were identical (i.e., same engine, same speed, and same ambient variables). Fuel consumption was measured by devices on the vehicles. The results from the test were used to validate the results from the simulation model. The study considered variations in truck characteristics such as varying cruise control parameters and different truck masses, so a

range of findings was provided. The results, for example, showed that a fuel consumption reduction of 4.7% to 7.7% can be attained with ACC in comparison to a truck with conventional CC. The results suggest that fuel reduction can be achieved as a result of both reduction in air drag and the control strategy. The smaller the distance between vehicles, the greater the reduction in air drag. Another study, mentioned earlier, which is being carried out under the FHWA EARP, examines the business case for DATP, and the extent of its benefits in the areas of fuel consumption, safety, system efficiency, and other transportation impacts. Testing was performed at the National Center for Asphalt Technology (NCAT) test course in Opelika, AL in conjunction with vehicle simulation and aerodynamics modeling. There are a host of other papers that summarize testing and simulation procedures and the results (Alam 2011; Bonnet and Fritz 2000; Browand et al. 2004; Chan 2014; Davila 2013; Lammert et al. 2014; Roeth 2013; Tsugawa 2013; Tsugawa et al. 2011). There are even studies that test and simulate the technology's contribution to safety (Kunze et al. 2010). See Table 2.2 for a summary of results on fuel savings from the testing of autonomous truck platooning.

Some papers focus solely on simulations. There are two papers that discuss large-scale simulations on a German autobahn road network (Larson et al. 2013, 2014). Another discusses the challenges of platooning on public motorways (Bergenheim et al. n.d.). This last paper analyzes the challenges associated with the SARTRE platoon concept, which takes the stance that in order to be viable, the platoons will need to be able to operate on the existing public roadways without much, if any, modification. Some issues that come up in this concept include:

- navigating to a platoon;
- proper gap size for joining and leaving a platoon;
- time needed for creating, joining, or leaving a platoon;
- transition from manual to autonomous operation;
- how to decide [in the event of a platoon splitting] when it is safer to remain in automated control or for the driver to gain back control;
- platoon influence on traffic flow;
- how a platoon allows for a vehicle to exit the roadway at a junction by traveling through the platoon and if this is allowed or not;

- string stability (with regard to vehicle platooning, string stability, very broadly, refers to keeping the spacing between consecutive vehicles in a platoon as close to predetermined values as possible);
- fuel consumption;
- infrastructure-related issues;
- new hazards that may arise as a result of platooning: “impaired drivers, altered driver behavior, technical failures of the vehicles, and new applications using an existing road infrastructure”;
- design of an appropriate longitudinal and lateral control system so that platoon vehicles can travel closer together to receive fuel efficiency benefits;
- devising a communication system that connects the vehicles in a platoon; and
- addressing technical challenges when considering safety requirements.

A similar list of aspects that will need to be considered can be found in EARP’s Phase One document. In order to refine the SARTRE platooning concept, the concept was analyzed using a simulation tool called PELOPS (Program for the Development of Longitudinal Traffic Processes in System Relevant Environment). PELOPS is “a sub-microscopic traffic model that represents a combination of a detailed sub-microscopic vehicle model and a microscopic model”. Such a model allows for the investigation of the vehicle behavior, traffic flow, and interactions between the driver, the vehicle, and the traffic. Different use cases (i.e., create platoon, maintain platoon, leave platoon, join platoon, dissolve platoon, guide to platoon, charge platoon, register information, and handle platoon status) were used with simulation scenarios. A generic platoon control (a dynamic link library), which can be built in the vehicle, has the ability to take over control of the vehicle. This allows the vehicle to be operated without a human operator. This is the case only for the following vehicles since the lead vehicle is controlled manually by a human driver. A virtual manager was used to simulate a human machine interface in the real vehicle, managing information to and from the driver. In addition to the PELOPS database, external vehicle models can be incorporated into PELOPS through data exchange. PELOPS can also be used with visualization software to see the traffic simulation during runtime. The results, which include the amount of time it takes to create,

Table 2.2: Summary of Results from the Testing of Autonomous Truck Platooning

Country/Type of Testing	Truck Platoon Characteristics	Estimated Fuel Savings (%)	Reference	Agencies/Projects Involved in Testing Include:
Road test on six segments of approximately 40 miles each along Interstate 80, west of Salt Lake City, Utah, USA	Two tractor-trailer diesel trucks traveling 36 ft apart at 65 mph	7% (4.5% for the lead truck and 10% for the rear truck)	Roeth (2013); http://www.peloton-tech.com/about/	Peloton; North American Council on Freight Efficiency; CR England; National Renewable Energy Laboratory (NREL); Auburn University; Peterbilt/PACCAR; Denso; Meritor-WABCO; ATRI
Crows Landing airfield runway in the San Joaquin Valley of California, USA	Two heavy duty Freightliner tractors with two empty 53' trailers at 55 mph at five different truck spacings in the range of 3-10 m (9.8-32.8 ft)	Average saving in the range of 10% or more at 3- and 4-m spacing (9% for the lead truck and 11-12% for the tail truck); Average saving of 9% at 10 m spacing	Browand, McArthur, and Radovich (2004)	California PATH Program: University of California, Berkeley; University of Southern California; Caltrans
Road test on 8 km section of State Route 722 (temporarily closed to public traffic), Nevada, USA	Three Freightliner Century class-8 tractor-trailer trucks at 4-10 m (13.1-32.8 ft) gaps at 90 kph (56 mph)	4.3% for first truck, 10% for second truck, 13-14.5% for third truck at 6 m gap	Schladover (2010), Schladover (2012), Lu and Shladover (2014) http://www.path.berkeley.edu/research/automated-and-connected-vehicles/truck-platooning	California PATH Program: University of California, Berkeley; Caltrans; Nevada DOT; FHWA Exploratory Advanced Research Program
100 km test track and 8 km along expressway (before public use) in Japan	Three 25-ton tractor-trailer empty-loaded diesel trucks 4.7 and 10 m (15.4 and 32.8 ft) apart at 80 kph (50 mph)	14% at 10 m gap (7.5% for lead truck, 18% for middle truck, 16% for tail truck) on expressway; 13.8% at 10 m gap (10% for lead truck, 17.5% for middle truck, 14% for tail truck) on test track; 15.9% at 4.7 m gap on test track	Tsugawa, Kato, and Aoki (2011), Tsugawa (2013)	Energy ITS Project; METI; NEDO; Meijo University, JARI
Test track and section of highway in Sweden	Two heavy duty Scania diesel trucks weighing 39.3 and 39.2 tons, traveling at 90 kph (56 mph)	1.3–7.1% (savings of 4.7-7.7% at 70 kph estimated via simulation)	Alam, Gattami, and Johansson (2010)	Scania CV AB, VINNOVA - FFI, Swedish Research Council

Table 2.2 continued

DaimlerChrysler test track in Papenburg, Germany	Two heavy-duty ACTROS semi-trailer diesel trucks, 14.5 ton lead truck, 28 ton trail truck with 5-16 m (16.4-52.5 ft) spacing	15-21% at 80 kph (50 mph) at 6.7-16 m spacing, 10-17% at 60 kph (37 mph) at 5-16 m spacing	Bonnet and Fritz (2000)	European Commission; PROMOTE-CHAUFFER Project; DaimlerChrysler AG; Renault Electronic Department
Test track and 3100 km (1,926 mile) of testing in real traffic on public roads in Germany	Four heavy-duty tractor-trailer trucks (of the brands MAN and IVECO) at 10 m (32.8 ft) gaps at speeds between 37 and 50 mph	substantial fuel savings on test track but significantly reduced savings driving on public roads with traffic because of variation in speed	Kunze, Ramakers, Henning, and Jeschke (2010), http://www.ika.rwth-aachen.de/en/research/projects/driver-assistance-vehicle-guidance/1636-konvoi.html ; http://www.fhwa.dot.gov/advancedresearch/pubs/12033/004.cfm	KONVOI Project: RWTH Aachen University and numerous freight forwarders and other private industry partners
Test tracks (7560 m IDIADA High Speed Track) in L'Albornar, Spain and public motorway in Gothenburg, Sweden	Volvo mixed-vehicle platoon made up of two trucks and 3 cars, respectively, at speeds up to 90 kph (56 mph), with gaps between 5 and 15 m (16.4 and 49.2 ft); two-truck platoon at 20 and 25 m (65.6 and 82 ft) gaps	7-16% (up to 8% for lead vehicle and up to 16% for following vehicles)	Davila and Nombela (2010), Davila (2013), Chan (2014), http://www.sartre-project.eu/en/about/news/sidor/20120917_1.aspx	SARTRE Project: collaborative project of 7 partners from 4 countries - Applus+ IDIADA, Institut Für Kraftfahrzeuge Aachen, Ricardo UK, SP Technical Research Institute of Sweden, Tecnalía, Volvo Cars, Volvo Technology
8.5-mile oval at Continental Tire Uvalde Proving Grounds test track, Texas, USA	Two class 8 Peterbilt tractors each with a 53' van body trailer at speeds ranging from 55 mph to 70 mph, with 20-75 ft gaps, at 65,000 and 80,000 lb GVWs	3.7-6.4% (best combined result for 55 mph, 30-ft (9 m) gap, 65,000 lb GVW)	Lammert, Kelly, and Walkowicz (2014)	USDOE Advanced Vehicle Testing Activity through Intertek Testing Services, NREL, Peloton
Public highway with "live traffic" from Stuttgart, Germany to the Port of Rotterdam in Rotterdam, Netherlands	Three autonomous and connected Mercedes-Benz Trucks	up to 10% fuel savings and CO ₂ emissions reduction	Daimler (2016), https://www.trucks.com/2016/03/21/daimler-tests-self-driving-truck-platoon-in-live-traffic/	Netherlands European Truck Platooning Challenge 2016 (Netherlands Government), Daimler

join, leave, and dissolve the platoon from different positions (i.e., behind, side, and front), were provided. Results were also given for the distance between platooning vehicles and string stability.

2.1.2 Autonomous Vehicle Technology Policy

The details of the technology characteristics – both the uncertainty of its arrival and the extent of its benefits - go hand in hand with the policy associated with the technology. There are various new and proposed policies on autonomous vehicles in the United States, Europe, and Japan. In the United States, NHTSA released a preliminary policy statement (National Highway Traffic Safety Administration 2013b), which includes:

- definitions and examples of the different levels of autonomous vehicle technology (as described earlier in this paper);
- an overview of NHTSA’s research plan which focuses on the safety issues related to vehicle automation. The research, which currently covers the areas of human factors, system performance requirements, and electronic control system safety, will be used to inform policy decisions and aid in developing a set of requirements for autonomous vehicles amongst other things; and
- recommendations for state regulations for governing the testing and operation of autonomous vehicles. At this point, NHTSA does not recommend that states allow the operation of the autonomous vehicles for purposes other than testing.

The laws in most states do not explicitly prohibit or regulate the operation of autonomous vehicles. To date, seven states (California, Florida, Michigan, Nevada, North Dakota, Tennessee; Utah) and Washington, D.C., have enacted legislation for autonomous vehicle technology (National Conference of State Legislatures 2016). While the details of the legislation differ, the major themes remain consistent. In order to set up a modeling context that represents a reasonable and appropriate operating environment for autonomous trucks and truck platoons, it is worthwhile to explore the different aspects of the laws – those that are consistent among the different bills as well as those that are specific to a particular state or set of states.

The bills (*see CA SB 1298, FL HB 1207, MI SB 169, MI SB 663, ND HB 1065, NV SB 313, TN SB 598, DC B 19-0931, HB 280*), generally speaking, authorize the operation of autonomous vehicles on public roads (and in many cases, in specific geographic areas on those roads), mainly for testing purposes. Most of the legislation allows specifically for the testing of passenger cars. Nevada, in May 2015, however, became the first state in the U.S. to grant a license for an autonomous truck to operate on open public highways (Nevada Department of Motor Vehicles 2016). In order to operate these autonomous vehicles, there are a number of specified requirements that have to be met. The basis for these requirements lies in the definitions that are put forth in the legislation. The bills, for example, give definitions for relevant terms such as “autonomous technology”, “autonomous vehicle”, “operator”, and “manufacturer”. Autonomous technology is defined as technology that can drive a vehicle without the active physical control or monitoring by a human operator. An autonomous vehicle, then, is a vehicle equipped with autonomous technology.

On the basis of such definitions, requirements are set. In order for an autonomous vehicle to get registered, it has to meet Federal Motor Vehicle Safety Standards and other state and federal related safety standards and performance requirements. These standards are essentially minimum acceptable safety performance requirements for motor vehicles or items of motor vehicle equipment. Additionally, the manufacturer performing testing is required to provide evidence of an instrument of insurance.

While being operated, the licensed driver must “be seated in the driver’s seat, monitoring the safe operation of the autonomous vehicle, and capable of taking over immediate manual control of the autonomous vehicle in the event of an autonomous technology failure or other emergency”. In sync with those driver requirements are requirements specific to the vehicle itself. The vehicle must include a means to engage and disengage autonomous technology, a visual indicator inside that indicates when the autonomous technology is engaged, a system to alert the operator when there is a technology failure, and a way to allow the driver to take control or come to a complete stop in such situations, among other requirements. In terms of the operation on the public roadway, many of the bills indicate that the autonomous vehicle must be able to operate such that it can comply with the applicable motor vehicle laws and traffic laws of that

particular state. These requirements suggest that a driver will have to be in the vehicle. Nonetheless, some legislation hints at being open to empty vehicles. California's bill, in particular, states that there may be additional requirements if there is a request for a "no-driver" autonomous vehicle (Padilla 2012). Florida's bill articulates that an autonomous vehicle can be operated without a driver present only when the vehicle is being tested on a closed course (Brandes and Corcoran 2012).

Legislation will evolve as the answers regarding the technology become more apparent. Some of the bills even include wording that states that additional requirements and standards can be set forth as deemed necessary. A couple of examples contained in California's legislation are a limit on the total number of autonomous vehicles that can operate on public roads, and the setting of new license requirements to operate autonomous vehicles (Padilla 2012). Michigan even calls on its committees on transportation and commerce to recommend any additional legislative or regulatory action that they find to be necessary for the continued safe testing of autonomous vehicles (State of Michigan 97th Legislature 2014).

2.1.3 Connected Vehicle Technology Policy

Regarding connected vehicle technology, NHTSA released a rulemaking notice in 2014. The document "initiates rulemaking that would propose to create a new Federal Motor Vehicle Safety Standard...to require vehicle-to-vehicle communication capability for light vehicles (passenger cars and light truck vehicles) and to create minimum performance requirements for V2V devices and message" (National Highway Traffic Safety Administration 2014). The current NHTSA proposed rule-making focuses on a mandate for V2V radios in all new cars. It is believed that NHTSA is likely to make a similar decision regarding rules related to heavy trucks.

In addition to that rulemaking, FHWA released a report titled "Vehicle to Infrastructure (V2I) Deployment Guidance and Products" (Federal Highway Administration 2014a). As inferred by the title, the document does not mandate the development of V2I technologies but instead provides guidance. The purpose of the document is to assist FHWA staff as well as transportation system owners and operators to

deploy V2I technology in the context of Federal-Aid Highway requirements. It is also intended to help ensure interoperability and efficient and effective planning and operations.

As advancements continue to be made in the development of the technology and policy, a more concrete definition of the technology operating on public roadways will manifest itself. The following section shifts focus to efforts that have already been carried out with regard to modeling the characteristics of the technology in an environment representative of that in which the technology would operate, while recognizing limitations and uncertainties on the available information.

2.2 Modeling and Performance Measurement

While testing and simulation, as discussed above, are also used to quantify the benefits and costs of the technology, modeling and performance measurement do so in a way that is more oriented toward the transportation planning context. In other words, modeling and performance measurement efforts, which are discussed in this section, place more of a focus on what impact this technology will have while operating in regular traffic and how such technology applications impact overall traffic and traffic-related measures.

First, the existing literature on modeling and performance measurement of autonomous vehicle technology in general is explored. One such paper estimated the energy consumption implications of partial automation of light duty vehicles (Hayeri et al. 2014). The paper recognized various aspects at different levels of automation that can affect energy consumption: congestion, driving cycle, platooning, travel demand, land use, travel information systems, equipment and technology, vehicle characteristics (i.e., vehicle weight, vehicle design, and market share), other modes, and commercial vehicles. The paper only focused on level 0 to 2 automation. The technologies in these categories include: lane departure warning, collision warning, blind spot warning, speed limit detection, traffic warning, vehicle-to-vehicle communication, adaptive cruise control, lane keeping, collision detection braking, active braking, parking aid system, dynamic route guidance, and platooning. The methodology used values from the literature to estimate energy savings attributable to the technology. The study combined estimates from various sites and analyses and made assumptions in areas where data were limited, ignoring interactions among the fuel savings effects of different technologies. Using the estimates, mathematical

formulas for reduction in accident-related congestion, reduction in other congestion, increase in driving efficiency, equipment operation, and rebound in travel demand were developed. The net change in fuel consumption was then computed as

$$\Delta\hat{\gamma}^{TOT} = \Delta\hat{\gamma}^{AC} + \Delta\hat{\gamma}^{NAC} + \Delta\hat{\gamma}^{ED} + \Delta\hat{\gamma}^{EQP} + \Delta\hat{\gamma}^{RBD}$$

where TOT represents total, AC represents accident-related congestion, NAC represents non-accident related congestion, ED represents efficient driving, EQP represents energy-consuming equipment, and RBD represents rebound in travel demand. The results yielded fuel savings as a percent of congestion for each technology for low, medium, and high cases of technology adoption. Platooning, dynamic route guidance, parking aid system, and active braking technology resulted in the highest fuel savings with up to 18%, 20%, 22%, and 25%, respectively. All other technologies resulted in savings between 0% and 6%.

As of yet, only a limited number of studies have made use of traffic simulation and travel demand modeling, approaches that are more in line with the efforts of this dissertation. Bierstedt et al. (2014) is one such effort. The paper addresses the effects of next generation vehicles on travel demand and highway capacity. It assesses “the most likely effects of autonomous vehicles on traffic generation and highway capacity and congestion over time as AVs come to represent a greater percentage of the vehicles on the road”. In conjunction with developing new projections based on existing industry projections and exploring the potential for both vehicle miles traveled (VMT) increase (on the basis that the technology could encourage people to travel more) and decrease, the paper examines potential impacts of autonomous vehicles on freeway capacity and efficiency. The examination considers various characteristics including speed, headway, and uniformity. To analyze the potential impacts, specifically as a result of employing adaptive cruise control (ACC), freeway simulations were run in VISSIM, a microscopic traffic flow simulation tool. Running the simulations required the development of a simple congested freeway network, which consisted of seven segments including mainline roadway, on-ramps, and off-ramps. An ACC vehicle model was then developed by making changes to an existing vehicle model in VISSIM. Conservative and aggressive scenarios were represented to demonstrate the range of ACC characteristics related to headways and acceleration/deceleration rates. Both scenarios assumed that 50% of the fleet was equipped

with ACC technology. The preliminary results for freeway performance included total delay in hours, average delay per vehicle in seconds, and total travel time in hours. The conservative scenario (higher headways and lower acceleration/deceleration rates) resulted in increased delay and travel time relative to the base case, while the aggressive scenario resulted in decreased delay (i.e., 39 hours to 27 hours of total delay) and travel time (331 hours to 317 hours of total travel time) relative to the base case. An intermediate scenario showed very little change and change in level of service was marginal in all of the ACC scenarios. Another study that used traffic simulation used MATLAB/Simulink to analyze the safety and traffic flow effects of platooning connected autonomous vehicles (Fernandes and Nunes 2012).

Another effort to model travel demand of autonomous vehicles took an existing disaggregated travel demand model for the state of New Jersey and expanded it to a transportation demand model for the entire United States (WyrOUGH 2014). After the national daily demand was determined, a model was developed to meet this demand using a national system of autonomous taxis. The thesis used a methodology that consisted of six major tasks: 1) generation of populace, 2) workplace assignment, 3) school assignment, 4) tour assignment and activity patterns, 5) trip destination assignment, and 6) arrival and departure time assignment. The findings were presented with various trip statistics by trip type including number of trips, passenger miles, and mean and median trip length.

A similar effort also used an activity-based model to evaluate the implications of autonomous passenger vehicles in the Puget Sound region (Childress et al. 2015). This effort considers changes to an existing activity-based model necessary to measure the impacts that autonomous vehicles will have on behavior and operational characteristics of the transportation network. It also discusses how modeling must be improved to answer questions that arise with regard to this technology. The study looks at four different scenarios which “explore how driverless cars can influence demand through changes in capacity, perceived travel time, parking cost, and operating cost:”

1. **Increased Capacity:** In this scenario the hourly capacity on all of the roadway network links was increased by 30%.
2. **Increased Capacity and Value of Time Changes:** This scenario built on Scenario 1; it assumed increased capacity as well as a less negative perception of time spent

traveling for those individuals using AVs. It also assumed that adoption would initially be limited to high-income households given the initial high price of the AVs. Accordingly, trip-based values-of-times were reduced by 65% for high-income households, from \$24/hour to \$15.60/hour. Automobile travel time was directly modified to 65% of skimmed travel time for high value-of-time trips.

3. **Increased Capacity, Value of Time Changes, and Reduced Parking Costs:** In addition to the assumptions in Scenarios 1 and 2, Scenario 3 assumed that all cars were automated. Travel time was reduced to 65% of skimmed travel time for all trips. As in the other scenarios, capacity was increased by 30%. A new facet of this scenario was that cost of parking was reduced by half. This reduction in cost reflected the AV's ability to self-park in cheaper locations and make better use of existing parking capacity.
4. **Per-Mile Auto Costs Increased:** This scenario assumed that "all trips are provided by a taxi-like system at a set rate" and that "all costs of driving are passed on to the user". The cost in this scenario was \$1.65/mile compared to the current total cost of about \$0.60/mile. In order to reflect a worst-case scenario, this scenario did not consider an increase in capacity (i.e., does not consider AV's ability to provide additional capacity).

Various measures including total daily change in vehicle miles traveled (VMT) and vehicle hours traveled (VHT), number of trips, distance traveled by trip type, delay and speed on freeways and arterials, and mode share, were provided for each scenario. In the three capacity increase scenarios, the VMT was higher than the VMT in the base case. In Scenarios 1 and 2, the VHT decreased, but in Scenario 3 increased, reflecting a system wide perception of travel time as less negative. In Scenario 4, VMT decreased as a result of the high cost of traveling. This resulted in lower VHT, reduced delays, and increased speeds. Results were also obtained for differences in tour lengths, spatial distribution effects of AVs, and perceived accessibility. The authors of the paper took these results as an implication that AVs could both help and hinder the policy goals of the Puget Sound Regional Council. Speed and capacity increases, for example, may improve regional mobility. On the other hand, such improvements in regional mobility could result in an

increase in travel demand, and thus more congestion and emissions. The results also showed that the range of assumptions can lead to quite different answers regarding the questions about this technology. Accordingly, the report suggests that future years be evaluated. It may even be appropriate to model shared AVs as a separate mode. Moreover, stated preferences (given the uncertainty surrounding the technology) as well as the impacts of multi-tasking, habits, and life-style choices should be captured. The study laid out reasonable scenarios but the actual future may be much different. As stated in the report, this uncertainty “makes it even more critical that we improve our tools now to support the policymakers and planners who will have to grapple with this new technology.”

Studies that use travel demand modeling to focus on medium and heavy duty trucks are less common. A PATH program paper, “Assessment of the Applicability of Cooperative Vehicle-Highway Automation Systems (CVHAS) to Bus Transit and Intermodal Freight: Case Study Feasibility Analyses in the Metropolitan Chicago Region”, represents one of the earlier efforts to assess the impact of automated highway systems (Shladover 2004). Motivated by the fact that Chicago is a major freight hub whose efficiency of freight movement is diminishing as a result of congestion, this study considered various alternatives, some without CVHAS technologies and some with CVHAS technologies, on a truck-only roadway. The road network, 44.5 miles for the short-term and 145 miles for the long-term, was decided based on criteria outlined in the report. As put forth in the study, one of the reasons to consider the CVHAS technologies for trucks is that it seems that the earliest deployments of CVHAS technologies will be on heavy vehicles operating on their own right-of-ways (some of the reasons for that line of thought were discussed earlier in this chapter).

The CVHAS technologies that were included in the evaluation included automatic steering control, automatic speed and spacing control, and fully automated driving. These technologies were used in the development of five alternative operational concepts:

- Alternative 1: Baseline (do nothing)
- Alternative 2: Truck-only facility without CVHAS technologies
- Alternative 3: Truck-only facility with CVHAS technologies (automatic steering) for equipped trucks only

- Alternative 4: Truck-only facility with CVHAS technologies (automatic steering, speed, and spacing control with 2 or 3 truck platoons) for equipped trucks only
- Alternative 5: Truck-only facility without CVHAS technologies; open to all trucks before a certain year and after that converting the facility to an automated truck-way

The feasibility of each of the CVHAS operational concepts was assessed by evaluating the impacts of each alternative. Traffic impacts were estimated using Chicago Area Transportation Study (CATS) forecasting models. Separate assignments were run to estimate highway VMT and travel speeds for the eight time periods (i.e., time-of-day traffic assignment procedure) and the results of the assignments were added together to get daily volumes. Only Alternatives 1 and 2 were tested with the CATS model. The impacts of the other scenarios were estimated using the modeling results from the alternatives that were modeled. Results included daily vehicle volume, vehicle-miles-traveled, vehicle-hours-traveled, average travel speed, truck facility traffic volumes for the CVHAS scenarios, and automated truck lane capacity for different platoon sizes and different operating speeds. Overall, the results demonstrate that the new truck-only facility would result in time savings for the trucks that switched to the new facility as well as for the trucks and passenger cars that continued to use existing facilities as a result of reduced congestion. Given limited resources, the model was not run to estimate the network impacts of the proposed facility in future years. Instead, trends were assumed in order to estimate timesaving benefits.

In addition to analyzing traffic impacts, the impacts of the technologies on safety and fuel consumption and emissions were discussed. Though there was not enough data available to support a quantitative analysis of the safety benefits, it was mentioned that safety-related benefits would result from separation of truck/non-truck traffic as well as from the CVHAS collision warning technologies. Regarding fuel consumption, the paper includes information on testing results that support the claim that operating trucks in automated close-formation platoons can save 15-20% of fuel consumption when the trucks are operating at highway speeds.

Another project, also carried out by the PATH program, is “Evaluation of Bus and Truck Automation Operations Concepts” (Tsao et al. 2004). The project considered the benefits and impacts of Truck Automated Highway System (AHS) technology by comparing three alternatives.

- Alternative 1: General-Use Lane (i.e., adding a conventional general-use lane in each direction on the freeway)
- Alternative 2: Truck-AHS (i.e., constructing a physically separated one-lane Truck-AHS in each direction within or along the right-of-way of an existing freeway)
- Alternative 3: Truck Lane (i.e., constructing a physically separated lane restricted to truck travel within or along the right-of-way of an existing freeway)

One key aspect of this project was defining the AHS concept. On the AHS, the trucks traveled in closely-spaced convoys of a target maximum size of 20 trucks. The lead truck of the convoy was a human driver who supervised the whole convoy and operated the shuttle which traveled, at a consistent headway throughout the day, from one end of the corridor to the other and back. Any truck or truck convoy that wanted to use the Truck-AHS had to join a truck convoy that was already on the Truck-AHS. Both convoy merging and convoy splitting at the dedicated on- and off-ramps were automated processes. At the staging area, if possible, the trucks would be organized by characteristics (i.e., size, weight, power, etc.) and by destination. The truck lane had the same configurations and same access and egress points of the truck-AHS. In both cases, the trucks could travel backwards to get to an access point that allowed them to get on the facility quicker than they would if they traveled forward. Likewise, the trucks could travel past an exit to go to an egress point that put them closer to their final destination. The speeds on the Truck-AHS and truck lane were 75 miles per hour and 60 miles per hour, respectively.

This concept was applied to a portion of I-5 from the California-Mexico border to the Oregon-California border. There were assumptions that the truck arrivals were deterministic and uniformly distributed at an access point before getting onto the AHS (i.e., the arrival times of trucks are equally spaced out but correspond to the demand pattern). For travel demand, three scenarios were considered: current demand, 125% of current demand, and 150% of current demand. The demand was split between the different network

components. First, the amount of truck traffic to be removed from the conventional lane and put onto the truck-AHS or the truck lane was estimated. Based on this, two different problems were solved – one for the conventional lanes and another for the truck-AHS or truck lane. There were three levels of service and three corresponding time periods (AM/PM Peak, Near Peak, and Free Flow), flow rates, and speeds. Using the flow rates, the number of non-trucks was obtained by subtracting the average number of trucks from the flow rate of the corresponding hour. Performance measures were given for each demand level and for each alternative. Travel times for all vehicles were calculated using the assumed speeds and freeway segment lengths. For the conventional lanes, truck labor costs were calculated using truck travel time and truck fuel consumption was calculated using an average gas mileage of 10 miles per gallon. For the truck lanes, the method for identifying the trucks that would use the truck-AHS lane and for estimating the performance measures were broken into different steps:

- Use AHS or not? This was based on the truck trip distance threshold of 200 miles. For a truck to travel in the truck-lane, the threshold was 50 miles. As a part of the results, truck trip length distributions were provided.
- Where to enter and exit?
- AHS traffic by OD per day and the resulting conventional-lane traffic by section per day?
- Truck travel time on AHS?
- Labor requirement for AHS travel? This step determined the total labor cost per day taking into consideration that only one driver was needed to operate the convoy.
- Fuel requirement for AHS travel? For fuel consumption, the size of the convoy was obtained. The average fuel requirement was calculated assuming a 10% fuel saving for all trailing trucks of the convoy. No fuel savings were considered for the truck lane.

With regard to total travel time and total truck travel time, the General-use Lane alternative was better than the Truck-AHS and the Truck-Lane alternatives for all three levels of demand. The Truck-AHS alternative provided travel time savings for the long-haul, but only at the expense of short-haul trucks and passenger cars. For truck labor costs and truck fuel consumption, the Truck-AHS was the better alternative compared to the

Truck Lane alternative. Nevertheless, as suggested in the paper, the labor and fuel savings associated with the Truck-AHS alternative should be compared with the cost of the infrastructure, as well as with the safety and technical feasibility, to get a more holistic view of the implications of implementing the alternatives. Additionally, it was noted that this evaluation was carried out for three specific operational systems and for a specific corridor. Moreover, there were data limitations, especially with regard to the origin-destination data for truck trips and trip time-dependent data, so various estimation methods were used.

Outside of PATH program efforts, a model was developed under the FHWA EARP (Auburn University et al. 2015). In this traffic model, a simulation of the CACC (cooperative ACC) -equipped two-truck platoons was run on a 5.3 mile section of Interstate 85 in the Auburn-Opelika area. In order to develop the initial model, which was developed in CORSIM, traffic volumes were obtained from Alabama Department of Transportation. These volumes, which were provided as average annual daily traffic, were multiplied by a K-factor to get peak hourly volume, and subsequently multiplied by the directional factor, D, to get the peak hourly volume by direction. The peak hour volumes were calculated at the origin point (between exits 57 and 58 on I-85) and at each on- and off-ramp along the route up to exit 62. Additional information provided by ALDOT was percentage of trucks on the roadway and on the on- and off-ramps.

Additional model simulations were developed to incorporate varying parameters for headway between the lead truck and following truck (1.25 s, 1.0 s, 0.75 s, and 0.5 s), market penetration of the technology (20%, 40%, 60%, 80%, and 100%), and traffic volume (baseline traffic volume, 115% of baseline volume, and 130% of baseline volume). Varying percentages of baseline traffic volumes were used to take future year traffic growth into consideration and to consider scenarios in which traffic volume approaches roadway capacity. A total of 63 model simulations were developed and run.

The results obtained from the model runs were average speed and travel delay. Average speed results were provided for different combinations of parameters (i.e., average speed at different headways, average speed for different market penetration for each headway for each traffic volume scenario). Travel delay was provided as an aggregate of all vehicles (i.e., both passenger cars and trucks) on the roadway. Overall, as traffic

volumes increased, the benefits of the technology also increased. Benefits also increased with decrease in headways and increase in market penetration. On this last point, regardless of the traffic volume, the 20% market penetration scenarios did not lead to significant improvements in efficiency. Significant benefits started to show when the market penetration was over 60% and the headways were less than 1.25 seconds.

2.3 Performance-Based Freight Corridor Planning

The third area of this literature review focuses on performance-based freight corridor planning. Performance-based freight corridor planning refers to an overall planning approach in which the performance along freight corridors, stretches of roadway which are of significance to the movement of freight, is assessed and the resulting information used to guide decisions that support freight-related goals.

A key component of corridor planning is corridor studies, which consist of a series of steps that include defining the corridor to be studied, identifying the problem, and developing evaluation criteria, carrying out an evaluation, and ultimately recommending preferred alternatives. These corridor studies, in general, are more commonly being used in transportation planning. Amongst these studies are a number of state DOT-sponsored freight-specific and mixed passenger-freight corridor analyses (Adams et al. 2007; Cambridge Systematics Inc. and ATRI 2013; FHWA and CDOT 2011; Hadi et al. 2010; IDOT and INDOT 2012; Liao 2009; Louis Berger Group Inc. 2014; Schneider and Fish 2008; Southworth and Gillett 2011; Wittwer et al. 2005).

Such studies recognize the economies of scale that result from infrastructure investment that concentrates passenger and freight traffic along high capacity roadways, such as the Interstate Highway System and other major highways. However, while corridor-based approaches to infrastructure investment have worked well in the past, the combination of constant traffic growth and fiscal constraints is now placing a growing burden on many of these routes. Among other things, this has led to the emergence of corridor management plans and guidebooks for carrying out corridor studies (Carr et al. 2010; Smith 1999).

Federally-supported research on significant freight corridors has also emerged (Mallett et al. 2006). Moreover, the passages of the last two federal transportation bills,

Moving Ahead for Progress in the 21st Century Act of 2012 (MAP-21) and the Fixing America's Surface Transportation (FAST) Act of 2015 have further emphasized the significance of freight corridor planning. MAP-21 put forth an explicit policy framework supporting freight transportation planning and in doing so, laid out a number of requirements at the federal, state, and regional levels – all geared towards ensuring that the nation can achieve its freight goals related to: economy, congestion, environment, productivity, safety and security, infrastructure condition, advanced technology, performance, innovation, competition, and accountability in the operation and maintenance of the network (FHWA 2013). Another significant aspect of MAP-21 was its focus on performance. MAP-21 required USDOT to establish measures for states to use for the purpose of assessing freight movement on the Interstate System. In conjunction with that requirement, MAP-21 required each state, as well as MPOs, to set performance targets related to the established measures and to integrate the targets into their planning processes. States were also charged with reporting progress on reaching the targets and addressing congestion at freight bottlenecks. Moreover, the legislation called for the development and improvement of data and tools that could be used to support an outcome oriented, performance-based approach to evaluating proposed freight transportation projects.

As it relates to corridors, MAP-21 called for the USDOT, along with states, to establish a National Freight Network (NFN), which consisted of a Primary Freight Network (PFN), other parts of the Interstate not designated in the PFN, and critical rural freight corridors. The FAST Act, which further reinforces and supports this focus on freight transportation, provides for a new National Highway Freight Network (NHFN), which replaces the NFN established under MAP-21. Nevertheless, this network is very similar to the NFN (Lindley 2016). The NHFN is comprised of a Primary Highway Freight System (PHFS) (i.e., portions of roadway most critical to freight), Interstate Routes not on the PHFS, Critical Rural Freight Corridors (CRFC), and Critical Urban Freight Corridors (CUFC). There are many criteria for selecting the freight corridors. Some of these criteria include that the corridors carry high truck traffic volumes and commodity tonnages, provide access to various freight-related areas and facilities, have high importance to a state's economy, and have high importance to freight movement within a region. By identifying which corridors are most critical, the NHFN assists both the USDOT and states

in strategically directing resources for the improvement of freight on highways.

While performance-based freight corridor planning had been implemented prior to MAP-21 and the FAST Act, State DOTs and MPOs have been increasingly taking actions to meet the federal requirements in the bills. In order to do so, many agencies have either developed freight plans for the first time or adapted existing plans to meet the requirements of the legislation. The agencies have also been developing freight specific performance measures and targets. Not too long after MAP-21 was passed, the American Association of State Highway and Transportation Officials (AASHTO) put out recommended measures: Annual Hours of Truck Delay and a Truck Reliability Index (AASHTO 2012). More recently, the FHWA Office of Freight Management along with other stakeholders have been developing freight-specific performance measures. Some measures specific to bottlenecks include total delay, mean travel-time index, planning time index, 80th percentile travel-time index, hours of congestion per year, 95th percentile queue length, and average queue length (Margiotta et al. 2015).

It is likely that the trend of a growing emphasis on freight, and performance-based freight corridor planning, will continue. A question of concern in this dissertation is how to apply this approach to the case of autonomous truck platoons. State DOTs and MPOs are starting to carry out studies that measure the potential impacts of autonomous and connected vehicles in general. Given that the details of the technology and its impact on transportation are highly uncertain, employing performance-based planning with regard to autonomous and connected vehicle technology has been coupled with scenario planning. The Atlanta Regional Commission (ARC), for example, used scenario planning for envisioning how technology will impact the region in the future (D'Onofrio 2016). The primary tool used to evaluate the scenarios was an activity-based model. The model incorporated autonomous vehicles in order to assess their potential impact on the transportation system (Kim et al. 2015). Results included number of trips, average trip length, daily vehicle miles and hours traveled, and annual delay per person. The results and the things learned from the process were incorporated into planning by considering the technology in the region's policy framework. The findings also led to additional ARC studies that will be carried out in the future. The Florida Department of Transportation (FDOT) is leading the Florida Automated Vehicles program, which encompasses a number

of research projects, pilot projects, and working groups that will ultimately help FDOT prepare for the deployment of autonomous and connected vehicles on public roadways (Florida Department of Transportation 2016). The goal of the program’s stakeholder working groups is to “make recommendations to address potential policy adoption or amendments, engineering and design standard changes, and infrastructure investment priorities” (Florida Department of Transportation 2016). Other state DOTs and MPOs have similar efforts. Though many of these efforts recognize AV/CV technology for commercial trucks, very few, if any, focus on the specific application of platooning autonomous trucks on public roadways.

2.4 Identifying the Gap

Summarily, this literature review seeks to ask the question: “What is the outlook on autonomous and connected truck platooning technology?” Accordingly, the answers to this question tie into this dissertation by providing information necessary for modeling and performance measurement. More specifically, the details of the technology influence and shape decisions related to forecast years and market share. The information also informs the development of the model so that it reflects the characteristics of the technology (i.e., the characteristics that must be understood in order for them to be modeled in a representative manner). With regard to performance measurement, the information on benefits and costs aids in the decision of which metrics to consider and provides the quantitative basis for developing the inputs to be used in the performance measurement calculations.

As demonstrated in the previous sections of this chapter, there are growing bodies of literature in the areas of autonomous truck platoon technology and policy, modeling and performance measurement of autonomous truck platoon technology, and performance-based freight corridor planning. Identifying the gap, then, was a matter of exploring the existing literature that lies at the intersection of these three areas, as shown in Figure 2.2.

In considering the efforts that are most in line with that intersection (see Table 2.3), various limitations and gaps were identified. As demonstrated in the literature review, attempts to measure the impacts of autonomous trucks, outside of an actual physical testing, have been carried out in various manners. Many of those efforts use simulation models that

focus on the operation of the platoons, and in some cases, on test tracks or on roads that have very little traffic. They do not necessarily consider the traffic and congestion that would exist as a result of other vehicles sharing the roadway facility with the trucks and convoys, and hence how this congestion would influence the performance of the trucks. Such simulations are not reflective of transportation models which are typically used to estimate current or forecast future demand, and to assess the impacts of various alternatives based on such demand.

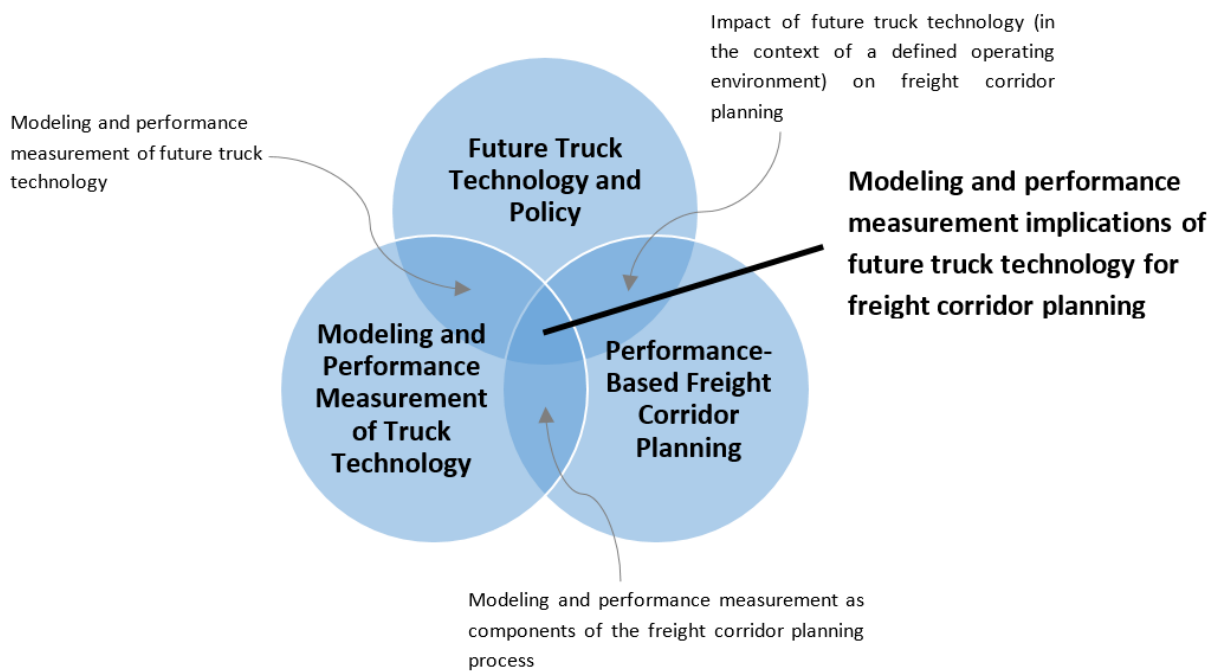


Figure 2.2: Summary of Literature Review Areas

Those efforts that do place performance measurement of the technology in a transportation planning context are not without their limitations either. The two PATH program papers discussed earlier use travel demand models that model both trucks and passenger vehicles. The PATH program project in Chicago uses the region’s travel demand model to model various alternatives, but the CVHAS alternatives are not modeled. The performance of those alternatives is estimated based on the results of the “without CVHAS

Table 2.3: Summary of Autonomous Truck Platoon Modeling and Performance Measurement Efforts

Title	Author	Year	Study Overview	Limitation(s)
Fuel Consumption Reduction Experienced by Two Promote-Chauffeur Trucks in Electronic Towbar Operation	Christophe Bonnet, Hans Fritz	2000	Presents fuel consumption reduction results of a two-truck convoy from experiments on a test track in Papenburg, Germany. Simulations use set of formulas along with values for platoon characteristics to calculate fuel consumption reduction.	Coarse simulation based on simple models. Only gives information on fuel consumption reduction for a two-truck platoon. Not simulated on an actual road network.
Assessment of the Applicability of CVHAS to Bus Transit and Intermodal Freight: Case Study Feasibility Analyses in the Metropolitan Chicago Region	Steven Shladover	2004	Models five different alternatives of truck-only facilities with and without CVHAS technologies in order to assess the feasibility of the technology in the Chicago intermodal freight market.	Does not actually model the CVHAS technology. Models the non-CVHAS alternatives and uses those results to make estimates for the CVHAS technology alternatives.
Evaluation of Bus and Truck Automation Operations Concepts	H Jacob Tsao, Lan Zhang, Lin Lin, Deepa Batni	2004	Considers the benefits and impacts of Truck Automated Highway System (AHS) technology (i.e., truck convoys operating on highway) by comparing three alternatives along the I-5 freight corridor in California.	Does not have origin-destination data for truck trips and does not have time-dependent data, so uses various estimation methods. Does not consider infrastructure costs. Based on a specific shuttle system concept for convoys.
Challenges of Platooning on Public Motorways	Carl Bergenhem, Qihui Huang, Ahmed Benmimoun, Tom Robinson	2010	Discusses SARTRE platoon concept and challenges. Describes and presents a traffic simulation model using Program for the Development of Longitudinal Traffic Processes in System Relevant Environment (PELOPS) - combination of driver, vehicle, and environment models.	Includes but does not focus on trucks. Analysis more concerned with technical details of the technology (i.e., influence of sensor systems inaccuracies on string stability) than with safety, fuel consumption, and emissions benefits.
An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning	Assad Al Alam, Ather Gattami, Karl Henrik Johansson	2010	Develops a framework for HDV platooning, establishing constraints for platoon fuel optimality. Derives vehicle models (based on powertrain characteristics) and simulation models, and presents a system architecture. Uses simulation models and experimental results to investigate fuel reduction potential of technology.	Simulation is based on a single vehicle model which focuses on powertrain characteristics, ambient settings, and the system architecture. Does not consider passenger traffic on the road.

Table 2.3 continued

Fuel-Efficient Distributed Control for Heavy Duty Vehicle Platooning	Assad Alam	2011	Develops a framework for HDV platooning, establishing constraints for platoon fuel optimality. Derives vehicle models (based on powertrain characteristics) and simulation model, and presents a system architecture. Uses simulation models and experimental results to investigate fuel reduction potential of technology.	Simulation is based on a single vehicle model which focuses on powertrain characteristics, ambient settings, and the system architecture. Does not consider passenger traffic on the road.
Coordinated Route Optimization for Heavy-duty Vehicle Platoons	Jeffrey Larson, Christoph Kammer, Kuo-Yun Liang, Karl Henrik Johansson	2013	Uses local controllers along a road network to facilitate platoon formation and develop algorithms. Using these algorithms, implements a large-scale simulation of the German autobahn road network to demonstrate fuel savings.	Not based on actual travel data. Does not consider influence of congestion.
A Distributed Framework for Coordinated Heavy-duty Vehicle Platooning	Jeffrey Larson, Kuo-Yun Liang, Karl Henrik Johansson	2014	Uses local controllers along a road network to facilitate platoon formation and develop algorithms. Using these algorithms, implements a large-scale simulation of the German autobahn road network to demonstrate fuel savings.	Not based on actual travel data. Does not consider influence of congestion.
Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report	Auburn University, ATRI, Meritor WABCO, Peloton Technology, Peterbilt Trucks	2015	DATP concept is designed and tested on a test course in Opelika, AL and a vehicle simulation is run. In order to get impacts on traffic flow and mobility, a traffic simulation is run for different scenarios (varied by traffic volume, headway, market penetration) along a 5.3 mile stretch on I-85 in the Auburn-Opelika area.	Limited to two-vehicle platoons operating on a very short roadway segment. Does not model different times of day, other roadway types, or truck lane restrictions. Platoons cannot be formed dynamically.

technology” alternatives. The other PATH program model uses entropy maximization and performance estimator tools to estimate the impact of the technology along a freeway. This effort is limited in that it does not use origin-destination data for truck trips; volume by time of day is estimated based on assumptions regarding flow rates for different time periods of the day. Moreover, this project does not explicitly model for a specific future year. Instead, changes in the conditions are considered by modeling different demand levels (i.e., 100%, 125%, and 150% of current demand). For the Chicago analysis, future year was also not modeled. Instead, trends were assumed in order to estimate future year results. Neither study considers the impacts of induced demand (i.e., additional traffic that could result from the technology). The modeling efforts by the FHWA EARP use a microscopic traffic simulation model based on actual truck counts. While the model approach would be acceptable in a planning context, the analysis is limited to a 5.3-mile stretch of roadway.

This dissertation does not seek to address all of these limitations. However, it does address a couple of them. For one, not all efforts simulate the technology itself. Instead, in some cases, models are run without the technology, and then the impacts of the technology are estimated by making assumptions on how the technology would influence the results from the without-technology model. In this dissertation, the technology itself is modeled. Subsequently, the results from the model are used to quantify the impacts of the technology. Secondly, a future year is modeled using future year data projections. Instead of assuming trends, the modeling in this dissertation is carried out using forecasted data. In addition to addressing these limitations, this dissertation presents an alternative approach that has not yet been used to demonstrate how autonomous truck platoons can be modeled. This approach involves the use of OD commodity data, data from FHWA’s Freight Analysis Framework (FAF) database in particular. Developing such an approach is worthwhile, given that many MPOs and state DOTs make use of this database for freight planning. Lastly, previous efforts do not shed light on how transportation planning agencies could make use of such tools for planning purposes. This dissertation also addresses that gap.

The following chapters explain how the technology is modeled using OD commodity data for a future year. The chapters go into the details of the approach and the

results obtained from applying the approach to commonly used planning data. Moreover, given that past efforts do not provide insight into how the technology and the implications of the technology can be incorporated into the freight planning process, a framework is offered for doing so.

CHAPTER 3: METHODOLOGY

The methodology presented in this dissertation is composed of three phases. The first phase consists of developing a non-technology model and a set of autonomous truck platoon models and then running the models. The second phase is performance measurement. This phase consists of developing a performance measurement framework and using this framework along with the model results obtained in phase one to measure safety, economic, congestion, and emissions impacts of the technology. The third phase is the planning phase. In this phase, the modeling and performance measurement tool, developed in phases one and two, is placed in a scenario planning framework with the purpose of using the model and performance measurement results to guide policy development. A more detailed description of the steps in phases one and two are provided below. The framework and policy proposals developed for phase three are discussed in the next chapter, Chapter 4.

3.1 Phase 1: Model Development

3.1.1 Non-Technology Model

In order to effectively direct resources, there is a need to know where the freight is moving within the state, the value of the freight, and the cost of delay based on what is being shipped. While this dissertation does not focus on the value of time component, it does make use of a model that was developed to simulate commodity flow and its equivalent truck traffic along the I-85/I-285 corridor in Georgia, as shown in Figure 3.1 (Southworth and Smith 2016). More specifically, this model was used, with several adaptations, as the non-technology model for this dissertation. In order to set up the model, the following steps were carried out. The steps are also illustrated in a flow chart in Figure 3.2.

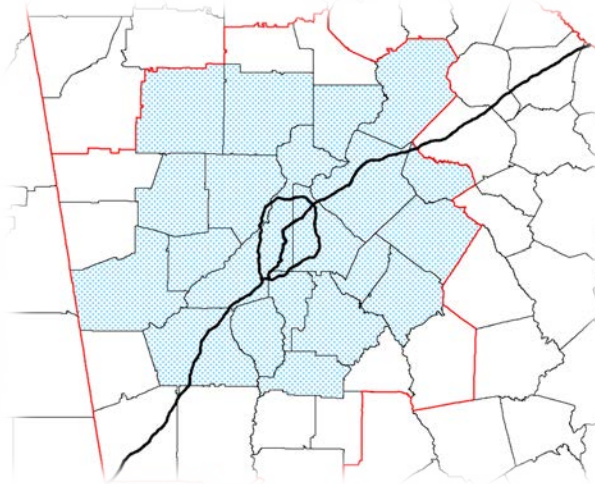


Figure 3.1: I-85/I-285 Corridor in Georgia

1. **Set up map and create network.** First, a map was created in TransCAD (Caliper Corporation 2014). This map includes, among other components, the Freight Analysis Framework (FAF) highway network, domestic FAF centroids, and selected county centroids (i.e., counties within the 32-county Atlanta region, as defined by the FAF). The centroids were connected to the network; this was necessary in order to put the flow data from a given centroid onto the network during the traffic assignment process.
2. **Download OD tables and identify flow types.** Concurrent with the first step, 43 Standard Commodity Transportation Group (SCTG) commodity flow tables were downloaded using FHWA’s FAF Data Tabulation Tool. For each SCTG class-specific commodity flow table, each OD pair was identified and designated as internal-internal (I-I) flow, internal-external/external-internal (I-E/E-I) flow, or external-external (E-E) through flow. Internal-internal flows are those that both start and end in the Atlanta region. Internal-external/external-internal flows are those that either start or end in the Atlanta region. External-external through flows are those that neither start nor end in, but would potentially go through the Atlanta region.

FAF currently provides these OD flow estimates for base year 2012 as well as years 2013, 2014, and 2015. Additionally, FAF provides forecasts, which are an extrapolation of current trends, for every five years between 2020 and 2045. While FAF4 is currently available, it was not available during the time that the modeling

component of this dissertation was being carried out. Additionally, while tonnage, value, and ton-miles are currently available in FAF4, the network database and flow assignment information for FAF4 are not. So FAF3 is the version that was used for this dissertation. FAF3 provides network database and flow assignment information for 2007 and 2040. While the model in the project (Southworth and Smith 2016) was developed using 2007 data, a future year (2040) model was set up for this dissertation. The year 2040 was chosen as the forecast year mainly based on data availability. Using 2040 as the forecast year is also in line with current projections of when full automation will be reached, and is also consistent with the current “long-range” planning horizons of transportation agencies.

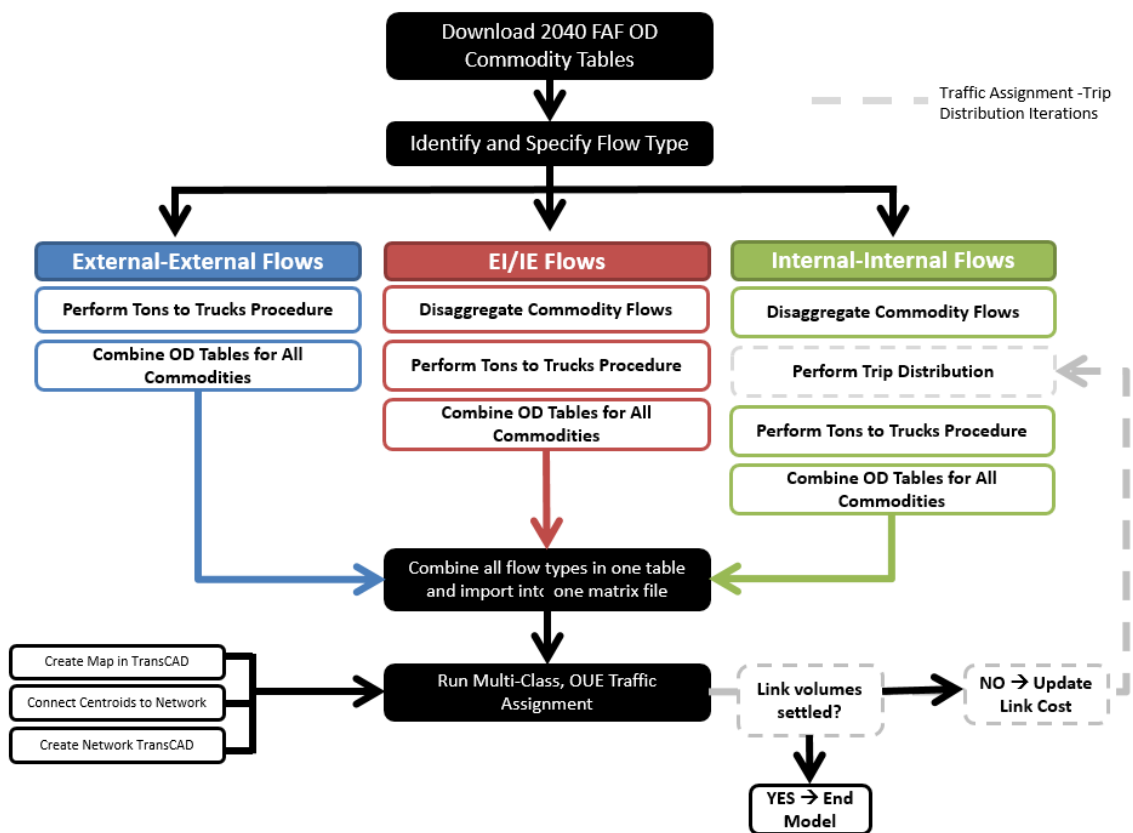


Figure 3.2: Flow Chart of Non-Technology Model Steps

3. **Perform spatial disaggregation.** Since the Atlanta region is the area for which a higher level of detail was desired, only the flows to and/or from the Atlanta region's FAF zone (I-I, E-I, and I-E) were disaggregated to the county level. In order to do this, first disaggregation factors were developed. The disaggregation factors were developed using 2040 employment and population projections from the Atlanta Regional Commission (ARC) (Atlanta Regional Commission 2016a). ARC's forecasts only provide projections for the 20-county region, but the FAF region includes 32 counties. To deal with this mismatch, it was assumed that the other 12 counties will make up the same percentage of the total population and total employment in 2040 as they have in recent years as reported in Census data (U.S. Census Bureau n.d.). The employment (2013) and population (2014) of those 12 counties combined make up only 3.6% and 5.6%, respectively, of the 32-county totals.

After these O and D projections were developed, the OD flow tables for internal flows and internal-external/external-internal flows were disaggregated using TransCAD's Matrix-Disaggregate command, which relies on the user-provided disaggregation factors. Using this command, the FAF-level OD flow matrices were disaggregated to FAF- and county-level OD flow matrices.

$$OD\ Flow(i, j) = OD\ Flow(I, J) \times p_i \times a_j$$

Equation 3.1: Matrix Disaggregation Equation

where,

- $OD\ Flow(i, j)$ = the tons of commodity shipped from zone i to zone j in the FAF- and county-level matrix, where i and j are either counties within the Atlanta region or FAF zones elsewhere
- $OD\ Flow(I, J)$ = the tons of commodity shipped from zone I to zone J in the FAF-level matrix, where I and J are both FAF zones
- p_i = production factor which represents the share of tonnage in the FAF region that is produced by county i (i.e., ratio of county employment to region employment)

- a_j = attraction factor which represents the share of tonnage in the FAF region that is attracted to county j (i.e., ratio of county population to region population)

For external trip ends, p_i and a_j are both equal to 1, indicating that the entire commodity share for the external FAF zones is not disaggregated.

4. **Perform tons to trucks procedure.** Once the matrices were disaggregated, the OD flows were converted from tons shipped to truck trips using a method developed by the Battelle Memorial Institute (Battelle 2011). The flow chart of the method shows the different steps (see Figure 3.3). The procedure identifies the five primary truck configurations and nine major truck body types. This identification is primarily based on the 2002 Vehicle Inventory and Use Survey (VIUS) database, a database which provides state- and national-level estimates of numbers of trucks by truck type. The truck configurations include: 1 - single unit trucks (SU); 2 - truck plus trailer combinations (TT); 3 - tractor plus semitrailer combinations (CS); 4 - tractor plus double trailer combinations (CD); and 5 - tractor plus triple trailer combinations (CT). For each origin-destination pair, the tonnage was allocated to the five different truck configurations based on zone to zone distance. Following this, the tonnages by truck configuration were multiplied by commodity-specific truck equivalency factors for each of the nine truck body types to convert the tonnages to their equivalent number of trucks. The number of trucks was summed over all of the truck body types to get a total number of trucks for each truck configuration. Empty trucks were calculated using empty truck factors. The commodity-filled trucks and empty trucks were added together to get total annual number of trucks by truck type. The number of trucks was divided by 365 to get the Average Daily Truck Traffic (ADTT) for each truck type.

It is worth noting here that while the VIUS program was discontinued after 2002, the value of this commodity-to-truck conversion data, along with other VIUS data elements, has led to its scheduled reinstatement as a federally supported data program, with the California DOT currently in the process of developing its own VIUS dataset (Institute of Transportation Studies at the University of California Irvine 2014).

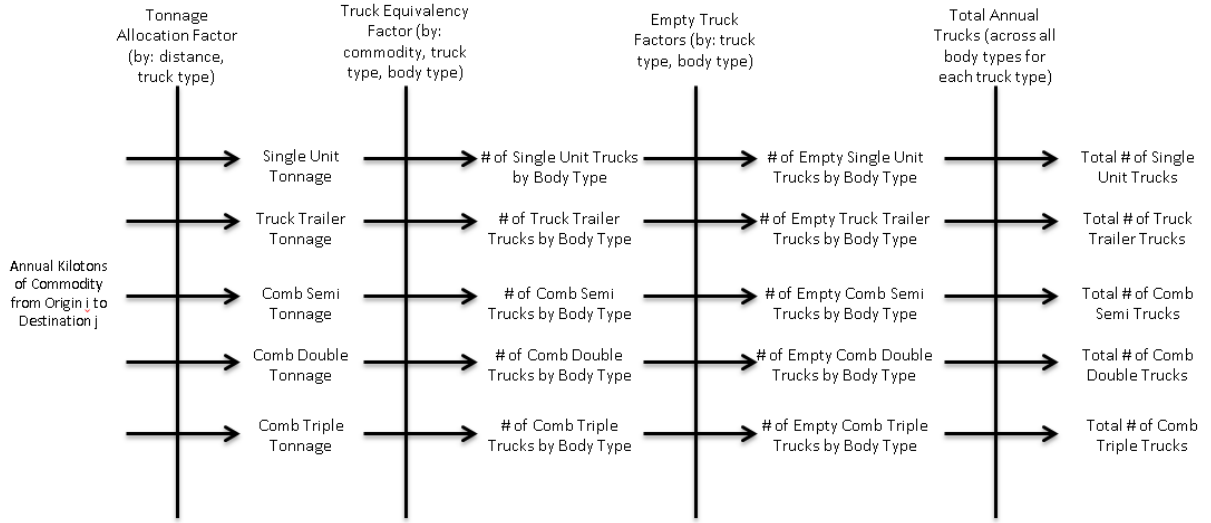


Figure 3.3: Tons to Trucks Conversion Process

The equation for the number of trucks of truck type j is as follows:

$$Y_j = \frac{X_{ij} \beta_{ij1}}{\omega_{ij1}} + \frac{X_{ij} \beta_{ij2}}{\omega_{ij2}} + \frac{X_{ij} \beta_{ij3}}{\omega_{ij3}} + \dots + \frac{X_{ij} \beta_{ij9}}{\omega_{ij9}} = \sum_{k=1}^{k=9} \frac{X_{ij} \beta_{ijk}}{\omega_{ijk}}$$

Equation 3.2: Tons to Trucks Equation

where,

- Y_j = number of trucks of truck type j
- X_{ij} = tons of commodity i shipped by trucks of truck type j
- β_{ijk} = the percent of commodity i moved by truck type j with body type k
- ω_{ijk} = the average payload of truck type j with body type k transporting commodity i .

5. **Run the traffic assignment.** After the OD flows were disaggregated and converted from annual tons to daily trucks, the tables for each commodity were imported into matrices by truck type and combined for all commodities. The daily truck matrices were converted into hourly matrices by multiplying the daily matrices by a K-factor of 0.08, representing 8% of the daily truck traffic on the road during the peak hour. Since the focus in this dissertation is on trucks, the peak hour represented in the model refers

to the truck peak hour. The ten matrices, two for each truck type (one to denote trucks that cannot travel on links inside I-285 and the other to denote trucks that can), were run in a multi-class origin user equilibrium (OUE) traffic assignment in TransCAD. The OUE assignment, a relatively new assignment, works by creating a set of flows for each origin (Slavin et al. 2010). To do this, min- and max-path trees (a minimum-cost path and a maximum-cost path from the origin to each of the other nodes) are created. Then, the flows are equilibrated, meaning the flows on the max-path are shifted to the min-path until the cost difference between the paths is minimal. The process is reiterated until the resulting origin-specific set of flows, or bush, is optimal. The OUE method is unique in its method of shifting flows from max paths to min paths, which only uses paths in the bush, the acyclic network whose root is its identifying origin node. The OUE assignment provides a path-based solution without explicit enumeration of paths. This has significant implications for shorter run times. This characteristic also allows the path-based results to be available for purposes such as select link analysis. TransCAD's select link analysis tool is especially useful for corridor studies given that it can identify which OD flows are using the corridor or sections of the corridor as specified by the user. The OUE assignment can also compute solutions to a much tighter convergence than can be reached with the traditional algorithms. It is posited that for low gaps, OUE is always faster than other assignment algorithms and that OUE produces a better solution than the Frank Wolfe algorithm at the same relative gap. There is also a warm start option for OUE, which allows the modeler to build on a previous assignment result, thus reducing computational run-times.

Prior to the OUE network assignment, the truck OD-flows, specified by truck type, were converted to passenger car equivalents (PCE), using PCE conversions reported in "Heavy Vehicle Effects on Florida Freeways and Multilane Highways", a report prepared for Florida Department of Transportation by the University of Florida Transportation Research Center (Washburn and Ozkul 2013). The report provides truck type specific PCE values, based on Highway Capacity Manual equations, for various roadway grades and various proportions of trucks and buses within the mixed traffic stream.

For the assignment, first the passenger vehicle volumes and non-FAF truck volumes were preloaded. Since there is not very reliable and accurate data that indicates what the peak hour for trucks is, a range was considered. Accordingly, one of the non-technology model runs assumed 8% of daily truck traffic and 2% of daily passenger car traffic during the truck peak hour (Scenario 1). This suggests that trucks try to avoid the overall peak hour. A second non-technology model run assumed both 8% of daily truck and passenger car traffic during the truck peak hour (Scenario 2). This suggests that trucks and passenger cars have the same K-factor during the same hour of the day. However, for some links, the FAF40 traffic forecast produces some unrealistic volume to capacity (v/c) values on the corridor (v/c ratios over 4). So, the 8% K-factor preloads were adjusted so that the v/c ratio did not exceed a certain value – either a value of 1 or the value of the FAF-provided 2007 v/c ratio if the FAF-provided 2007 v/c ratio was greater than 1. The use of these values implies that 2040 traffic conditions will be at least as congested as 2007 conditions.

After specifying the preload and other link-specific information, including capacity, free flow travel time, the truck type-specific free flow operating costs and set of restricted links, and alpha and beta parameters, these truck matrices were assigned to the network. The results from this traffic assignment were then used to calculate updated generalized truck operating costs (adjusted for congestion) along each link for each truck type. These costs were then run through a shortest path algorithm to create OD truck operating cost matrices for each truck type. The operating cost equation is shown in Equation 3.3.

$$OC_{OD}^v = \sum_{l \in L_{OD}^v} \left[\left(\frac{1}{0.6978} \right) (labor_l + fuel_l^v) \right]$$

Equation 3.3: Operating Cost Function

where,

- OC_{OD}^v = truck operating cost from origin O to destination D using truck type v
- l = link
- L_{OD}^v = set of links on the shortest path from O to D using truck type v
- $labor_l$ (labor cost along link l) = $\$23.61/hour * t_l$

- t_l = travel time along link l in hours
- $fuel_l^v$ (fuel cost of truck type v along link l)
 - $S \geq 55 \text{ mph}$: $\frac{\$2.707}{gal} * d_l / \left[\frac{1}{(1.53 \times 10^{-6} \times M_v) + (2.94 \times 10^{-5} + 1.94 \times 10^{-13} \times M_v) \times S_l^2} \right]$
 - $S < 55 \text{ mph}$: $\frac{\$2.707}{gal} * d_l / \left[\frac{33,000}{M_v} \left[\frac{1.536}{0.17 + (2.43/S_l)} \right] \right]$
 - d_l = length of link l in miles
 - M_v = truck weight of truck type v in pounds
 - S_l = truck speed along link l in mph

Fuel consumption rates came from the National Center for Freight & Infrastructure Research and Education, the labor rate was based on ATRI's 2015 estimates for driver wages and benefits, and the fuel rate was obtained from EIA (Hussein et al. 2009; Torrey and Murray 2015; U.S. Energy Information Administration 2016). The ratio of 1/0.6978 indicates that labor and fuel make up 69.78% of the total truck operating costs minus the truck tolls, which are not common in the Atlanta region, and which only make up about 1.3% of the total truck operating costs.

These truck operating cost matrices by truck type were then used, along with value of time and travel time reliability costs, to develop 43 commodity-specific generalized cost matrices by making use of the truck type distribution for each commodity (see Equation 3.4). More details on these value of time and travel time reliability cost calculations can be found in the project report (Southworth and Smith 2016).

$$GC_{OD}^c = [(\%SU_{OD}^c * OC_{OD}^{SU}) + (\%TT_{OD}^c * OC_{OD}^{TT}) + (\%CS_{OD}^c * OC_{OD}^{CS}) + (\%CD_{OD}^c * OC_{OD}^{CD}) + (\%CT_{OD}^c * OC_{OD}^{CT})] + [VOT_c * (t_{OD} + RR_c * SD_{t_{OD}})]$$

Equation 3.4: Generalized Cost Equation

where,

- GC_{OD}^c = generalized cost from origin O to destination D for commodity

- $\%SU_{OD}^c$ = percent of trucks traveling from O to D that are SU
- $\%TT_{OD}^c$ = percent of trucks traveling from O to D that are TT
- $\%CS_{OD}^c$ = percent of trucks traveling from O to D that are CS
- $\%CD_{OD}^c$ = percent of trucks traveling from O to D that are CD
- $\%CT_{OD}^c$ = percent of trucks traveling from O to D that are CT
- VOT_c = value of time of commodity c
- t_{OD} = shortest path travel time between O and D
- RR_c = reliability ratio of commodity c
- $SD_{t_{OD}}$ (standard deviation of time for OD) = $CV_{t_{OD}} * t_{OD_{cong}}$
 - $CV_{t_{OD}} = aCI_{t_{OD}}^b d_{OD}^g$, coefficient of variation (standard deviation of travel time divided by average travel time) in a time period t
 - a = constant/scale factor (0.16)
 - b = elasticity coefficient for CI (1.02)
 - g = elasticity coefficient for distance (-0.39)
 - $CI_{t_{OD}} = \frac{t_{OD_{cong}}}{t_{OD_{FF}}}$, congestion index (average travel time divided by free flow (FF) travel time) in the same time period t
 - d_{OD} = distance in kilometers

A significant component of the traffic assignment is the Bureau of Public Roads (BPR) function, which introduces congested time into route choice. The BPR delay function takes on the form:

$$t \times \left[1 + \alpha \left(\frac{x}{C} \right)^\beta \right], \text{ where}$$

Equation 3.5: BPR Function

where,

- t = free flow travel time
- C = capacity

- x = flow (number of cars)
- α = coefficient
- β = coefficient

The α and β coefficients used in this dissertation come from average, minimum, and maximum values for alpha and beta used by MPOs in regions with a population greater than 1,000,000 (Cambridge Systematics Inc. et al. 2012). These coefficients were assigned based on the facility type as specified in the FAF network (i.e., freeway or arterials). Table 3.1 shows the values that were used.

Table 3.1: BPR Parameters

	Alpha	Beta
Freeways	0.1	4.0
Arterials	1.0	6.0

These values were chosen to allow the freeways to be a more attractive option so that the assigned trucks would consider using the freeways. Otherwise, the levels of congestion forecasted for 2040 by the FAF, and the subsequent preloading of the background traffic, resulted in all FAF trucks avoiding the Interstate when higher parameters for freeways and lower parameters for arterials were selected. To maintain consistency between the traffic assignment and the results, these values were also used in the post assignment calculations (i.e., traffic measures and performance measures). The implications of using these specific values are discussed in the results chapter, Chapter 4.

6. **Carry out trip distribution - traffic assignment iterations.** In this step, which only applies to internal-internal flows, iterations between the trip distribution and traffic assignment steps were carried out to redistribute the internal-internal flows until an equilibrium was reached. For the distribution for each commodity, three inputs were needed: 1) a disaggregated production and attraction table that provides the number of

tons that start in and end in a given county; 2) a commodity-specific impedance matrix; and 3) commodity-specific beta values.

The commodity-specific impedance matrix used for this procedure used OD congested generalized costs that were calculated in Equation 3.4. The inverse power function (see Equation 3.6) was used to create the friction factors that were used to distribute the tons of commodity between county OD pairs.

$$f(d_{ij}) = d_{ij}^{-b}, b > 0$$

Equation 3.6: Inverse Power Function

where,

- d_{ij} = congested cost to travel between zone i and zone j (i.e., GC_{OD}^c from Equation 3.4)
- b = commodity-specific beta values reported in Southworth and Smith (2016)

A doubly constrained gravity model was run for each of the 43 commodities. This model (see Wilson 1971) has the following form:

$$T_{ij} = A_i O_i B_j D_j f(d_{ij})$$

where,

- T_{ij} = the number of trips from origin i to destination j
- A_i = factor that balances trips originating in zone i
- O_i = the number of trip ends beginning in origin i
- B_j = factor that balances trips ending in zone j
- D_j = the number of trip ends ending in destination j
- $f(d_{ij})$ – see Equation 3.6

The resulting matrices, one for each commodity, were total kilotons in 2040 by origin and destination pair. The resulting OD flows were again converted from tons to trucks and combined with the E-I/I-E flows and the E-E through flows. The traffic assignment was then run again. This procedure was repeated until the flows along the

links reached equilibrium (i.e., the number of trucks by link from the latest assignment did not vary from the previous assignment).

3.1.2 Autonomous Truck Platoon Model

A total of 14 different corridor-flow scenarios are reported in this dissertation, 12 of which included ATP technology (see Table 3.2). These scenarios were developed based on dimensions that are defined by the following questions:

- **What is the forecast year?** 2040 was selected as the future year to model the technology. 2040 was chosen for the reasons discussed earlier in this chapter.
- **What is the K-factor for trucks and passenger cars?** Based on GDOT traffic counts, K-factors (the percent of the 24-hour traffic volume on the road during the peak hour) are around 8% along I-85 and I-285 (Transmetric America Inc 2015). These K-factors are based on all of the traffic on the road. There is not much insight on what percent of trucks avoid rush hour. Therefore, trucks may have a peak hour other than the peak hour for passenger cars. Given this uncertainty, a range of peak hour conditions was considered. As discussed earlier in this chapter, all scenarios assumed 8% of the daily truck traffic during truck peak hour and depending on the scenario, either 2% or an adjusted 8% (adj. 8%) for passenger traffic during truck peak hour.
- **Are the trucks using ATP technology?** Scenarios 1 and 2 assume that all trucks are diesel powered trucks traveling individually. Scenarios 3 through 14 assume that some trucks are traveling in platoons. Under the ATP technology dimension, the following additional dimensions were considered.
 - **In what type of environment will the ATPs operate?** There is an ongoing discussion in the literature surrounding whether or not vehicles equipped with autonomous vehicle technology should be able to operate in mixed traffic or if they should be restricted to dedicated lanes. This dissertation considers both mixed traffic and dedicated lane conditions. The dedicated lane conditions include using existing capacity (i.e., taking away a lane from the unequipped vehicles) as well as using new capacity.

The dedicated lane (hereafter referred to as the ATP-only lane) was implemented along a portion of the I-85/I-285 corridor. This lane would allow eligible trucks traveling in the Atlanta region to “bypass” one of the most congested portions of the Interstate, further maximizing the benefits of the technology. Various sources were consulted to select a segment of roadway that carries a significant amount of truck traffic, is highly congested now and likely in the future, and is a reasonable distance (“reasonable” here being based on truck only lanes that exist or have been assessed in past studies). These sources include GDOT traffic counts, ARC level of service figures, and the FAF database (Atlanta Regional Commission 2016b; Federal Highway Administration 2014b; Transmetric America Inc 2015). The “dedicated lane segment” that was ultimately selected to implement the ATP-only lanes, was one that runs from the intersection of I-20 and I-285 on the west to the intersection of I-85 and I-985 (see Figure 3.4). The segment, indicated by the bolded line, is about 40 miles long.

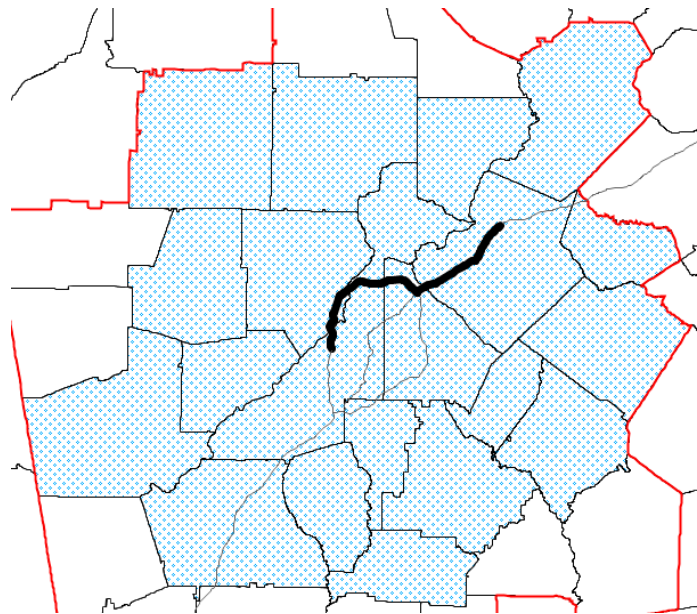


Figure 3.4: Dedicated Lane Segment

- **What truck types will be eligible to use the technology?** Out of the five truck types that were modeled, single unit trucks (SU) and tractor plus semitrailer combinations (CS) were identified as the truck types that can use the technology. This decision was largely based on the proof of concepts currently being carried out in the USA and Europe with these truck classes. The findings from these proof of concepts were the basis of many aspects of the simulation model.
- **What OD distance will be eligible?** A distance of 200 miles was selected as the threshold distance for which trucks would platoon (i.e., trucks traveling between OD pairs with a distance equal to or greater than 200 miles would use the technology). The distance of 200 miles was decided to be a reasonable threshold because it is a distance that borders short haul and long haul truck freight movements (Bureau of Transportation Statistics n.d.; Dye n.d.). Generally speaking, it is reasonable to assume that the benefits of platooning are more worthwhile for longer distance trips, so it is likely that trucks traveling longer distances would join platoons. In addition to the threshold distance of 200 miles, sensitivity analysis was carried out to assess the impact that this assumption has on the results. The two thresholds used in the sensitivity analysis were 0 miles and 500 miles.
- **How many trucks will travel together in a single platoon? How many drivers will be required to operate the platoon?** Many of the testing efforts have demonstrated the feasibility of platooning with trucks ranging from two to four trucks per platoon. Three truck platoons and five truck platoons were considered for this dissertation. In Scenarios 3-14, it is assumed that each truck has a driver. However, in the sensitivity analysis, three-truck platoons with two drivers and five-truck platoons with three drivers were also considered.
- **What percent of the trucks, out of those that are eligible based on truck type and OD distance, will be equipped with the technology?** The assumption made for the technology market share dimension is that, for all the truck trips that meet the truck type and threshold distance requirements

for platooning, 100% of those trucks will operate in an ATP. Because of the limited insight into this particular dimension, sensitivity analysis was carried out. The analysis considered an alternative market share of 50%.

Another potential ATP dimension deals with induced demand that results from the use of the technology. The platooning technology may make truck travel more attractive, causing mode shift, especially from rail to truck. This would potentially increase the truck traffic on the corridor. While this is a very important component of the larger implications of the technology, it was not considered in the model.

Table 3.2: Summary of Scenarios

Scenario	Future Year	K-factor for Trucks for Truck Peak Hour	K-factor for Passenger Cars for Truck Peak Hour	ATP Technology	ATP Operating Environment	Trucks eligible for technology	OD Distance Requirement	Trucks/ Drivers per Platoon	ATP Market Share
1	2040	8%	2%		Mixed traffic				
2		8%	adj. 8%						
3		8%	2%	X		SU, CS	>= 200 mi	3	100%
4		8%	adj. 8%	X		SU, CS	>= 200 mi	3	100%
5		8%	2%	X		SU, CS	>= 200 mi	5	100%
6		8%	adj. 8%	X		SU, CS	>= 200 mi	5	100%
7		8%	2%	X	Dedicated lane using existing capacity	SU, CS	>= 200 mi	3	100%
8		8%	adj. 8%	X		SU, CS	>= 200 mi	3	100%
9		8%	2%	X		SU, CS	>= 200 mi	5	100%
10		8%	adj. 8%	X		SU, CS	>= 200 mi	5	100%
11		8%	2%	X	Dedicated lane using new capacity	SU, CS	>= 200 mi	3	100%
12		8%	adj. 8%	X		SU, CS	>= 200 mi	3	100%
13		8%	2%	X		SU, CS	>= 200 mi	5	100%
14		8%	adj. 8%	X		SU, CS	>= 200 mi	5	100%

In order to run Scenarios 3 through 14, adjustments were made to the model to incorporate the characteristics of the technology. These adjustments included both editing existing steps and incorporating additional steps. Steps 1 through 3 of the non-technology models were not adapted. Changes were incorporated into the following steps: Step 4:

perform tons to trucks procedure, Step 5: run the traffic assignment, and Step 6: carry out trip distribution-traffic assignment iterations. These changes, which are reflected in the updated flow chart (see Figure 3.6), are discussed below:

Perform Tons to Trucks Procedure

After the normal tons to trucks procedure was carried out, as discussed in Step 4 above, autonomous truck platoon truck types were added to the table. These included four ATP types in total: three single unit truck ATP (SU ATP 3), three tractor plus semitrailer combination ATP (CS ATP 3), five single unit truck ATP (SU ATP 5), and five tractor plus semitrailer combination ATP (CS ATP 5).

For each OD pair with a distance equal to or greater than 200 miles, the number of three-truck ATPs was obtained by dividing the number of trucks of the corresponding truck type (either single-unit or combination semi-trailer) by three. Similarly, the number of five-truck ATPs was obtained by dividing the number of trucks of the corresponding truck type by five. As a result of this step, each autonomous truck platoon could be modeled as one long truck in the traffic assignment.

Run the Traffic Assignment

A number of the network parameters in the traffic assignment had to be adjusted to reflect the various scenario dimensions, the characteristics of the ATP technology, and the use of ATP-only lanes. These various parameters are explained.

- *Passenger car equivalents (PCE)* - The PCE values used for SU trucks and CS trucks traveling individually are 2.06 and 2.12, respectively. Given the potential benefit of reduced space that ATPs will take up on the roadway, the PCEs of the ATPs would not simply be these values multiplied by the number of trucks in the platoon. The PCEs were specified by network link type to differentiate when the trucks are traveling individually from when the trucks are traveling in the platoons. The following equation was used to determine the PCEs for the ATPs.

$$\begin{aligned}
& PCE_{SU/CS_{ATP_n}} \\
& = \begin{cases} PCE_{SU/CS_{individual}} \times n, & \text{non - ATP lanes} \\ PCE_{SU/CS_{individual}} \times n \times (1 - f), & \text{ATP eligible lanes} \end{cases}
\end{aligned}$$

Equation 3.7: ATP PCE Equations

where,

- $PCE_{SU_{individual}} = 2.06$
- $PCE_{CS_{individual}} = 2.12$
- $n = 3 \text{ or } 5$, denoting the number of trucks in the platoon
- $f = 0.46$, denoting the percent decrease in the amount of road space taken up by trucks in platoons versus those same trucks traveling individually

There is very little data that exists regarding the PCEs of autonomous truck platoons. The value of f used in this dissertation was selected based on results from two separate proof of concept efforts. The Dutch company TNO claims that two platooning trucks will decrease the amount of space, that those two trucks traveling individually would otherwise take up, from 82 meters to 44 meters (Janssen et al. 2015b). This claim was further supported by the Daimler Group, which, with its three-truck platoon, demonstrated that the platoon takes up 80 meters as opposed to the 150 meters that it would if the three trucks were traveling individually (Menzies 2016). These results equate to a 46.3% and a 46.7% decrease, respectively.

- *Truck Operating Costs* - It is very likely that the implementation of the autonomous trucks will impact the truck operating costs. Accordingly, the differential in the cost of the current truck technology and the autonomous truck platooning technology needed to be considered in the model. It is posited that the autonomous trucks will be more fuel efficient – one because of the more efficient driving patterns that the technology would offer and two because of the drag reduction effects of traveling in a closely packed platoon. Accordingly, while the cost per gallon would be the same, the cost of total fuel consumed for an autonomous truck would be less than that of the unequipped truck. Labor costs would change; the extent by which the costs would change would depend on the platoon logistics. Even in the case that a

driver is still required for each truck, the nature of work for a driver in the autonomous truck platoon may be valued differently than that for a driver of an unequipped truck or an equipped truck not traveling in a platoon. On the other hand, if only one driver, in the lead truck, for example, is required for the entire platoon while the following trucks are driverless, the labor savings would reflect the need for less drivers. The truck and trailer payments, in the case of the autonomous and connected trucks, would include the cost of the technology. Out of the potential aspects of the operating costs that may be impacted, fuel, labor, and technology costs were taken into consideration in this dissertation. The following is an explanation of how the future truck technology cost function differs from Equation 3.3, the cost function for the non-technology model.

The change in fuel cost depends on the fuel savings benefits associated with autonomous truck platooning. The literature on such fuel savings provides a wide range of savings based on the position of the truck in the platoon. The values for percent savings that were used to update the fuel cost portion of the function are: 4.3% for the lead truck, 10% for the middle truck, and 14% for the tail truck, an average of 9.43% fuel savings for each truck (Lu and Shladover 2014). These values are associated with 85 km/h (52.8 mph). Fuel savings below 85 km/h were based on a relationship between speed and aerodynamic drag's contribution to fuel consumption (Zabat et al. 1995). Specifically, fuel savings at speeds of less than 85 km/h were estimated such that the ratio of fuel savings to aerodynamic drag contribution at a particular speed was proportional to the ratio of fuel savings to aerodynamic drag contribution at a speed of 85 km/h. Only a few studies have tested platoons at various speeds to see what impact speed has on fuel savings (Bonnet and Fritz 2000; Lammert et al. 2014). The results from these studies indicate and suggest in discussion that this relationship between aerodynamic drag and fuel consumption and savings does not hold up at high speeds. Moreover, the tests demonstrated that fuel savings were highest for speeds around 55 mph. Accordingly, for speeds above 55 mph, the fuel savings were based on the decrease in fuel savings from increased speed as demonstrated in a recent NREL study (Lammert et al. 2014). Using the points obtained from these two methods,

MATLAB was used to fit a function to the data (see Figure 3.5). The function for the equation, which is represented by the red line in the figure, is written out in Equation 3.8 (see ‘percent fuel savings’).

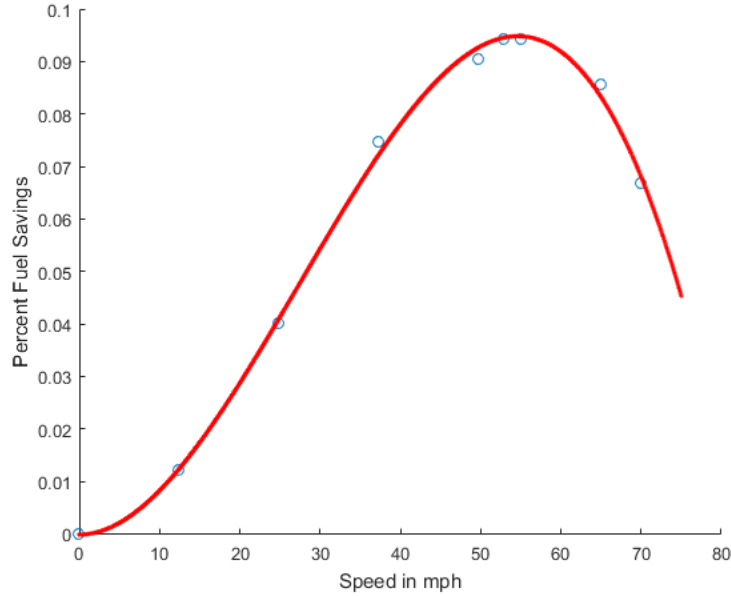


Figure 3.5: Platoon Fuel Savings as a Function of Speed

Due to the uncertainty of the technology’s impact on labor rates, it was assumed that the hourly labor rate would remain the same as the rate used in the non-technology case. However, for sensitivity testing, as mentioned earlier in this chapter, the number of drivers for the three-truck platoon was varied to two drivers and the number of drivers for the five-truck platoon was varied to three drivers. Additional per mile costs for technology were added. The resulting equation is shown in Equation 3.8.

$$OC_{OD}^v = \sum_{l \in L_{OD}^v} \left[n * (labor_l + fuel_l^v * (1 - P)) + n * (labor_l + fuel_l^v) \left(\frac{0.3022}{0.6978} \right) + n * T_l \right]$$

Equation 3.8: Operating Cost Function for Autonomous Truck Platoons

where,

- OC_{OD}^v , l , L_{OD}^v , $labor_l$, S_l , and $fuel_l^v$ are explained in Equation 3.3

- $P = aS_l^3 + bS_l^2 + cS_l + d$
 - P = percent fuel savings
 - $a = -1.1646 \times 10^{-6}$
 - $b = 9.5453 \times 10^{-5}$
 - $c = -7.8016 \times 10^{-7}$
 - $d = -1.3064 \times 10^{-4}$
- T_l , technology cost = $\begin{cases} \$0.0302/\text{miles} \times d_l & \text{for SU trucks} \\ \$0.0179/\text{miles} \times d_l & \text{for CS trucks} \end{cases}$

The technology costs for the equation were estimated using cost estimates for level 3 truck technology and average miles driven until replacement for straight trucks and truck tractors (Ronald Berger 2016; Torrey and Murray 2015). Although the cost of infrastructure is a significant factor in deciding the feasibility of the platoons operating on dedicated lanes, it was not considered in this dissertation.

- *Preload and Capacity* – Preload and capacity values varied by scenario. The hourly truck traffic was assumed to be 8% of the daily truck traffic for all scenarios. The hourly passenger car preload was assumed to be either 2% or the adjusted 8% of the daily passenger car traffic. For each run, the hourly non-FAF trucks and passenger car traffic were preloaded to the network prior to the traffic assignment of the FAF trucks to the network.

The hourly capacity values used for the model were those provided in the FAF database for 2040. For the dedicated lane segment, this hourly capacity was adjusted to reflect the impact of the ATP-only lane on the capacity. For the “dedicated lane using existing capacity” scenarios, the capacity for the general purpose lanes was reduced by 2034 vehicles per hour per lane (vphpl). 2034 vphpl is the average per lane capacity along the links that make up the dedicated lane segment. Reducing the capacity by 2034 vphpl suggests that a general purpose lane would be taken away. For the “dedicated lane using new capacity”, the capacity of the general purpose lanes remained the same. This indicated that, by adding a lane, the capacity available for the unequipped traffic would not change. In both cases,

the capacity of the ATP-only lane was set to 2034 vphpl. Preload and capacity values used for each traffic assignment are summarized in Table 3.3.

Two different traffic assignments were run for the scenarios involving autonomous truck platoons on dedicated lanes. This was done so that the ATP-only lanes could be represented without having to add network links in the software. So, for Scenarios 7 through 14, the first traffic assignment preloaded passenger cars and non-FAF trucks and then assigned the non-ATP FAF trucks on top of the preloaded traffic. The second traffic assignment preloaded passenger cars, non-FAF trucks, and the non-ATP FAF trucks from the first traffic assignment and then assigned the ATP FAF trucks on top of the preloaded traffic.

Table 3.3: Capacity and Preload by Scenario

Traffic Assignment	Truck Types*	Capacity (veh/hr)*	Mixed Traffic Lanes Preload*
1	SU, TT, CS, CD, CT	FAF40 Capacity	2% passenger car preload + 8% non-FAF preload
2	SU, TT, CS, CD, CT	FAF40 Capacity	adj. 8% passenger car preload + 8% non-FAF preload
3	SU, TT, CS, CD, CT, SU ATP 3, CS ATP 3	FAF40 Capacity	2% passenger car preload + 8% non-FAF preload
4	SU, TT, CS, CD, CT, SU ATP 3, CS ATP 3	FAF40 Capacity	adj. 8% passenger car preload + 8% non-FAF preload
5	SU, TT, CS, CD, CT, SU ATP 5, CS ATP 5	FAF40 Capacity	2% passenger car preload + 8% non-FAF preload
6	SU, TT, CS, CD, CT, SU ATP 5, CS ATP 5	FAF40 Capacity	adj. 8% passenger car preload + 8% non-FAF preload
7A	SU, TT, CS, CD, CT	FAF40 Capacity – 2034	2% passenger car preload + 8% non-FAF preload
7B	SU ATP 3, CS ATP 3	2034	2% passenger car preload + 8% non-FAF preload + truck PCEs from 7A results
8A	SU, TT, CS, CD, CT	FAF40 Capacity – 2034	adj. 8% passenger car preload + 8% non-FAF preload
8B	SU ATP 3, CS ATP 3	2034	adj. 8% passenger car preload + 8% non-FAF preload + truck PCEs from 8A results

Table 3.3 continued

9A	SU, TT, CS, CD, CT	FAF40 Capacity – 2034	2% passenger car preload + 8% non-FAF preload
9B	SU ATP 5, CS ATP 5	2034	2% passenger car preload + 8% non-FAF preload + truck PCEs from 9A results
10A	SU, TT, CS, CD, CT	FAF40 Capacity – 2034	adj. 8% passenger car preload + 8% non-FAF preload
10B	SU ATP 5, CS ATP 5	2034	adj. 8% passenger car preload + 8% non-FAF preload + truck PCEs from 10A results
11A	SU, TT, CS, CD, CT	FAF40 Capacity	2% passenger car preload + 8% non-FAF preload
11B	SU ATP 3, CS ATP 3	2034	2% passenger car preload + 8% non-FAF preload + truck PCEs from 11A results
12A	SU, TT, CS, CD, CT	FAF40 Capacity	adj. 8% passenger car preload + 8% non-FAF preload
12B	SU ATP 3, CS ATP 3	2034	adj. 8% passenger car preload + 8% non-FAF preload + truck PCEs from 12A results
13A	SU, TT, CS, CD, CT	FAF40 Capacity	2% passenger car preload + 8% non-FAF preload
13B	SU ATP 5, CS ATP 5	2034	2% passenger car preload + 8% non-FAF preload + truck PCEs from 13A results
14A	SU, TT, CS, CD, CT	FAF40 Capacity	adj. 8% passenger car preload + 8% non-FAF preload
14B	SU ATP 5, CS ATP 5	2034	adj. 8% passenger car preload + 8% non-FAF preload + truck PCEs from 14A results

Several things should be noted regarding Table 3.3. For each truck type, two matrices were included: one for trucks that can travel inside the perimeter (ITP), meaning inside of I-285, and the other for trucks that cannot. The capacities given above are only for the dedicated lane segment. The capacity for traffic assignment A refers to the general purpose lane capacity along the dedicated lane segment. The capacity for traffic assignment

B refers to the capacity of the ATP-only lane. The capacity for the segments of roadway other than the dedicated lane segment is always FAF40, which represents the FAF database-provided hourly capacity values. The preloads for the mixed traffic scenarios and for traffic assignment A in Scenarios 7 through 14 were applied to all segments of roadway. For traffic assignment B, the preload specified is the preload on the general purpose lanes. The preload for ATP-only lanes, which is not indicated in the table, was set to 0.

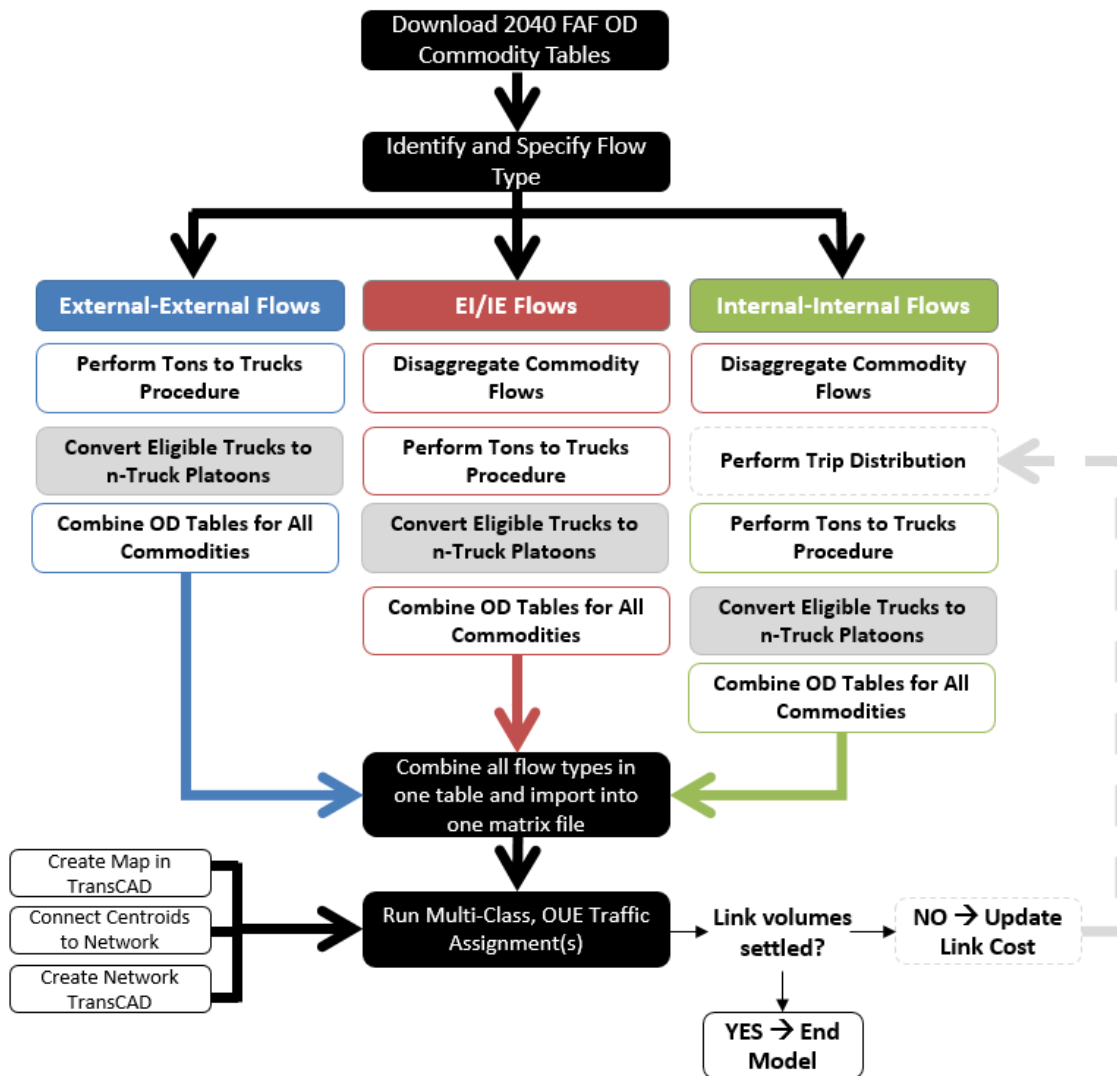


Figure 3.6: Flow Chart of ATP Model

Carry out trip distribution - traffic assignment iterations

As in the non-technology model, distribution – assignment iterations were run to take into consideration the effect of trucking costs on a truck's origin and destination. This step differed in the ATP model in that the costs used to redistribute the tons of commodity were influenced by the costs of the technology, the costs and benefits associated with the technology, and the ATP-only lanes.

The operating costs along each link were calculated as a weighted average of the operating costs of the different truck types on that link. The costs along a path were summed to give the OD cost. The OD cost was used as the impedance matrix in the trip distribution models. After the distribution procedure, the tons to trucks conversions and traffic assignment steps were repeated, and iterations between trip distribution, tons-to-trucks conversion and traffic assignment were carried out until a stable set of highway link volumes was reached.

This equilibration procedure provided various results: PCEs, link and OD travel times, link volume to capacity ratios (v/c ratios), vehicle miles traveled (VMT), vehicle hours traveled (VHT), link speeds, volume delay function (VDF), and estimated truck flows. The results are presented in the next chapter.

3.2 Phase 2: Performance Measurement Framework Development

Once the traffic assignment results were obtained, they were used in conjunction with other information, to calculate performance measures. This section of the chapter explains how the performance measures were selected and how they were calculated.

3.2.1. Performance Measurement Selection

In order to place this work in a relevant transportation planning context, the measures considered were those that a transportation planning agency would use. A metropolitan planning organization, or MPO, for example, may have various goals and a set of corresponding objectives to further define each goal. Furthermore, for each objective, performance measures are typically set to monitor progress toward the stated goals. Regarding selecting the desired performance measures, three steps were taken. More discussion on each step is provided below.

1. **Select performance measurement areas.** Performance measurement areas were identified by considering the intersection of the goals and objectives of transportation planning entities and areas of benefit associated with AV/CV truck technology. The national goals established in the MAP-21 legislation are related to safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays (FHWA 2015). MAP-21 lists eight metropolitan long-range transportation planning factors. These factors call for action to: support economic vitality; increase safety; increase security; increase accessibility and mobility; protect the environment, conserve energy, and improve quality of life; enhance system integration and connectivity; promote system management and operation efficiency; and preserve the existing system (FHWA 2015). Specific to freight, MAP-21 states that the National Freight Policy “establishes a policy to improve the condition and performance of the national freight network to provide the foundation for the United States to compete in the global economy and achieve goals related to economic competitiveness and efficiency; congestion; productivity; safety, security, and resilience of freight movement; infrastructure condition; use of advanced technology; performance, innovation, competition, and accountability in the operation and maintenance of the network; and environmental impacts” (FHWA 2015). The Fixing America’s Surface Transportation (FAST) Act of 2015 further emphasizes the focus on freight. The Fast Act calls for a “National Multimodal Freight Policy that includes national goals to guide decision-making” and the “development of a National Freight Strategic Plan” to implement the Policy’s goals (Office of the Under Secretary for Policy n.d.). The Plan is expected to address the conditions and performance of the multimodal freight system, identify strategies and best practices to improve the performance of the national freight system, and mitigate the impacts of freight movement on communities. The legislation also calls for projects that can improve safety, eliminate freight bottlenecks, and improve critical freight movements.

State DOTs and MPOs strive to meet the requirements established in the federal legislation, and as such, the goals of state DOTs and MPOs are in line with

the goals laid out in MAP-21 and FAST. GDOT, for example focuses on four core goals: workplace betterment for employees, safety investments and improvements, system preservation, and on-schedule mobility-focused projects. Some of the objectives under those four areas include the following: reduce fatalities, preserve and maintain interstate highways and multilane roads, preserve statewide bridge conditions, reduce congestion cost, and improve mobility. The Atlanta Regional Commission, as discussed in its Regional Transportation Plan (RTP), specifies four performance emphasis areas: mobility, connections/accessibility; economic growth; and safety.

The other aspect of selecting performance measurement areas hones in on the potential benefits of the AV/CV technology. Here there are a number of posited benefits, as discussed in Chapter 2 of this dissertation. Those that appear often in the literature include reduced crashes, fuel savings and emissions reductions, cost savings, and congestion and parking cost reductions. Given the overlap between the transportation planning goals and the benefits of the technology, safety, economy, congestion, and emissions were selected as the performance measurement areas for this dissertation.

2. **Identify possible performance measures within each area.** Under the areas of safety, economy, congestion, and emissions, potential performance measures were identified. These measures came from transportation planning agency documents including ARC's RTP (Atlanta Regional Commission 2016c), the Atlanta Regional Freight Mobility Plan Update, the GDOT FY2013-2017 Strategic Plan (Georgia Department of Transportation 2016), and Georgia's Strategic Highway Safety Plan (Governor's Office of Highway Safety 2012).
3. **Select performance measures for each performance measurement area.** The final performance measures were ultimately selected by considering what measures would be most useful to an MPO and what measures could be obtained based on available information. These measures are included in Table 3.4.

Table 3.4: Goals, Objectives, and Performance Measures

Goals	Objectives	Performance Measures
Increase the safety of the transportation system	<ul style="list-style-type: none"> Reduce crash-related injuries and fatalities on the transportation system 	<ul style="list-style-type: none"> Number of truck-involved crashes Number of truck-involved crashes per truck VMT
Support the state’s economic growth and competitiveness	<ul style="list-style-type: none"> Reduce congestion-related costs to the trucking industry and the public 	<ul style="list-style-type: none"> Truck operating costs Congestion cost for the trucking industry
Reduce congestion on the roadway	<ul style="list-style-type: none"> Reduce travel time delay and associated costs Increase the reliability of the highway network 	<ul style="list-style-type: none"> Peak hour travel time in minutes Ratio of peak hour travel time to free flow travel time (travel time index) Difference in average travel time of ATPs on dedicated lane and average travel time of trucks in general purpose lanes
Reduce emissions from the transportation sector	<ul style="list-style-type: none"> Reduce GHG, PM_{2.5}, and NO_x emissions 	<ul style="list-style-type: none"> Total tons of truck emissions (GHG, PM_{2.5}, NO_x) Trucking industry percent contribution to total emissions (GHG, PM_{2.5}, NO_x) Percent difference in estimated emissions (GHG, PM_{2.5}, NO_x) from an n-truck platoon and emissions from n trucks traveling separately

3.2.2 Performance Measurement Calculations

Each performance measure is described in more detail below. The descriptions include an explanation, or definition, of the measure, and the information needed to calculate the measure. It should be noted that, given the current data limitations regarding the impact of autonomous and connected vehicle technology on overall safety, safety measures were considered qualitatively, through discussion.

Safety Performance Measures

- **Number of truck-involved crashes** – annual number of crashes on the corridor involving trucks.

- **Number of truck-involved crashes per truck VMT** – annual number of crashes on the analysis corridor involving trucks divided by the annual truck vehicle miles traveled on the analysis corridor.

Economic Performance Measures

- **Truck operating costs** – the average per mile or per hour operating cost for a truck to travel from its origin to destination.
- **Congestion cost for trucking industry** – additional truck operating cost that results from delay caused by congestion. The cost of congestion was calculated as the difference between truck operating costs during congested conditions and free flow conditions.

Congestion Performance Measures

- **Peak hour travel time in minutes** – average time, during peak hour, that it takes to travel along the dedicated lane segment. The peak hour travel time was provided as output from the traffic assignment. The average travel time along each of the links that make up the dedicated lane segment were summed together to give the average travel time along the segment.
- **Travel time index (TTI)** – the ratio of peak hour travel time to free flow travel time. Each link's free flow travel time was based on the free flow speed and link distance. The peak hour travel time for each link, which was calculated using the BPR function, was provided as output from the traffic assignment. These two values were used to calculate values for the TTI along the dedicated lane segment.
- **Travel time difference between ATP trucks and unequipped trucks** - difference in average travel time of ATPs in the ATP-only lane and average travel time of trucks in general purpose lanes. This measure only applied to the scenarios in which the dedicated lane segment was incorporated. The average travel time of trucks in the general purpose lanes was obtained from the first traffic assignment. The average travel time of the ATP trucks in the dedicated lane was obtained from the second assignment.

Emissions Performance Measures

- **Total truck emissions (GHG, PM_{2.5}, NO_x)** – peak hour emissions from trucks traveling on the dedicated lane segment. The total CO₂ equivalents, PM_{2.5}, and NO_x emissions from trucks were obtained using 2040 grams/mile emissions rates from the Environmental Protection Agency’s Motor Vehicle Emission Simulator (MOVES) (Liu et al. 2016; U.S. Environmental Protection Agency 2014). These emissions rates were based on AM peak conditions for the month of July. For each pollutant, the emissions rates are provided for speeds between 5 mph and 77 mph at 1 mph increments for each vehicle type and each vehicle model year. For each vehicle type, a single emissions rate for each speed was obtained by weighting the emissions rates by vehicle model year by the vehicle model year distribution for 2040.
- **Trucking industry percent contribution to total emissions (GHG, PM_{2.5}, NO_x)** – portion of emissions that comes from trucks. This measure was obtained by calculating the total emissions from trucks and dividing the result by total emissions from all vehicle types, which includes passenger cars and trucks. Emissions for passenger cars were also obtained from MOVES.
- **Percent difference in estimated emissions (GHG, PM_{2.5}, NO_x) from an n-truck platoon and emissions from n trucks traveling separately** – percent difference in the total emissions produced by an n-truck platoon and the total combined emissions from n trucks traveling separately. This measure is a function of emissions rates and fuel savings. That is, for the autonomous truck platoons, the percent emissions reductions were assumed to be equal to the percent fuel savings.

The performance measures were calculated for all 14 scenarios. The results and discussion on these measures are included in the next chapter.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter consists of four sections. In the first section, the results of the traffic assignments are presented. The second section is the performance measurement section, which demonstrates how the traffic assignment results were utilized to gather information related to safety, economy, congestion, and emissions. The third section discusses the sensitivity analyses that were carried out. The fourth section demonstrates how the modeling and performance measurement tool can be applied in a planning context by way of a scenario planning framework in which scenario consequences are used to guide policy development.

4.1 Traffic Assignment Results and Discussion

The traffic assignment results include truck volume, passenger car equivalents, volume to capacity ratio, travel time, speed, vehicle miles traveled, and vehicle hours traveled. TransCAD software was used to obtain these results for each link. The traffic assignment results in this section are provided as totals or averages over the links of interest – either the segment on which the ATP-only lane is implemented (which is hereafter referred to as the “dedicated lane segment”) or the length of the study corridor. For each result category, a brief description of its meaning is included. This description is followed by a series of selected figures and tables, as well as a discussion, which summarize the results.

4.1.1 Truck Volume

Truck volume, or the number of trucks, was estimated using TransCAD’s multi-class assignment, and reported as the number of trucks by truck type as well as the total number of trucks. Table 4.1 shows the average number of trucks on the dedicated lane segment. The number of trucks is very similar in all 14 scenarios.

Figure 4.1 and Figure 4.2 show the distribution of trucks by truck type along the dedicated lane segment. As demonstrated in Figure 4.1, in the non-ATP scenarios, single unit trucks (SU) make up 67% of trucks, followed by tractor plus semitrailer combinations (CS), which make up 25% of trucks. In the ATP scenarios, these two truck types remain

the most common truck types, with a fair amount of them traveling in platoons. A combined 77% of the trucks in ATP scenarios are SU or CS trucks that do not meet the 200 mile OD distance threshold for platooning and thus, travel individually. 15% of the trucks in the ATP scenarios are platoons of either three or five trucks. The remaining trucks are truck plus trailer combinations (TT) and tractor plus double trailer combinations (CD). Tractor plus triple trailer combinations (CT) are not included since those trucks do not travel on the study corridor.

Table 4.1: Average Number of Trucks on the Dedicated Lane Segment

Scenario	Total
1	3995
2	3994
3	4008
4	4007
5	4008
6	4007
7	4007
8	4001
9	4007
10	4001
11	4008
12	4009
13	4008
14	4009

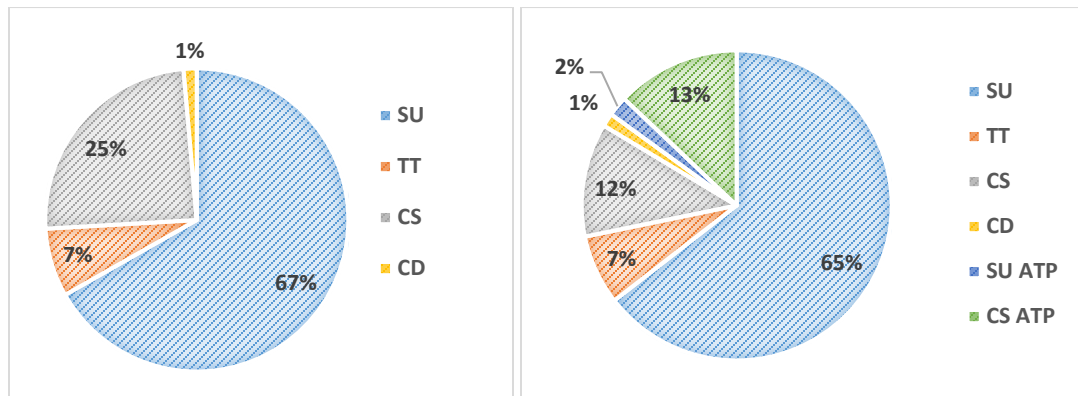


Figure 4.1: Truck Type Distribution for Non-ATP Scenarios (L)

Figure 4.2: Truck Type Distribution for ATP Scenarios (R)

4.1.2 Passenger Car Equivalents

Passenger car equivalents (PCE) is a measure used in traffic analyses to convert a mixed vehicle class volume to an equivalent passenger car volume. It is used to determine the effect of traffic on the operating efficiency of the roadway facility. Figure 4.3 shows the average truck PCEs along the links of the study corridor.

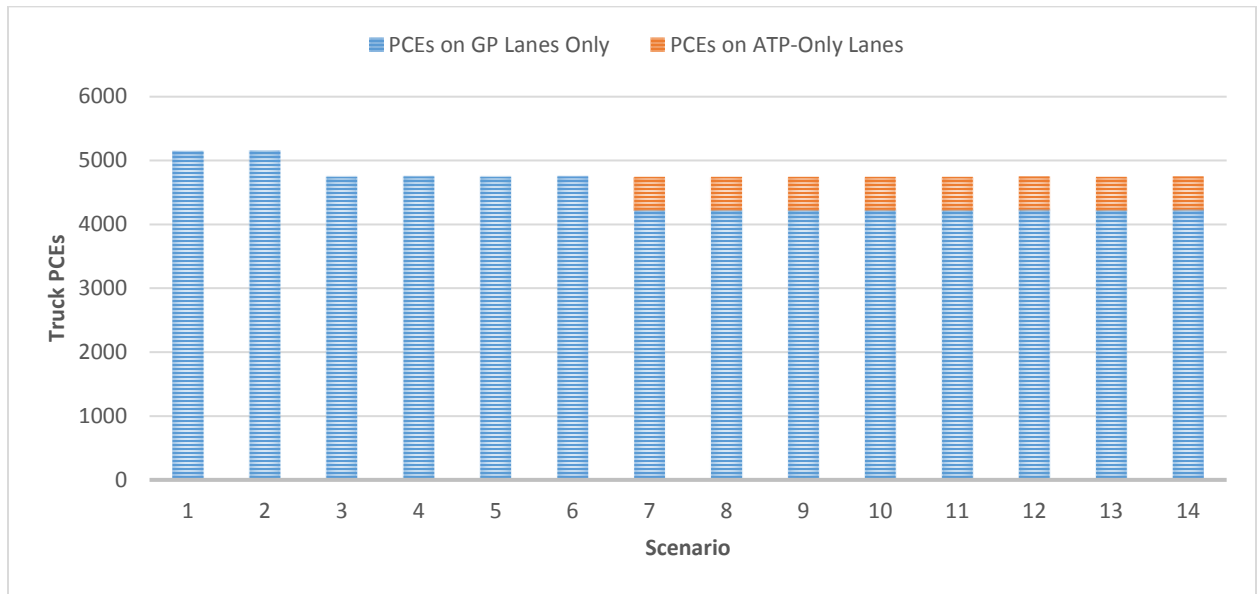


Figure 4.3: Average Truck Passenger Car Equivalents on Study Corridor

While the scenarios maintain about the same number of trucks on the corridor (see Section 4.1.1), Scenarios 3 to 14 have a smaller amount of PCEs compared to Scenarios 1 and 2 because of the assumed PCE-reducing benefits attributed to the ATP technology. The PCEs between the ATP scenarios vary only slightly. However, for a given project (ATP-only lane using existing or new capacity) and K-factor, the three-truck ATP scenario and the five-truck ATP scenario produce the same results. For example, both Scenarios 12 and 14 result in 1014 PCEs. This is due to both scenarios having the same number of trucks traveling in platoons and the PCE reduction factor being the same for three-truck and five-truck ATPs. This consistency in results, with the exception of minor differences in rounding, holds true for the other traffic assignment areas.

4.1.3 Volume to Capacity Ratio

The volume to capacity (v/c) ratio is a fraction that indicates the portion of the available roadway capacity used by the vehicles on the road. To calculate the volume to capacity ratio, the hourly PCE volume of all of the vehicles (heavy trucks and passenger cars) on the road was divided by the FAF database-provided hourly capacity. Table 4.2 and Table 4.3 show the average v/c ratios along the study corridor and along the dedicated lane segment, respectively. The general purpose lane v/c ratios for the ATP scenarios (Scenarios 1 and 2) are less than the general purpose lane v/c ratios in the non-ATP scenarios (Scenarios 3 through 14), reflecting the lower PCE values in the ATP scenarios. Though the v/c ratios in the general purpose lanes for Scenarios 3 through 6 appear to be the same as those for Scenarios 11 through 14, those in the latter scenarios are slightly less. For example, the v/c ratio for Scenario 4 is 0.963 and the v/c ratio for Scenario 12 is 0.957.

Table 4.2: Average Volume to Capacity Ratio of Links along Study Corridor

Scenario	GP Lanes Only	Including ATP-Only Lanes
1	0.64	
2	1.01	
3	0.59	
4	0.96	
5	0.59	
6	0.96	
7	0.63	0.49
8	1.01	0.81
9	0.63	0.49
10	1.01	0.81
11	0.59	0.49
12	0.96	0.81
13	0.59	0.49
14	0.96	0.81

For a given scenario, the average v/c ratio for ATPs (those that travel on ATP-only lanes for a portion of their trip) is always lower than the average v/c ratio on the general purpose lanes. The v/c ratios for the ATP-only lane (see Table 4.3) suggest that the lane is

underutilized. The average v/c ratios experienced by the ATPs along the entire study corridor (Table 4.2) are greater than those experienced by ATPs along the dedicated lane segment (Table 4.3), since the average v/c ratio along the study corridor also takes into consideration the segments on which the ATPs have to operate in mixed traffic.

Table 4.3: Average Volume to Capacity Ratio of Links along Dedicated Lane Segment

Scenario	GP Lanes	ATP-Only Lane
1	0.79	
2	1.10	
3	0.76	
4	1.07	
5	0.76	
6	1.07	
7	0.95	0.17
8	1.37	0.17
9	0.95	0.17
10	1.37	0.17
11	0.72	0.17
12	1.03	0.17
13	0.72	0.17
14	1.03	0.17

4.1.4 Travel Time and Speed

Travel time is the time, in hours, that it takes for a vehicle to cover a specified distance under given conditions. The travel time is calculated in TransCAD as the BPR function which uses the v/c ratio, and alpha and beta parameters, as indicated in Chapter 3, as inputs. While reading this section, and other sections that present the results for travel time-dependent measures, the impact that alpha and beta parameters have on the results should be kept in mind. Even though the parameters used here are close to the default values for the BPR function, they are lower than the average of the alpha and beta parameters used by large MPOs (Cambridge Systematics Inc. et al. 2012). Accordingly, the results underestimate the effect that congestion has on system performance.

Figure 4.4 shows the travel time for a single vehicle on the dedicated lane segment for each scenario. As illustrated in the figure, the shortest travel time is experienced by the ATPs on the ATP-only lane, while the longest travel time is experienced by unequipped vehicles in the general purpose (GP) lanes after one lane of capacity in each direction is converted to an ATP-only lane (Scenarios 7 through 10). While the free flow travel time is about 37 minutes, the longest travel time, seen in Scenarios 8 and 10, is close to 67 minutes. Also, and as expected, the travel times for the 2% passenger car K-factor scenarios (all odd numbered scenarios) are less than the travel times for the comparable at-capacity (adjusted 8% K-factor) scenarios.

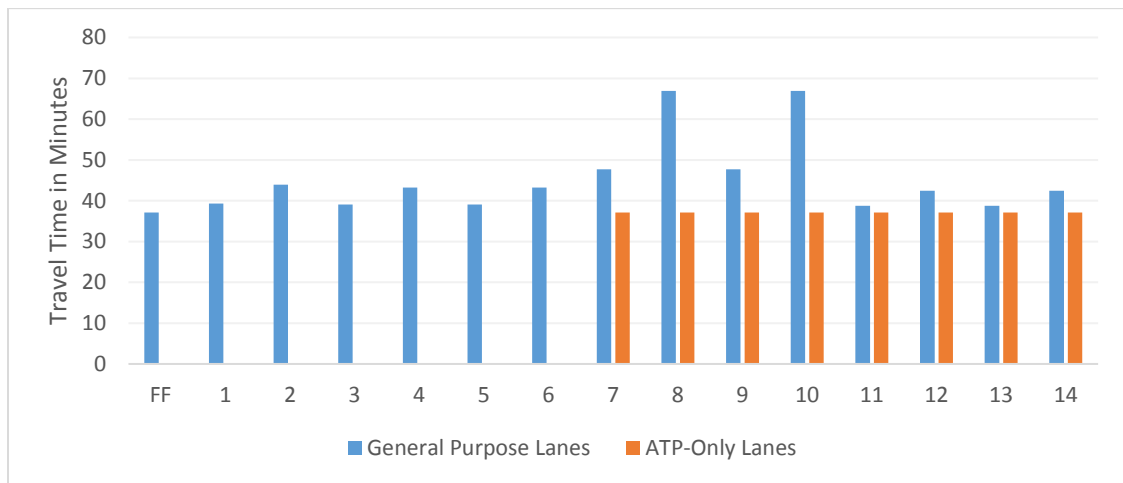


Figure 4.4: Travel Time for a Single Vehicle on Dedicated Lane Segment

Speed, which is given in miles per hour, is determined by travel time and distance. For a given link, the speed is the same for all classes of vehicles. The exception to this is the ATPs traveling on the ATP-only lane, which has a speed that is different from that of the general purpose lanes. As shown in Table 4.4, the slowest average speed is about 36 mph, while average speeds on the ATP-only lane are approximately at the specified free flow speed, or 65 mph. In Scenarios 8 and 10, though, the range and standard deviation of the speeds on the general purpose lanes are 54 mph and about 9 mph, respectively, with speeds as low as 2 mph.

Table 4.4: Average Speed along Dedicated Lane Segment

Scenario	GP Lanes	ATP-Only Lanes
FF	65.0	
1	61.3	
2	54.9	
3	61.8	
4	55.8	
5	61.8	
6	55.8	
7	50.6	65.0
8	36.1	65.0
9	50.6	65.0
10	36.1	65.0
11	62.3	65.0
12	56.9	65.0
13	62.3	65.0
14	56.9	65.0

4.1.5 Vehicle Miles Traveled and Vehicle Hours Traveled

Vehicle miles traveled (VMT) is the total number of miles traveled by all vehicles. For a single link on the network, VMT is calculated by multiplying the number of vehicles on the link by the link distance. Table 4.5 shows VMT for trucks and all traffic, which includes both trucks and passenger cars. In the at-capacity scenarios, trucks make up close to 25% of the vehicles on the road, which is higher than typical truck shares. This is due to the adjustment in the passenger car preload values to attain reasonable levels of congestion. After adjusting the VMT to reflect the inclusion of passenger cars at a consistent 8% K-factor over all links, this truck share drops to 15%. Comparatively, GDOT traffic count data over the last 5 years has percent truck VMT values ranging between 8% and 17%, with current percentages along the dedicated lane segment as high as 15% (Transmetric America Inc 2015).

In all ATP scenarios, platooning trucks are responsible for 18% of the truck VMT. This equates to about 8% of the total VMT for the 2% scenarios and close to 5% of total VMT for the adjusted 8%, or “at-capacity”, scenarios.

Table 4.5: Truck and Total VMT along Study Corridor

Scenario	Truck VMT	Total VMT	Truck % of Total VMT
1	632,946	1,518,241	41.7%
2	633,234	2,585,716	24.5%
3	637,109	1,522,404	41.8%
4	637,440	2,589,922	24.6%
5	637,108	1,522,403	41.8%
6	637,398	2,589,879	24.6%
7	637,052	1,522,347	41.8%
8	637,089	2,589,571	24.6%
9	637,049	1,522,344	41.8%
10	637,047	2,589,528	24.6%
11	637,099	1,522,395	41.8%
12	637,541	2,590,023	24.6%
13	637,096	1,522,392	41.8%
14	637,499	2,589,980	24.6%

Vehicle hours traveled (VHT) is the total number of hours traveled by all vehicles. Similar to VMT, VHT is calculated for a single link on the network by multiplying by the number of vehicles on the link by the travel time along that link. Table 4.6 shows the vehicle hours traveled by trucks and total traffic. The truck percent of total VHT is consistent with that of the truck percent of total VMT.

Table 4.6: Truck and Total VHT along Study Corridor

Scenario	Truck VHT	Total VHT	Truck % of Total VHT
1	10,119	24,257	41.7%
2	11,045	44,824	24.6%
3	10,131	24,202	41.9%
4	10,959	44,277	24.8%
5	10,131	24,202	41.9%
6	10,959	44,276	24.8%
7	10,709	25,679	41.7%
8	12,435	49,749	25.0%
9	10,709	25,679	41.7%
10	12,435	49,749	25.0%
11	10,093	24,128	41.8%
12	10,855	44,012	24.7%
13	10,093	24,128	41.8%
14	10,854	44,011	24.7%

4.2 Performance Measurement Results and Discussion

These above described traffic assignment results, along with network information (i.e., distance) and technological and operational data (i.e., labor costs, fuel savings, emissions reduction potentials), were used to calculate performance measures. The following sections present performance measures for the areas of safety, economy, congestion, and emissions.

4.2.1 Safety

As mentioned in Chapter 3 of this dissertation, the safety performance measures were considered qualitatively, so calculations in this area were not carried out. The decision to assess safety from a more qualitative stance was largely based on lack of evidence on safety benefits that will be realized as a result of the trucks platooning on highway environments.

Examples of safety performance measures that may be used are number of truck-involved crashes and number of truck-involved crashes per truck vehicle miles traveled.

- **Number of truck-involved crashes** – the number of crashes on the study corridor in which one or more trucks are involved. This measure can be obtained by using truck crash rates (i.e., truck-involved crashes per truck VMT times truck VMT). It can also be obtained using the number of total crashes and the percent of crashes involving trucks based on past data.
- **Number of truck-involved crashes per truck VMT** – annual number of crashes on the analysis corridor involving trucks divided by the annual truck vehicle miles traveled on the study corridor. The measure, which is the truck crash rate, can be calculated by dividing the number of truck-involved crashes by truck vehicle miles traveled.

In order to incorporate the benefits of the technology, the crash rate or number of crashes may be assumed to be a certain percent less for the ATP scenarios as compared to the non-ATP scenarios. There are some estimates in the literature about what this percent reduction may be. For example, there are claims that self-driving cars, at 10% market penetration, will be 50% safer than non-autonomous vehicles and 90% safer at 90% market

penetration (Fagnant and Kockelman 2013). According to the Insurance Institute for Highway Safety, nearly a third of all crashes would be prevented if all vehicles were equipped with adaptive headlights, blind-spot assistance, forward collision warning, and lane-departure warning (Insurance Institute for Highway Safety, 2012). While these and other estimates vary greatly, it is well understood that the safety benefits will be dependent on technology along with the technology market penetration. Differing from current vehicles on the road, safety will also have to be considered as it pertains to system reliability and cyber security. As more testing is carried out, the safety benefits of the technology will become clearer.

4.2.2 Economy

Truck Operating Costs

There are close to 3,000 OD pairs in the model of which a substantial number of trucks (at least one truck per day on average) use some portion of the study corridor. A single OD pair was chosen to demonstrate the truck operating costs that were calculated. The OD pair chosen was Birmingham, AL to Greenville, SC, which has an origin to destination distance of about 293 miles. This OD pair was chosen because it has substantial traffic, including ATP traffic, on the corridor and it takes a route on which the dedicated lane segment is a part of. Table 4.7 shows the truck operating cost for a single unit truck and a tractor plus semitrailer combination, traveling individually and traveling as a part of an ATP. The OD costs for all trucks vary between \$360 and \$434. These costs equate to an average of \$1.25/mile for unequipped SU trucks and \$1.42/mile for unequipped CS trucks. For ATP SU and CS trucks, the average costs per mile are \$1.23 and \$1.37, respectively.

The differences in these costs can be attributed to four main factors: congestion level (i.e., passenger car K-factor), project, truck type, and technology. As expected, the costs in the at-capacity scenarios are higher than the costs in the corresponding 2% K-factor scenarios because of the higher levels of congestion in the at-capacity scenarios. The difference is not very large, however. This brings into question the extent of the benefits of the technology. The SU benefits seen from platooning versus traveling separately range from 1% to slightly over 5%. The 5% benefit is seen in Scenarios 8 and 10 when the

unequipped vehicles have to travel in increased congestion exacerbated by the decreased capacity along the dedicated lane segment. Consequently, Scenarios 8 and 10 are also the scenarios for which the non-ATP costs are the highest. For CS trucks, the cost savings benefits are slightly higher (between 2% and 8% cost savings), given the lower cost of technology assumed for these trucks as compared to the SU technology costs. The cost of ATPs remains the same throughout the scenarios, with the exception of the mixed traffic scenarios in which there is a high level of congestion.

Table 4.7: OD Truck Operating Costs for a Single Truck Traveling from Birmingham, AL to Greenville, SC

SCENARIO	SU	CS	SU ATP	CS ATP
1	\$363	\$410		
2	\$364	\$415		
3, 5	\$363	\$410	\$360	\$400
4, 6	\$364	\$414	\$361	\$404
7, 9	\$369	\$418	\$360	\$400
8, 10	\$379	\$434	\$360	\$400
11, 13	\$363	\$410	\$360	\$400
12, 14	\$364	\$413	\$360	\$400

If the technology costs are not considered, the savings are slightly greater. For a 293-mile trip, the technology costs are approximately \$8.85 and \$5.25 for SU and CS trucks operating in an ATP. Accordingly, if only costs savings attained through reduced fuel consumption and reduced capacity in the dedicated lane are considered, the SU truck and CS truck operating in an ATP receive as much as 8% and 9% savings, respectively. Regarding truck type, the cost of operating an SU truck is always lower than the cost of operating a CS truck. This is expected, (despite the higher technology costs for SU trucks), because of SU trucks weighing less on average and the fuel efficiency of the SU trucks being slightly higher. For all scenarios, the difference in SU trucking costs and CS trucking costs ranges from 11% to 14%.

Cost of Congestion for Trucking Industry

The cost of congestion was obtained by calculating the difference between the operating cost and free flow cost and multiplying that by the number of trucks. Figure 4.5 shows the total hourly cost of congestion on the dedicated lane segment for the at-capacity scenarios. As illustrated, the cost of congestion is highest in Scenarios 8 and 10. Removing a general purpose lane increases costs for all vehicles that are not traveling in an ATP. For trucking in particular, the cost increases are attributed to labor and fuel. The cost of congestion is lowest in Scenarios 12 and 14. This is due to the added lane. Both ATP and non-ATP traffic experience increased capacity, and lesser delays, in return.

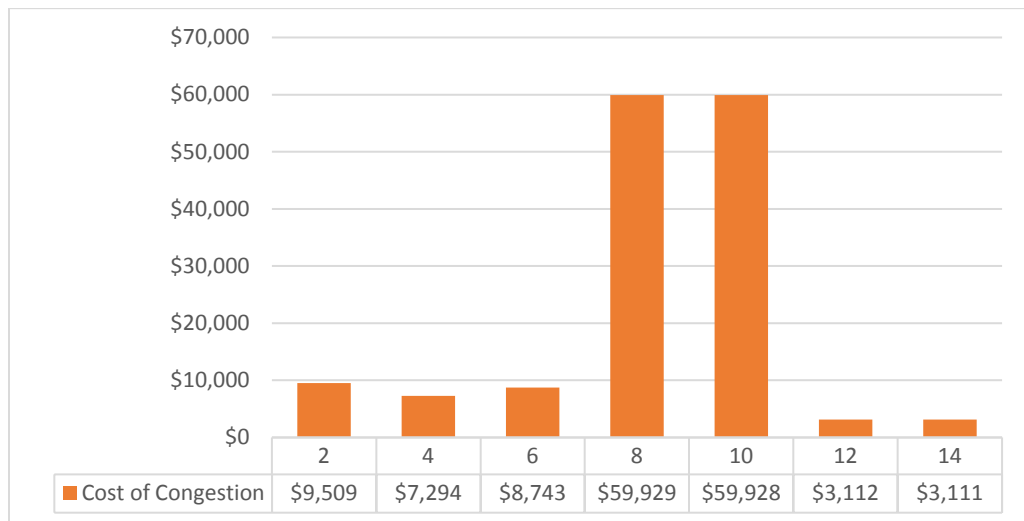


Figure 4.5: Peak Hour Cost of Congestion on Dedicated Lane Segment

The values presented in Figure 4.5 are solely based on truck operating costs. However, these are not the only costs that the trucking industry has to take into consideration. Hence, additional costs associated with time spent in traffic can be captured through the concept of value of time. The value to time component provides a more complete picture of the trucking costs and can be used as a way to assess the impact of travel time delay and unreliability for individual trucks. As mentioned by the Federal Highway Administration (Federal Highway Administration 2005): “*Research on the*

trucking industry shows that shippers and carriers value transit time at \$25 to \$200 per hour, depending on the product being carried. Unexpected delays can increase that value by 50 to 250 percent. Timely, reliable goods movement allows businesses to reduce manufacturing and inventory costs and to improve responsiveness to rapidly changing markets and consumer desires.”

There have been a number of efforts to include delay related costs that are not captured solely in the operating costs (see Southworth 2016). One approach to estimating a generalized transportation cost is to add travel time unreliability costs to operating costs:

transportation costs

$$= \text{operating costs} + (\text{VOTR} * \text{TTR} * \text{per hour operating cost})$$

Equation 4.1: O&M plus Travel Time Variability Costs

Here, value of time reliability (VOTR) refers to “the value of the on-time vehicle arrival (un)reliability” (Southworth 2016) and travel time reliability (TTR) is equated to the standard deviation of time as defined by Black, Fearon, and Gilliam (2009). Assuming a value of 1.6 for VOTR, applying Equation 4.1 to Scenario 8 results in percent differences in non-ATP and ATP transportation costs along the dedicated lane segment of 36% and 43% for SU and CS trucks, respectively. For Scenario 12, in which a lane is added, providing travel time reductions for all traffic (in the case that there is not a rebound in travel demand), these benefits are between 3% and 9%. The cost of delay is not as significant in the new capacity scenarios because travel time on the ATP-only lane does not differ much from travel time on the general purpose lane. This topic of value of time is discussed in more detail, with empirically derived valuations from past freight studies, in Southworth and Smith (2016).

Similar to the cost of delay for trucks, there is a value of time associated with trips made by passenger cars. Like the non-ATP trucks, the passenger cars only benefit from the removal of trucks from the general purpose lanes, and in the cases in which a lane is taken away, the passenger cars experience added delay.

4.2.2 Congestion

The congestion measures include peak hour travel time, travel time index, and the difference in the travel time on the dedicated lanes and ATP-only lane. These first two measures call for peak hour travel time. The at-capacity scenarios are used here to denote peak hour travel time.

Peak Hour Travel Time

Similar to Figure 4.4 in the traffic assignment results section, Figure 4.6 presents the travel time, but only for select scenarios. Regarding travel time on the general purpose lanes, the travel times experienced in the non-ATP at-capacity scenario (Scenario 2) and the ATP in mixed traffic at-capacity scenarios (Scenarios 4 and 6) are about the same. The travel times in Scenarios 12 and 14 are only about one minute less. This suggests that the travel time impacts associated with the technology as simulated are modest at best, even where an extra lane is added and dedicated to truck platooning. Scenarios 8 and 10 have the longest travel time. The travel time on the ATP-only lane remains the same in all scenarios.

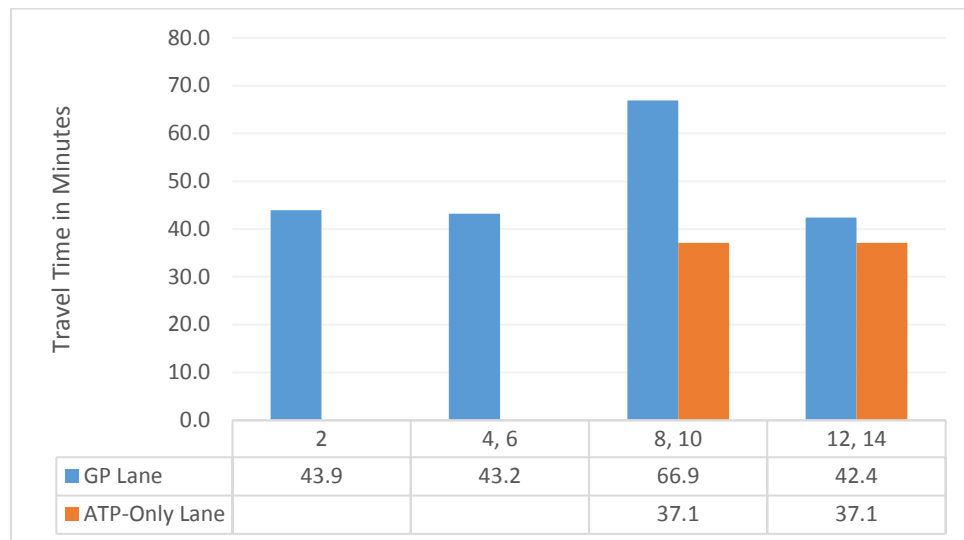


Figure 4.6: Truck Peak Hour Travel Time on Dedicated Lane Segment

Travel Time Index

The travel time index (TTI) is defined as the ratio of peak hour travel time to free flow travel time. For selected scenarios, TTI values corresponding to travel along the dedicated lane segment are presented in Table 4.8. A TTI of 1 indicates that the travel time is the same as the free flow time. A TTI of 1.8 for Scenarios 8 and 10 indicate that the travel time is 80% longer than the travel time in free flow conditions. These TTI values are consistent with the travel times above, and reflect the impact of scenario characteristics on travel time.

Table 4.8: Travel Time Index along the Dedicated Lane Segment

Scenario	GP Lane TTI	ATP-Only Lane TTI
2	1.18	
4, 6	1.16	
8, 10	1.80	1.00
12, 14	1.14	1.00

Difference in Average Travel Time

This measure looks at the difference in the average travel time for ATPs on the ATP-only lane and the average travel time for trucks in the general purpose lanes. The difference is based on the travel time along the dedicated lane segment. In all cases, the difference is positive, indicating that the travel time on the ATP-only lane is always shorter than the travel time in the general purpose lanes. As illustrated in Figure 4.7, the time difference ranges from 1.6 minutes to 29.8 minutes. To place these results into a more meaningful context and tie them back to travel time and travel time index, it should take about 37 minutes, traveling at 65 mph, to travel on this segment. An additional 29.8 minutes makes the trip about 67 minutes, an 80% increase from free flow speed.

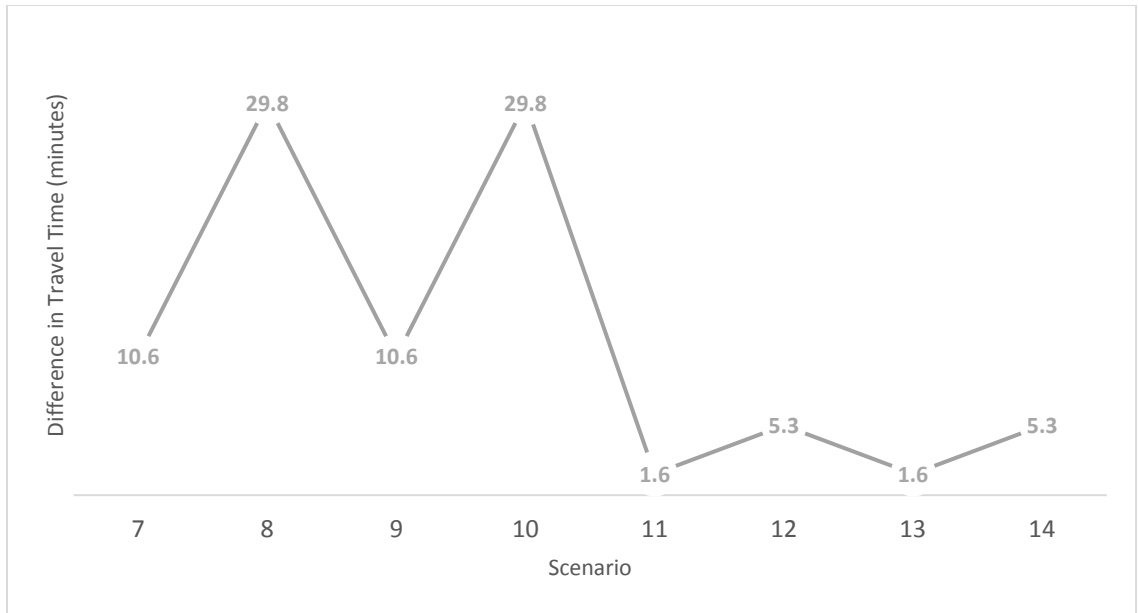


Figure 4.7: Travel Time Difference between ATP Trucks and Non-ATP Vehicles on the Dedicated Lane Segment

4.2.4 GHG, PM_{2.5}, and NO_x Emissions

Total Truck Emissions

This measure estimates the peak hour emissions from trucks along the dedicated lane segment. Table 4.9 shows emissions for CO₂ equivalents, PM_{2.5}, and NO_x for each at-capacity scenario. The emissions were obtained using 2040 emissions rates from EPA’s Motor Vehicle Emission Simulator (MOVES) (Liu et al. 2016; U.S. Environmental Protection Agency 2014)

The emissions are generally consistent with the other results presented thus far. For example, the emissions are greatest in Scenarios 8 and 10 in which there is a significant level of congestion. Aside from Scenarios 8 and 10, the other ATP scenarios show a decrease in emissions when compared with Scenario 2. A result that is less intuitive is that the emissions in Scenarios 12 and 14 are greater than the emissions in Scenarios 4 and 6. This is likely associated with the lower speeds in Scenarios 4 and 6 being more fuel efficient than those in Scenarios 12 and 14. This and similar results may suggest a need to adjust the alpha and beta parameters in the BPR function to produce travel times, and

subsequently speeds, that are more reflective of the high v/c ratios. This is discussed more in Chapter 5.

Table 4.9: Truck Emissions on Dedicated Lane Segment

Scenario	Truck CO ₂ eq. (metric tons)	Truck PM _{2.5} (g)	Truck NO _x (g)
2	165.8	1,707.6	110,931.6
4, 6	162.7	1,673.1	108,758.7
8, 10	183.3	1,849.5	121,388.2
12, 14	164.0	1,657.4	109,248.3

Regarding the inputs, assumptions regarding emissions rates and the emissions reduction potential of the technology may also change these results. Nevertheless, the emissions rates remained consistent throughout all of the scenarios, allowing for insight into the potential benefits of the technology.

Trucking Industry Percent Contribution to Total Emissions

Another metric of interest is how much of the total emissions the trucking industry is responsible for. Table 4.10 shows these values as estimated from the results in the traffic assignments and emissions factors from MOVES.

Table 4.10: Percent of Total Emissions from Trucks on Dedicated Lane Segment

Scenario	CO ₂ eq.	PM _{2.5}	NO _x
2	64.4%	64.1%	92.5%
4,6	64.0%	63.5%	92.2%
8, 10	65.2%	64.7%	93.7%
12, 14	64.2%	63.2%	92.0%

This small difference in the percentages between Scenario 2 and the ATP scenarios is due to the fact that the autonomous truck platoons make up a small portion of the traffic in the scenarios. It is expected that, with the same distribution of trucks and passenger cars, the difference between the portions of emissions from trucks in the non-ATP scenarios versus the ATP scenarios would increase more if the market share of the technology was increased.

Furthermore, the portions of emissions from trucks are higher than the portion of VMT that trucks represent in the at-capacity scenarios. If the number of passenger cars is again changed to reflect a consistent 8% K-factor on all links, these values drop slightly. In general, though, trucks represent a much larger percent of emissions than their percent of VMT. The breakdown of nationwide GHG emissions by transportation mode can be used to explain this situation. Of the GHG emissions from light duty vehicle and freight trucks, freight trucks make up 24% of the emissions (USDOT Center for Climate Change and Environmental Forecasting and Cambridge Systematics Inc. 2010), while only making up close to 13% of light duty vehicle and heavy truck VMT in the US (Bureau of Transportation Statistics 2016).

Percent Difference in Emissions from an n-Truck Platoon vs. n Trucks Traveling Separately

As it pertains to the emissions benefits of ATP technology, it is helpful to know the difference in emissions by trucks traveling separately versus trucks traveling in a platoon. Table 4.11 shows this measure for both SU and CS trucks for the at-capacity scenarios. The percent differences range from 0.9% to 9.6%. In Scenarios 4 and 6, the percent differences for SU and CS trucks are consistent across energy consumption and emission type. This is attributed to the non-ATP and ATP trucks operating at the same speeds. In the other scenarios, in which non-ATP and ATP trucks travel at different speeds, percent difference in emissions for SU trucks is still fairly consistent across emission type, suggesting that, for SU trucks, the emission types react similarly to the differences in speed experienced in those scenarios. For the CS trucks, however, the very high levels of congestion in Scenarios 8 and 10 result in a much higher percent difference for PM_{2.5} as compared to fuel consumption, NO_x, and CO₂ equivalents.

Table 4.11: Percent Difference in Emissions between non-ATP and ATP Trucks along Dedicated Lane Segment

	Scenarios 4 and 6		Scenarios 8 and 10		Scenarios 12 and 14	
	SU vs. SU ATP	CS vs. CS ATP	SU vs. SU ATP	CS vs. CS ATP	SU vs. SU ATP	CS vs. CS ATP
Energy Consumption	-2.4%	-9.6%	-8.2%	-2.6%	-3.2%	-0.9%
NO_x	-2.4%	-9.5%	-8.5%	-3.7%	-3.6%	-1.4%
PM_{2.5}	-2.4%	-9.5%	-8.3%	-8.7%	-4.2%	-2.9%
CO₂ eq.	-2.4%	-9.6%	-8.2%	-2.6%	-3.2%	-0.9%

While platooning can potentially reduce truck emissions, as demonstrated in Table 4.11, the technology, in combination with the dedicated lanes, could potentially cause more trucks to travel during a time in which emissions rates are higher. Currently, a significant percent of trucks moves when car traffic is lowest. This is typically at night when temperatures are lower. Being able to avoid the day time congestion by traveling in the dedicated lanes could shift more trucks to day time movement. In certain conditions, such as very hot or very cold weather, emission rates can be higher (United States Environmental Protection Agency Office of Transportation and Air Quality 2008). So the trucks shifting to day time travel, during the summer months, could result in higher emissions rates, either increasing total emissions or offsetting some of the emissions benefits than would be seen if the time-of-day pattern of truck movement did not change.

Not all of the results are included in these sections. Those that are included provide a good illustration of the differences in the scenarios. Overall, the results are logical; there was a number of trends that were expected as a result of the various scenario dimensions, and were substantiated by the results. There were also results that were less intuitive. It is important to keep in mind, though, that the results are based on very specific assumptions. Changing these assumptions could significantly change the results. Accordingly, the next section attempts to show the sensitivity of some of the areas in which assumptions were made.

4.3 Sensitivity Analysis

The scenarios developed for this dissertation show a wide range of results of the potential costs and benefits associated with truck platooning technology. In order to get a better idea of the impact of the scenario dimensions and the associated assumptions, a sensitivity analysis was carried out for four areas: K-factor, platoon OD distance requirement, market share, and number of drivers. The variation in these dimensions and the impact of these variations are discussed in this section.

4.2.3 8% K-factor for Passenger Preload

As mentioned in Chapter 3 of this dissertation, an 8% K-factor for passenger cars on all links resulted in unrealistic traffic volumes and congestion levels. These results are nonetheless insightful, as they show the sensitivity of the model to extreme congestion (a condition that is forecast for the I-85/I-285 corridor by the FAF Version 3 forecasts for 2040). These results also help to explain why the adjusted 8% K-factor, or “at-capacity”, approach was taken. While the PCEs and number of trucks did not change much across scenarios, despite the high level of congestion, the impact of the added congestion was clear. Figure 4.8 shows the travel times for Scenarios 2, 4, 6, 12, and 14 (the 8% K-factor sensitivity analysis was not carried out for Scenarios 8 and 10 since these scenarios already experience very high levels of congestion). The travel times for the 8% K-factor scenarios are over 2.5 times the travel time for the at-capacity scenarios. This equates to between 159% and 173% increase in travel time from the at-capacity scenario travel times and as much as a 223% increase over the free flow travel time.

Along with this increase in travel time, travel speeds decrease, truck vehicle hours traveled increase, and average v/c ratios increase. Along the dedicated lane segment, in particular, the v/c ratios were between 1.9 and 1.98 and the average speeds were between 20 and 22 mph.

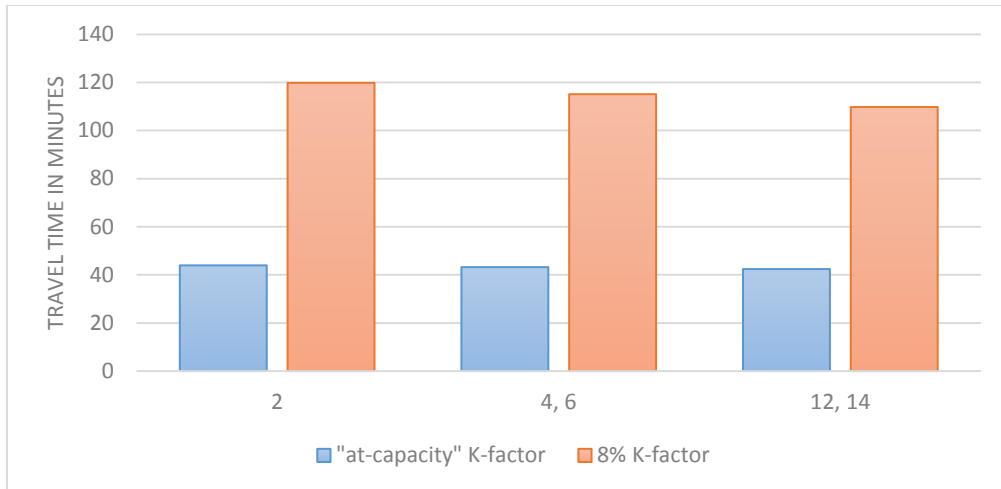


Figure 4.8: “At-capacity” vs. 8% K-Factor Travel Time for a Single Vehicle on Dedicated Lane Segment

4.2.4 OD Distance Requirement for Trucks to Platoon

One of the requirements for platooning set in this dissertation was that the trucks had to be traveling a distance of at least 200 miles. An actual distance limitation requirement, or whether or not there will even be one, is unknown.

One possibility is that all eligible trucks will platoon, suggesting a distance requirement of 0 miles. In this dissertation “eligible” refers to SU and CS trucks on the Interstate. The following observations were made as a result of allowing all SU and CS trucks to platoon for Scenarios 4 and 6:

- Slight increase in the number of trucks and vehicle miles traveled on the corridor
- 14% decrease in truck PCEs
- Decrease of 3 minutes in travel time on the dedicated lane segment; decrease in vehicle hours traveled
- Decrease in average v/c ratio on the dedicated lane segment from 1.07 to 0.93
- Average speed increase of 4 mph

Figure 4.9 shows the distribution of trucks by truck type along the dedicated lane segment. Allowing all of the SU and CS trucks on the Interstate to platoon increased the utilization of the ATP-only lane to 90% (up from 17%), with 92% of all trucks on the dedicated lane segment operating within a platoon.

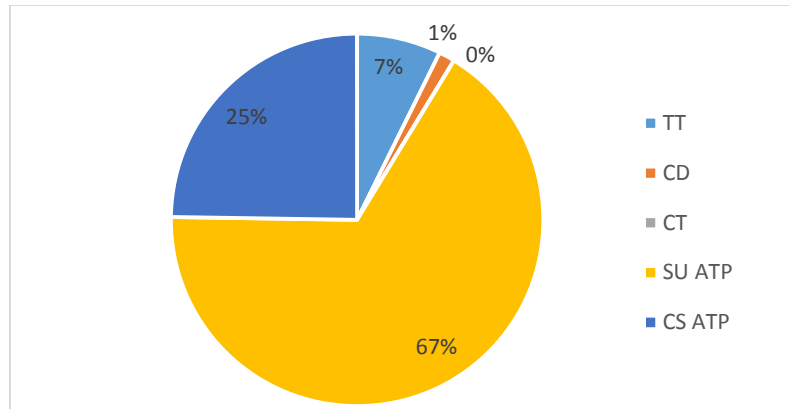


Figure 4.9: Distribution of Trucks on the Dedicated Lane Segment by Truck Type (no distance requirement for platooning)

Additionally, removing the distance requirement (i.e., distance requirement of 0 miles), can potentially reduce the trucks' percent contribution of CO₂ equivalents, PM_{2.5}, and NO_x to 62.3%, 61.2%, and 91.1%, respectively.

On the other side of this sensitivity analysis is a distance requirement of 500 miles to platoon. Since this distance requirement reduces the already low percent of trucks platooning on the corridor, the results of the analysis were very small (1% change). These small changes were increase in the number of PCEs, travel time, and v/c ratio, and a decrease in speed.

4.2.5 Market Share

Another variable impacting the technology's impact is how many trucks of those that are eligible, by distance and truck type, actually have the technology. Market share is considered 0% in Scenarios 1 and 2, and 100% in Scenarios 3 through 12. In addition to those market share assumptions, 50% market share was considered. 50% market share suggests that, of those SU and CS trucks with an OD distance of 200 miles or greater, only half of them will operate in platoons. Similar to the distance requirement of 500 miles, changing the market share of the technology to 50% did not change results much. Along with the lower number of platoons, there was a slight increase in PCEs, travel time, and average v/c ratio. This was expected since at 100% market share, trucks in ATPs only made up about 15% of the trucks on the corridor.

4.2.6 Number of Drivers in a Platoon

The last sensitivity analysis area was the number of drivers required to operate the platoon. Scenarios 3 through 14 assume that a driver is required in each truck. Allowing some of the trucks to operate without a driver would significantly reduce trucking costs while also helping to alleviate driver shortage issues. Table 4.12 shows the SU and CS OD costs for trucks traveling from Birmingham, AL to Greenville, SC. These costs result in up to 15% savings.

Table 4.12: Scenario 14 OD Costs - Three Drivers in a Five-Truck Platoon

SU	CS	SU ATP	CS ATP	SU % DIFF	CS % DIFF
\$ 360.23	\$ 409.75	\$ 309.76	\$ 349.95	-14%	-15%

While in the other results, the three- and five- truck platoon produce the same values, the OD costs in this sensitivity analysis are different in the two cases since labor costs are reduced by different factors. So instead of 15% savings, the three-truck ATP scenarios result in about 11% costs savings.

The results from the scenarios, including those from the sensitivity analysis, should be analyzed, keeping in mind that the problem evaluated in this dissertation does not incorporate the costs associated with the construction and maintenance of the dedicated lane. This cost component, however, is a key factor in a complete benefit-cost analysis of ATPs operating in dedicated lanes. Accordingly, this limitation should be addressed in future research and certainly in MPO and DOT efforts to assess the feasibility and potential impact of the technology. A related area of discussion that is crucial here is the need to distinguish between the benefits of the technology and the benefits that result from the separation of platoon traffic due to the implementation of the ATP-only lane. In order to see the benefits of just the technology, the results from Scenario 1 should be compared to those of Scenarios 3 and 5. Similarly, the results from Scenario 2 should be compared to results from Scenarios 4 and 6. Doing so compares the performance of the trucks with and without the technology, operating in mixed lane conditions. What the findings suggest is that, unless some of the trucks are allowed to operate without a human driver, the benefits

of the technology while operating in mixed traffic are not very high. At the same time, the case in which some of the trucks are allowed to operate without a human driver may require the equipped vehicles to be separated from the other traffic.

4.4 Scenario Planning Framework

The third and final phase of this dissertation was developed to place the modeling and performance measurement components into a planning context. To do so, a scenario planning framework was developed. This framework is based on a set of questions which are presented in Table 4.13.

Table 4.13: Overview of Scenario Planning Framework

Questions to Address (ARC, 2016)	Dissertation Phase
What future conditions or events are possible or probable?	Scenario development
What are the consequences or effects of those possible future conditions or events?	Modeling and performance measurement
What needs to be done to respond to those possible future conditions or events?	Development of policy recommendations

As shown in the table, the first question aligns with the scenario development aspect of this dissertation. The scenarios were developed considering various dimensions that are relevant to autonomous truck platoons operating on public roadways. The second question deals with modeling and performance measurement. This question seeks to identify the potential consequences associated with a given scenario. The third question pertains to the development of policy recommendations that can address those consequences. It is this third question that this section focuses on. For each scenario, it is determined how to properly respond, if at all, to the consequences by deciding what type of response the consequence calls for and developing a set of policy recommendations to respond appropriately. The categories of response that were used in this framework include “enable” and “prevent”. Having these two categories allows for simplicity while at the

same covering the spectrum of policies that can be carried out to get to the desired outcome. The consequences and the recommended policies are organized by the area of performance.

4.2.7 Safety-Related Consequences

In this dissertation, modeling and performance measurement were carried out on the assumption that the safety requirements of the technology would be addressed such that autonomous truck platooning would be allowable on public roads before or by 2040. Nevertheless, this section discusses several general safety-related consequences that could occur as a result of platooning on public roads. These consequences are listed in Table 4.14.

Table 4.14: Responses to Safety-Related Consequences

Consequence	Attributable to...	Response
Increased safety: reduced truck-involved crashes	Crash mitigation characteristics of technology; removal of driver error	Enable
Decreased safety: increased truck-involved crashes	Incompatibility between equipped and unequipped vehicles (i.e., cut-ins, merging conflicts)	Prevent

Increased safety: reduced truck-involved crashes

The National Highway Traffic Safety Administration (NHTSA) has already begun developing automated vehicle policy (National Highway Traffic Safety Administration 2013a). Among other aspects, the policy supports research on safety-related issues and puts forth recommendations for states regarding the safe regulation, licensing, and testing of autonomous vehicles. The research will help to ensure that all of the safety issues are explored and addressed, which will in turn provide NHTSA with the tools it needs to establish standards for these vehicles once they become commercially available. Policy proposal recommendations may be developed to complement and extend those existing policies. For example:

- **The Federal Government should develop safety standards for trucks equipped with ATP technology to meet before being allowed to operate on public roadways.** These standards should be integrated into the National Highway Traffic Safety Administration's Federal Motor Vehicle Safety Standards, thus representing minimum safety performance requirements that the trucks must meet. These minimum requirements should be demonstrated through equipment inspection and compliance testing. Testing environments should reflect the environment in which the trucks would operate (in dedicated lanes or in mixed traffic with unequipped vehicles, for example).
- **The Federal Government should provide incentives in the form of technology subsidies for autonomous and connected vehicle technology for trucks.** The subsidies should be provided with the intent of increasing the market share, i.e., the portion of the nationwide truck fleet with the technology. Increased market share of AV/CV technology should, in turn, result in greater safety benefits. Given the uncertainty of this cause and effect relationship, research should be carried out, in conjunction with this policy, to gain more insight into how the incremental market share of the technology will actually impact the safety benefits.

Decreased safety: increased truck-involved crashes

In order for the technology to be approved to operate on public roads, it will need to be as safe, if not safer, than the level of safety offered by current truck technology. An unintended consequence of the ATPs operating on public roadways would be an increase in truck-involved crashes. Several policies should be considered to prevent an increase in crashes while still making provisions for other benefits of the technology to be realized. For example:

- **State legislatures should develop protocol for ATPs transitioning from completely manned to partially or fully driverless.** States should initially require a driver in the truck at all times during operation. This is already the case in state bills regarding the testing of autonomous vehicles. Having a driver, or operator, in the truck would add another layer of safety in the case that the technology fails. After consistent demonstration of increased safety, the state should consider

allowing some of the trucks in the platoon to be operated without a driver. Determining what “consistent” entails may call for a requirement for carriers to report when an operator has had to intervene in a safety critical situation.

- **State transportation agencies should require the ATPs to operate on dedicated lanes.** Dedicated lanes for truck platooning would add an additional layer of safety by separating ATP traffic from other traffic. If the operation of ATPs has been restricted to dedicated lanes, additional policy should be drafted to call for state DOTs or metropolitan planning organizations to carry out feasibility studies for a dedicated lane that uses either existing or new capacity.
- **NHTSA should mandate minimum connected vehicle technology for all new cars.** Such technology should, at the least, allow the vehicles to recognize the presence of other vehicles. This mandate would, over time, prevent conflicts that would otherwise happen in a mixed environment (i.e., one that includes both equipped and unequipped vehicles). As mentioned in Chapter 3 of this dissertation, NHTSA currently has a proposed rulemaking for vehicle-to-vehicle communication for light vehicles (National Highway Traffic Safety Administration 2014). This could be applied to heavy vehicles as well.

4.2.8 Economic-Related Consequences

In a number of scenarios, the results implied potential costs savings for all trucks. In Scenarios 7 through 10, however, unequipped trucks deal with the burden of increased costs attributed to increased delay. Table 4.15 includes the economic consequences and what they are likely attributed to.

Table 4.15: Responses to Economic-Related Consequences

Consequence	Attributable to...	Response
Decreased costs for all trucks (significant for equipped trucks, moderate for unequipped trucks)	Fuel cost benefits of the technology, more fuel efficient operating speeds, and additional capacity (see Scenarios 4/6 and 12/14)	Enable
Decreased costs for equipped trucks and increased costs for unequipped trucks	Capacity being taken away from unequipped vehicles and given to ATPs (see Scenarios 7-10)	Prevent

Decreased costs for all trucks

- Involvement from all stakeholders, both public and private, will be key in the successful implementation of ATPs. As in past legislation (MAP-21 and FAST), **the Federal Government should require USDOT to encourage state DOTs to form state freight advisory committees. The list of roles of the committees should be expanded to include: “participate in the vision for autonomous truck platoons on public roadways”**. In particular, these committees should advise state DOTs on cost-related topics including the expected monetary benefit from the technology, ways to maximize the benefit, and feasibility of a dedicated toll lane. Cost benefits for all trucks were seen in Scenarios 4, 6, 12, and 14. The advisory committee should be tasked with exploring both options represented in these scenarios: ATPs operating in mixed lanes and ATPs operating in dedicated lanes using new capacity. The cost benefits in those ATP scenarios were between 1% and 3%. These benefits are low enough to question the attractiveness of the technology. Accordingly, a more specific role of the committee should be to gain insight from the industry perspective into the likelihood of truck operators investing in the technology if doing so resulted in the percent savings demonstrated in this dissertation. In the case that a truck operator would not invest in the technology to receive 1% to 3% savings, the committee should also gain insight into what percent savings is necessary for operators to invest in the technology. Given that technology costs typically decrease over time, the necessary percent savings could be

considered alongside the costs of the technology over time to estimate the time period after initial technology deployment for which truck operators would be willing to invest. In the case of dedicated lanes using new capacity, the committee should focus its efforts on determining under what conditions the trucking industry would be willing to pay for a dedicated lane.

- **State legislatures should develop protocol for ATPs transitioning from completely manned to partially or fully driverless** (see Section 4.4.1). A significant component of the potential costs savings associated with ATPs is the opportunity for trucks in a platoon to be unmanned. Allowing unmanned trucks in the sensitivity analysis resulted in savings of up to 15%. In addition to cutting down on labor costs, allowing unmanned trucks would help to address the driver shortage and driver retention issues faced by the trucking industry. The operation of unmanned vehicles would need to be leveraged with the associated safety implications and would likely require the platoons to operate on a dedicated lane. Transitioning from fully manned to partially or fully driverless is in line with the deployment of the technology by level. Such a transition would allow for level-specific safety performance to be demonstrated to a satisfactory extent before allowing the next level of the technology to be deployed. This transition would also allow time for the market share of the technology to increase as the levels of the technology progress. State legislatures should require the agencies to develop a transition plan that specifies the safety performance criteria at each level of the technology, and once those are met, make adjustments to the operational details of the platoons as seen fit to accommodate the next level of the technology. An overall analysis should include an estimated timeline of how long it would take, through the progressive deployment of the technology, to move from cost savings of 1% and 3% to cost savings of 11% and 15%.
- **State legislatures should require state DOTs and toll road authorities to work alongside MPOs to carry out feasibility studies for ATP-only toll lanes.** All ATP-only lane scenarios resulted in decreased travel costs through the region for equipped trucks. In order for an ATP-only toll lane to be feasible, the benefits of the technology would need to outweigh the cost of paying to use the lane. The

studies would need to answer questions related to where the best place to put the lane would be, whether or not there is an option to add capacity, and how much the toll would need to be to finance the cost of constructing and maintaining the lane. Although this dissertation does not incorporate the cost of adding dedicated lanes, the results that were attained can be used to answer the following question: for each scenario, what is the per mile price range for tolling that allows the trucking industry to still receive the benefits of the platooning technology. In the Birmingham, AL to Greenville, SC OD cost example, per mile costs for unequipped CS trucks and ATP CS trucks were \$1.42 and \$1.37, respectively. So, for CS trucks using the 40-mile ATP-only lane costs would need to be less than \$0.05/mile, discounted over the entire trip, to see cost-savings benefits. It should be noted that average toll costs for the trucking industry are about \$0.023/mile (Torrey and Murray 2015).

- **States should set an ATP operating speed on the ATP-lane.** As demonstrated in the results, speeds lower than 65 mph result in greater fuel efficiency and subsequently, decreased fuel costs. Specifically, the ATPs traveled at average speeds of 55.8 mph and 65 mph in Scenarios 4 and Scenario 12, respectively. Over the dedicated lane, the fuel costs for SU and CS ATPs were about \$3.50 more in Scenario 12. This is due to 65 mph being a less fuel efficient speed and equating to less aerodynamic drag benefits (Bonnet and Fritz 2000; Lammert et al. 2014). The speed that is set should consider cost efficiency, safety, and convenience. This should also be weighed against the travel time implications.

Decreased costs to equipped trucks and increased costs to unequipped trucks

Some of the ATP-only lane scenarios, in which a lane was taken away from the general purpose lanes resulted in more congestion and increased costs for the unequipped trucks. Implementing the technology should result in a decrease in trucking costs for those trucks equipped with the technology, but not at the expense of the other trucks. Policies should be put in place to ensure that the cost of trucking for unequipped trucks either remains the same or decreases. For example:

- **The Federal Government should take measures to increase the technology market share** (see Section 4.4.1). In the scenarios explored in this dissertation, unequipped trucks were restricted to the general purpose lanes. Because of this, the unequipped trucks neither benefited from the technology nor the ATP-only lane capacity. Instead, the unequipped trucks received cost benefits from the decrease in congestion due to the trucks traveling in platoons taking up less road space and the general purpose lanes being less congested from ATPs being removed from the general purpose lane and put onto the ATP-only lane. Since the ATP-only lane scenarios showed that the ATP-only lane was underutilized, moving more trucks to the ATP-only lane would get more trucks into platoons allowing more trucks to decrease their operating costs. Doing so would require more trucks to have the technology. As demonstrated in the sensitivity analysis, one way to foster a higher market share is to not have a distance requirement to use the technology. Allowing all SU and CS trucks to platoon increased the utilization of the ATP-only lane from 17% to 92%. Other example measures to increase market share include providing technology incentives and requiring the technology to be installed on newly manufactured trucks.

4.2.9 Congestion-Related Consequences

Congestion-related consequences, which are summed up in Table 4.16, are attributed to capacity changes due to the ATP-only lane and the PCE-reducing benefits of the technology.

Table 4.16: Responses to Congestion-Related Consequences

Consequence	Attributable to...	Response
Increased congestion for unequipped vehicles and decreased congestion for equipped vehicles	Less capacity in the general purpose lanes (see Scenarios 8 and 10)	Prevent
Decreased congestion for all vehicles	PCE reducing benefits of the technology and the implementation of ATP-only lane using new capacity (see Scenarios 3-6 and 11-14)	Enable

Increased congestion for unequipped vehicles and decreased congestion for equipped vehicles

- **State DOTs in collaboration with MPOs and other subject-matter experts should develop a plan to safely introduce autonomous/connected passenger cars onto public roadways at a substantial market share.** Alongside an increased share of autonomous/connected trucks and the subsequent moving of more trucks onto the ATP-only lane (see Section 4.4.2), having autonomous/connected passenger cars operate on the public roadways would potentially further reduce congestion in the general purpose lanes. This would depend heavily on the market share and the incremental benefits that can be realized when both equipped and unequipped vehicles are operating in the general purpose lanes. In conjunction with research on autonomous/connected passenger cars, autonomous taxi systems, in particular, should be considered for an application of the technology for passenger travel, as a way to reduce the number of passenger cars on the road. While the autonomous/connected passenger cars may not technically “platoon”, the technology would allow the equipped cars to travel at shorter headways, thus increasing capacity. This is particularly useful for Scenarios 8 and 10. The plan should consider how much of a capacity increase is necessary to reduce the v/c ratio from 1.37 to a more reasonable level of congestion and how much of a capacity increase autonomous/connected passenger cars at different levels of market share can provide.
- **MPOs and local governments should be required by State legislatures to support mode shift activities in order to reduce the number of passenger cars, and subsequently the amount of congestion, on the highways.** Supporting mode shift activities should consist of various strategies including promoting rideshare programs, developing complete street policies, integrating the use of alternative modes into design guidelines, and placing more emphasis on alternative modes in short- and long-range plans. The task of shifting commodities to other modes, namely rail, may be more difficult especially given the potential of the attractiveness of the technology to shift commodities to trucks, but should still be considered. The mode shift goal should indicate the level of congestion and the

corresponding amount of traffic, for both current and desired conditions. For example, Scenarios 8 and 10 have a v/c ratio of 1.37 on the dedicated lane segment. The number of passenger cars in those scenarios on average is 13,147. In order to decrease the v/c ratio to 1.1 (the v/c ratio in Scenario 2), if only passenger cars were to be shifted to other modes, then the passenger car traffic would need to decrease by about 14%.

- **MPOs and State DOTs should develop threshold standards for ATP-only lane projects.** Threshold standards should be put in place to ensure that no “existing capacity to ATP-only lane project” potentially increases the travel time in the general purpose lane vehicles by a certain percent. The threshold standard may state that any alternative that will likely increase the v/c ratio in the general purpose lanes by a certain percent should not be considered. With regard to equity, MPOs and State DOTs may even want to consider setting a standard for the percent difference in the level of congestion in the general purpose lanes versus the level of congestion in the ATP-only lanes. For Scenarios 8 and 10, the congestion in the general purpose lanes along the dedicated lane segment correspond to a v/c ratio of 1.37 while the ATP-only lanes have a v/c ratio of 0.17. The percent difference in these two v/c ratios is 156%.

Decreased congestion for all vehicles

The mixed lane and new capacity scenarios resulted in decreased congestion for all vehicles. The decrease in congestion for the mixed lane scenarios were not as great as those of the new capacity scenarios. Nevertheless, policies should be considered to enable decreased congestion in both cases. For example:

- **The USDOT should require states to re-assess and where appropriate revise following-distance restrictions.** The exact congestion benefits of truck platooning will depend on how close the trucks travel together. Given that the optimal gap between trucks in a convoy may violate certain states’ laws regarding how close cars can travel to each other, states should review and, consequently, reduce or eliminate such restrictions for autonomous/connected vehicles, subject to demonstrated safe driving within platoon requirements. Reducing or eliminating

these restrictions would allow the trucks to operate in closely packed platoons, allowing for congestion-reducing benefits that would otherwise be unattainable. The PCE reduction benefits assumed in this dissertation pertain to a gap of about 7 meters. This gap results in truck PCE reduction benefits of about 8%. While all states do not mention a specific distance, state legislation suggests that a subjectively safe distance is enforced. Georgia law, in particular, states that “the driver of a motor vehicle shall not follow another vehicle more closely than is reasonable and prudent, having due regard for the speed of such vehicles and the traffic upon and the condition of the highway” (GA Code 40-6-49). In the case of these more subjective laws, language may be added to the code to recognize that reasonable following distances will be lower for platooning technology.

- **The USDOT should require state DOTs and MPOs to carry out feasibility studies for new-capacity ATP-only lanes.** As expected, adding a new-capacity ATP-only lane (Scenarios 11-14) resulted in the greatest congestion benefits among the scenarios simulated. However, this option of adding a new-capacity lane dedicated to equipped trucks may not be feasible in some cases. Accordingly, transportation agencies should carry out studies to help decide whether or not they should pursue the implementation of such a lane. In addition to the physical aspect of feasibility, the studies should factor in the cost of construction and maintenance and willingness of the trucking industry to pay for the lane, most likely through tolling. To complement this policy, the Federal Government should earmark funds for state DOTs and MPOs to carry out feasibility studies for truck-only lanes that can perhaps be used by all trucks for now, and subsequently by ATPs exclusively once a significant market share for platooning exists. Restricting the dedicated lane to ATPs traveling 200 miles or more resulted in a low utilization, 17%, of the lane. Even though this changed to 92% when the distance requirement was taken away, a similar issue can exist even if there is no distance requirement, but the market share is low. State DOTs and MPOs will need to consider what level of utilization is necessary for the implementation of the dedicated lane to be warranted, citing financial and equity reasons. If the ATP market share does not meet that level, State

DOTs and MPOs should consider allowing unequipped trucks, equipped but non-platooning trucks, or autonomous and connected passenger cars to also use the lane.

4.4.4 Emissions-Related Consequences

Some scenarios result in increased emissions while other scenarios result in a decrease in emissions. Table 4.17 specifies which scenarios lead to a decrease and which ones lead to an increase.

Table 4.17: Responses to Emissions-Related Consequences

Consequence	Attributable to...	Response
Decreased total truck emissions	Fuel efficiency benefits of the ATP technology (See Scenarios 3-6 and 11-14)	Enable
Increased total truck emissions	Taking away a general purpose lane (Scenarios 7-10)	Prevent

Decreased total emissions

- **As the technology rolls out, NHTSA should look into developing stricter fuel efficiency standards.** Along with these standards, NHTSA should consider allowing platooning as a way to achieve those standards. This might be carried out in conjunction with NHTSA requiring trucks to be equipped with certain connected and autonomous vehicle technology for safety reasons. While the emissions results showed that the truck percent contribution to total emissions did not decrease significantly, the technology still demonstrated emissions reducing benefits. In Scenarios 4 and 6 (ATP mixed traffic scenarios), the total truck emissions decreased by 2% from the emissions in Scenario 2 (non-ATP scenario). Furthermore, comparing an unequipped truck with an ATP truck of the same truck type, the benefits of the ATP truck resulted in nearly 10% emissions reductions. While fuel efficiency standards are often met by equipment being added to each truck, in this case, adding equipment allows for platooning, which would then lead to the increased efficiency.

Increased total emissions

- **MPOs and State DOTs should develop threshold standards for ATP-only lane projects** (see Section 4.4.3). As mentioned in relation to increased congestion levels, threshold standards should be used to prohibit projects that will potentially worsen environmental impacts, in particular, an increase in airborne emissions. Unlike the other ATP scenarios, Scenarios 8 and 10 result in an increase in total truck emissions: 10.6% increase for CO₂ equivalents, 8.3% increase for PM_{2.5}, and 9.4% increase for NO_x. If, for example, the threshold standard was set at 2% increase in truck emissions during any hour of the day (without that increase being offset during other hours), these scenarios would be eliminated from the list of alternatives. Given a concerted effort to reduce GHG and other emissions from the transportation industry, the standards may be even stricter by rejecting any project that likely increases truck emissions at all.

These above policy recommendations are not exhaustive but provide an idea of how the results from the modeling and performance measurement tool may be used. One of the key concerns with regard to developing policy for AV/CV technology is whether or not public policy should encourage the development and deployment of the technology. Equity and fairness will likely be a concern that has to be addressed in pursuing the ATP technology, especially in the case of ATP-only lanes. Here it is assumed that public policy should be used to encourage the technology - it is clear that the technology is coming. To maximize the benefits and minimize the issues that would ensue if the technology operating on public roadways was not strategically regulated, public policy is an effective tool to use. Public policy does not necessarily need to be used to speed up deployment, but at the least should be used to guide the details of how the technology gets used on public roadways. Another concern is how to decide whether or not the agencies involved are pursuing the right type of policies given the uncertainty of the technology and the potential unintended consequences.

The next chapter, Chapter 5, discusses the contributions of this dissertation. Chapter 5 also gives further insight into how the modeling and performance measurement tool and

the scenario planning framework can be used moving forward and discusses limitations and what can be done to address these limitations.

CHAPTER 5: RESEARCH CONTRIBUTIONS, LIMITATIONS, AND FUTURE WORK

5.1 Research Contributions

The work carried out as a part of this dissertation makes three main contributions to the area of transportation modeling and performance measurement as it pertains to assessing the potential impact of autonomous truck platoons operating on public roadways. These contributions are consistent with the three phases of this dissertation: 1) modeling, 2) performance measurement, and 3) planning.

In Phase 1, a modeling tool was developed. This modeling tool consists of an iteratively linked, supply-demand equilibrium-based multi-commodity and multi-vehicle class truck trip distribution and a highway traffic assignment model, requiring changes be made to the typical travel demand modeling process to capture the characteristics of platooning technology. While there have been a number of autonomous truck platoon modeling and simulation tools developed, as discussed in Chapter 2 of this dissertation, this research is one of the first efforts to modify a traditional travel demand model to simulate autonomous truck platoons on a freight-significant corridor. In order to modify the model, the technology characteristics relevant to network performance were identified, and approaches to incorporate these characteristics into the model were developed and finally implemented by adapting existing steps as well as adding new steps. Another key component of this contribution is the use of the origin user equilibrium (OUE) traffic assignment, a relatively new path-based assignment, which allows the user to specify vehicle class- and origin-specific traffic flows, and assign them to the network simultaneously, and which has yet to be explored in depth with respect to multiple truck class-based, notably platoon-inclusive, freight movements. The significance of using this particular traffic assignment for this dissertation hinges on two characteristics. One, the OUE assignment maintains route flow proportionality (a condition that suggests that vehicle class proportion on each of two alternative, equal-cost paths should be the same regardless of origin, destination, or class) as a way to deal with multiple vehicle classes. Though an assumption, this proportionality condition limits the number of alternative paths

to a more manageable, and arguably more realistic, set of options than is the case where proportionality is not maintained. This is particularly useful in the case of dedicated lane facilities, as those implemented in some of the scenarios in this dissertation. Secondly, the path-based assignment makes it easy, through TransCAD's select link analysis tool, to identify the OD flows that travel on a specific set of links in the network, in this case, the I-85/I-285 corridor in Georgia. This is useful for pulling out truck cost data, which influences the flows and speaks to the feasibility of the technology. In addition to serving as an application of the OUE assignment, the development of the model presents a new application of the FHWA's Freight Analysis Framework, which is a widely used freight database within the United States.

In Phase 2, the results from an empirical application of this model were used to assess the safety-, economic-, congestion-, and emissions-related impacts of platooning technology. While performance measurement for truck freight is commonplace and many of the performance measures used were pulled from existing studies and planning efforts from state DOTs and MPOs around the nation, this framework introduced several new performance measures that are specific to autonomous truck platooning on public roadways that will be worth considering for future planning purposes. This application of the technology also resulted in the first assessment of ATPs on the I-85/I-285 corridor in Georgia.

In Phase 3, a scenario planning framework that uses the results from the modeling and performance measurement tool to guide policy development was established. Scenario planning is growing more commonplace as a way to deal with uncertainty in areas, notably new technology, that may impact transportation planning. Furthermore, the questions that are used in the framework are quite commonly associated with the scenario planning process. As a result of applying this question-driven framework, the contribution associated with this third phase is the creation of a set of example policy recommendations, linked to simulation results, to address autonomous truck platoon technology.

5.2 Limitations

Given the objective of developing tools that can be used to assist in long-range planning efforts, and guide decision-making with regards to autonomous truck platoons operating on public roadways, there are a number of limitations that still need to be addressed. These limitations can be categorized into the areas of: (1) uncertainty about the impacts of autonomous truck platoon technology, and (2) limitations of data and analysis tools.

Given that autonomous truck platoon technology is still in the development and testing stage, there is a high level of uncertainty associated with the details of the technology as it enters widespread use. In order to address the uncertainty, a number of assumptions based on the existing literature (though very limited in some matters), were made in the following areas:

- Deployment of the technology (forecast year)
- Technology market share
- Lane operating requirements for platoons (mixed traffic vs. separated facility)
- Passenger car equivalents and capacity impacts of connected vehicles
- Fuel savings potential of the technology
- Technology cost
- Number of trucks per platoon

Both scenario planning and sensitivity analysis were used as a way to address the uncertainty. Nevertheless, it was neither possible to include every possible scenario nor to include all possible scenario dimensions. As a result, this dissertation considered neither, for example, all possible combinations of the scenario dimensions nor the inclusion of AV/CV passenger cars (even though AV/CV technology is anticipated in the near future for passenger cars as well). Ultimately, the purpose of the scenarios was to capture key characteristics of the technology and vary the details of the characteristics enough to get a reasonable range of impacts of the technology.

Limitations also existed in the data and analysis tools that were used. For one, there are a number of limitations inherent in the four step model. Within the four step model, there are limitations in static assignments. Dynamic assignments may provide a more realistic approach to measuring traffic congestion impacts, even in a long-range planning

context. However, while dynamic assignment does exist, accurate data necessary to perform dynamic assignments for heavily trafficked trucking corridors are not yet widely available. In particular, empirical data on the time of day volumes of truck origin-to-destination movements need to be developed in support of long-haul highway corridor analysis. In order to address this issue, assumptions were made in this dissertation regarding peak hour K-factors: two values (2% and 8%) were chosen to provide a reasonable range of the traffic mix in the absence of dynamic data. Changes in K-factors and other traffic assignment parameters, such as alpha and beta values and trucking costs, and performance measurement inputs such as emissions factors, could potentially change the results. The modeling and performance measurement tool developed in this dissertation is therefore viewed as sufficient for sketch planning using available data sources. However, having more detailed and accurate data on the origin-destination and timing of truck movements can shift this tool to being used for investment grade decisions.

Additionally, there are limitations inherent in the Freight Analysis Framework. FAF forecasts are an extrapolation of current trends. They do not reflect major shifts in the national economy, future capacity limitations or expansions, or changes in transportation costs and technology. Limitations in the 2040 FAF and other forecasts, though, cannot be addressed aside from applying a certain level of “reasonableness”, since there is no way to know exactly what the highway network conditions will be like in 2040. Similar to this issue is the issue of commodity flow disaggregation. In using the FAF database, there is often a need to disaggregate the flows to a smaller geographical scale to obtain more detail in the areas of interest. The method used in this dissertation begins with a particular disaggregation of FAF inter-regional flows into county-to-county movements, with county-level production and consumption activity totals projected into the future using a simple proportional fitting method based on 2040 employment and population projections; it is said to be “simple” because it assumes that the amount of commodity produced in and consumed by a county within a given region is directly proportional to the size of that county’s workforce and total population, respectively. Furthermore, these same factors are used for all commodities. This simple approach has its limitations but suffices for the future year, high level model developed in this dissertation. These forecasts and projections can

be adjusted or replaced by more sophisticated methods as more information becomes available.

5.3 Future Work

Given the limitations of this dissertation and the uncertainty associated with the technology, there are a number of opportunities for future research, especially as more information surrounding the technology becomes available. There are five main areas for which future work opportunities are proposed as discussed below.

One area pertains to using the modeling and performance measurement tool developed in this dissertation to address additional scenario dimensions and parameters. Among other options, the technology costs and potential fuel savings of the technology should be varied, a range of PCE benefits of the technology should be explored, different alpha and beta parameters should be used, and AV/CV passenger vehicle technology should be incorporated into the model. Perhaps most importantly, the cost of the ATP-only lanes should be integrated into the model. The feasibility of truck-only toll lanes is worth studying here, since the trucking industry would potentially pay for such lanes if it can get cost and time savings benefits from using them. The value of using the dedicated lanes would need to be greater than the costs of the toll. Cost feasibility research would shed light on this topic.

The existing model can also be adjusted to include additional components that are relevant to the potential impacts associated with autonomous truck platoons. For one, partially driverless truck platoons may be viewed as a close alternative to rail given the ability of the platoons to reduce trucking labor costs, while maintaining the relative convenience of highway driving. This suggests opportunities to extend the tool to handle mode choice along competitive multimodal corridors that support both a large volume of truck and rail movements. Secondly, this dissertation focuses only on the I-85/I-285 corridor in Georgia. The tool can be expanded to handle a wider, regional or national perspective that encompasses multiple, including intersecting corridors. Finally, the model can be used to simulate alternatively powered platoons – for example, electric trucks; alternative fuel trucks; and overhead, catenary systems. These three proposed research opportunities are likely to imply travel cost changes significant enough to alter the volumes

of truck freight being transported long distances, perhaps requiring a reworking of the trip generation/attraction component of the traditional four step model, or even use of a direct demand model that simultaneously solves for trip generation and trip distribution.

Another area for future research is the replicability or transferability of the approach developed in this dissertation to other data sets and other model types (i.e., dynamic traffic assignments and tour-based models). The OD flow data used in the model came from the FAF database. The usefulness of the approach developed in this dissertation may be further exemplified by being used on another database, like Global Insight's TRANSEARCH INSIGHT database. As mentioned earlier in this chapter, the use of a dynamic traffic assignment, in place of a static assignment, may be more suitable to capture a more realistic illustration of the traffic conditions. Even further, applying this approach to a tour-based model recognizes that, though trucks may have an initial origin and final destination, the total trip is composed of multiple interdependent trips. Using different datasets and models, can help to get a clearer idea of the implications of the technology. It can also allow for a more thorough investigation of the sufficiency of the tools that we have now to incorporate the ATP technology.

A fourth area is microsimulation. Microsimulation should be used in conjunction with the higher level models to consider more detailed characteristics associated with the technology that cannot be easily captured in sketch planning or other more data aggregated tools. Some examples of these detailed characteristics include the simulation of platoon merging and splitting, cars merging onto and off of the highway in the midst of autonomous truck platoon traffic, and passenger car cut-ins. Microsimulation tools would also be able to model the dynamic formation and disjoining of truck platoons (i.e., a concept in which trucks enter and exit platoons at different times).

Finally, there are opportunities for future research in the area of performance measurement. While performance measures that are specific to autonomous truck platoons were introduced in this dissertation, there are opportunities to develop additional measures. These measures should be relevant to and in line with the goals of transportation planning agencies. In particular, research in this area should consider measures that will be able to be used once the data from connected vehicle technology is available. While it is not clear how available and easily accessible the data provided by connected vehicle technology will

be, it is likely that if it does become accessible in the context of transportation planning, it could potentially change the overall approach to the assessment of current and future transportation issues and the subsequent development, selection, and prioritization of alternatives to address those issues.

Overall, this dissertation attempts to move the needle on developing tools that can be used to guide decision making as it pertains to autonomous truck platoons. Given the uncertainty associated with platooning technology, there are a number of limitations associated with this research, and hence a number of future research opportunities. As the details of platooning technology become clearer, tools such as the one developed here can help transportation planners better incorporate such technological advances into their planning process.

REFERENCES

- AASHTO. (2012). *AASHTO SCOPM MAP-21 Notice of Proposed Rule-Making Checklist (Freight)*.
- Adams, T., Ebeling, M., Gardner, R., Lindquist, P., Stewart, R., Szymkowski, T., Hecke, S., Vonderembse, M., and Wittwer, E. (2007). *Upper Midwest Freight Corridor Study - Phase II*. Columbus, OH.
- Alam, A. (2011). "Fuel-Efficient Distributed Control for Heavy Duty Vehicle Platooning." KTH Royal Institute of Technology.
- Alam, A. Al, Gattami, A., and Johansson, K. H. (2010). "An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning." *2010 13th International IEEE*, Madeira Island, Portugal.
- American Transportation Research Institute. (2012). "Freight Performance Measures." <<http://atri-online.org/2012/02/28/freight-performance-measures/>> (Aug. 5, 2016).
- ATA Technology & Maintenance Council. (2015). *Automated Driving & Platooning: Issues and Opportunities*. Arlington, VA.
- Atlanta Regional Commission. (2016a). "Forecasts." <<http://www.atlantaregional.com/info-center/forecasts>> (May 18, 2016).
- Atlanta Regional Commission. (2016b). "Congestion Management Process." <<http://www.atlantaregional.com/transportation/congestion-management-process>> (May 31, 2016).
- Atlanta Regional Commission. (2016c). "The Atlanta Region's Plan."
- ATRI. (2014). *Critical Issues in the Trucking Industry - 2014*. Arlington, VA.
- Auburn University, American Transportation Research Institute, Meritor WABCO, Peloton Technology, and Peterbilt Trucks. (2015). *Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report*.
- Battelle. (2011). *FAF3 Freight Traffic Analysis*.
- Bergenheim, C., Huang, Q., Benmimoun, A., and Robinson, T. (n.d.). *Challenges of Platooning on Public Motorways*.
- Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L., and Walters, J. (2014). *Effects*

- of Next-Generation Vehicles on Travel Demand and Highway Capacity.*
- Black, I., Fearon, J., and Gilliam, C. (2009). "Forecasting and Appraising Travel Time Variability in Urban Areas: A Link-Based Approach." *Association for European Transport and Contributors*, 4–5.
- Bonnet, C., and Fritz, H. (2000). *Fuel Consumption Reduction Experienced by Two PROMOTE-CHAUFFEUR Trucks in Electronic Towbar Operation*. Papenburg, Germany.
- Boston Consulting Group. (2015). "Self-Driving-Vehicle Features Could Represent a \$42 Billion Market by 2025." *Press Release*, <<http://www.bcg.com/d/press/8jan2015-self-driving-vehicles-market-2025-832>> (Jun. 17, 2016).
- Brandes, and Corcoran. (2012). *CS/HB 1207: Vehicles with Autonomous Technology*. Florida House of Representatives.
- Browand, F., McArthur, J., and Radovich, C. (2004). *Fuel Saving Achieved in the Field Test of Two Tandem Trucks*.
- Bureau of Transportation Statistics. (n.d.). "Length of Haul." *United States Department of Transportation*, <http://www.rita.dot.gov/bts/programs/freight_transportation/html/length_of_haul.html> (May 31, 2016).
- Bureau of Transportation Statistics. (2016). "Table 1-35: U.S. Vehicle-Miles (Millions)." *National Transportation Statistics*, Washington, D.C.
- Caliper Corporation. (2014). "TransCAD." Caliper Corporation, Newton, MA.
- Cambridge Systematics Inc. (2013). *Freight Transportation Modal Shares: Scenarios for a Low Carbon Future*. Cambridge, MA.
- Cambridge Systematics Inc., and ATRI. (2013). *North Carolina I-95 Economic Assessment Study - Task 6: Trucking and Shipping Analysis*.
- Cambridge Systematics Inc., Vanasse Hangen Brustlin Inc., Gallop Corporation, Bhat, C. R., Shapiro Transportation Consulting LLC, and Martin/Alexion/Bryson PLLC. (2012). *NCHRP Report 716: Travel Demand Forecasting: Parameters and Techniques*. Washington, D.C.
- Carr, J. L., Dixon, C. D., and Meyer, M. (2010). *NCHRP Report 661: A Guidebook for Corridor-Based Statewide Transportation Planning*. Washington, D.C.

- Chan, E. (2014). "SARTRE Automated Platooning Vehicles." *Transport Research Arena*, Paris.
- Childress, S., Nichols, B., Charlton, B., and Coe, S. (2015). "Using an Activity-Based Model to Explore Possible Impacts of Automated Vehicles." *Transportation Research Board 2015 Annual Meeting*, Washington, D.C.
- Cullen, D. (2014). "Self-driving trucks: How the road ahead may shape up." *Fleet Owner*.
- D'Onofrio, D. (2016). "Using Scenario Planning to Envision the Role of Technology in the Atlanta Region's Future." *TRB 2016 Annual Meeting*, Washington, D.C.
- Daimler AG. (2015). "Freightliner Inspiration Truck – the first licensed autonomous driving truck in the US."
- Davila, A. (2013). *Report on Fuel Consumption*.
- DHL Trend Research. (2014). *Self-Driving Vehicles in Logistics. DHL Customer Solutions & Innovation*, Troisdorf, Germany.
- Dye, F. (n.d.). "Short Haul vs. Long Haul Trucking." *Chron*, <<http://work.chron.com/short-haul-vs-long-haul-trucking-22928.html>> (Jan. 18, 2016).
- Fagnant, D. J., and Kockelman, K. (2013). "Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers, and Policy Recommendations for Capitalizing on Self-Driven Vehicles." *Transportation Research Part A*, 1–20.
- Federal Highway Administration. (2005). *Measuring Travel Time in Freight-Significant*. Washington, D.C.
- Federal Highway Administration. (2014a). *2015 FHWA Vehicle to Infrastructure Deployment Guidance and Products*.
- Federal Highway Administration. (2014b). "Freight Analysis Framework Data Tabulation Tool." *Freight Analysis Framework Version 3*, <<http://faf.ornl.gov/fafweb/Extraction0.aspx>>.
- Fernandes, P., and Nunes, U. (2012). "Platooning with IVC-Enabled Autonomous Vehicles: Strategies to Mitigate Communication Delays, Improve Safety and Traffic Flow." *IEEE Transactions on Intelligent Transportation Systems*, 13(1), 91–106.
- FHWA. (2013). "MAP-21 Significant Freight Provisions."

- <<http://www.fhwa.dot.gov/map21/factsheets/freight.cfm>>.
- FHWA. (2015). "MAP-21 Moving Ahead for Progress in the 21st Century."
<<http://www.fhwa.dot.gov/map21/>> (Jan. 26, 2016).
- FHWA, and CDOT. (2011). *I-70 Mountain Corridor Final Programmatic Environmental Impact Statement*.
- Florida Department of Transportation. (2016). "Florida Automated Vehicles."
<<http://www.automatedfl.com/>> (Mar. 21, 2016).
- Georgia Department of Transportation. (2016). "GDOT FY 2013-2017 Strategic Plan."
- Governor's Office of Highway Safety. (2012). *2012 Georgia Strategic Highway Safety Plan*.
- Hadi, M., Ozen, H., Chi, H., Zhao, W., and Sarikonda, H. (2010). *Use of Advanced Analysis Tools to Support Freeway Corridor Freight Planning*. Tallahassee, FL.
- Hayeri, Y. M., Michalek, J., Hendrickson, C. T., and Samaras, C. (2014). "The Energy Implications of Partial Vehicle Automation." *Transportation Research Board*, 1–16.
- Hussein, M. I., Petering, M. E. H., and Horowitz, A. J. (2009). *A Policy-Oriented Cost Model for Shipping Commodities by Truck*. Milwaukee, WI.
- IDOT, and INDOT. (2012). *Illiana Corridor Study*.
- IHS Automotive. (2014). *Emerging Technologies: Autonomous Cars—Not If, But When*.
- Institute of Transportation Studies at the University of California Irvine. (2014). "2014 California Vehicle Inventory and Use Survey." *Statewide Freight Transportation Research Group*, <<http://freight.its.uci.edu/calvius/>> (Jun. 7, 2016).
- Insurance Institute for Highway Safety. (2012). "They're Working: Insurance Claims Data Show Which New Technologies are Preventing Crashes." *Status Report*, Virginia, 47(5).
- Janssen, R., Zwijnenberg, H., Blankers, I., and Kruijff, J. de. (2015a). *FUTURE OF TRANSPORTATION TRUCK PLATOONING: Driving the Future of Transportation*. Delft, Netherlands.
- Janssen, R., Zwijnenberg, H., Blankers, I., and de Kruijff, J. (2015b). *Truck Platooning: Driving the Future of Transportation*.
- Kim, K., Rousseau, G., Freedman, J., and Nicholson, J. (2015). "The Travel Impact of Autonomous Vehicles in Metro Atlanta through Activity-Based Autonomous

- Vehicle.” *15th TRB National Transportation Planning Applications Conference*.
- Kuehn, J., and Reiner, J. (2015). “Self-Driving Trucks Could Rewrite the Rules for Transporting Freight.” *Forbes*, New York, NY.
- Kunze, R., Haberstroh, M., Hauck, E., Ramakers, R., Henning, K., and Jeschke, S. (2010). “Automated Truck Platoons on Motorways - A Contribution to the Safety on Roads.” *15th International Conference: Road Safety of Four Continents*, Abu Dhabi, UAE.
- Lammert, M. P., Duran, A., Diez, J., Burton, K., and Nicholson, A. (2014). “Effect of Platooning on Fuel Consumption of Class 8 Vehicles Over a Range of Speeds, Following Distances, and Mass.” *SAE International*, (October).
- Larson, J., Kammer, C., Liang, K., and Johansson, K. H. (2013). “Coordinated Route Optimization for Heavy-Duty Vehicle Platoons.” *16th International IEEE Annual Conference on Intelligent Transportation Systems*, The Hague, The Netherlands, 1196–1202.
- Larson, J., Liang, K. Y., and Johansson, K. H. (2014). “A Distributed Framework for Coordinated Heavy-Duty Vehicle Platooning.” *IEEE Intelligent Transportation Systems Magazine*, 1–10.
- Liang, K.-Y. (2014). “Coordination and Routing for Fuel-Efficient Heavy-Duty Vehicle Platoon Formation.” KTH Royal Institute of Technology.
- Liao, C. (2009). *Using Archived Truck GPS Data for Freight Performance Analysis on I-94/I-90 from the Twin Cities to Chicago*. St. Paul.
- Lindley, J. (2016). “National Highway Freight Program, FAST Act Section 1116 Implementation Guidance.” USDOT.
- Litman, T. (2015). *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*. Victoria, Canada.
- Liu, H., Xu, Y., Rodgers, M. O., Akanser, A., and Guensler, R. (2016). *Improved Energy and Emissions Modeling for Project Evaluation (MOVES-MATRIX)*. National Center for Sustainable Transportation. Atlanta, GA.
- Louis Berger Group Inc. (2014). *Sketch Level I-70 Mountain Corridor Traffic and Revenue Study*. Denver, CO.
- Lu, X.-Y., and Shladover, S. E. (2014). *Automated Truck Platoon Control and Field Test*.

- Road Vehicle Automation*, (G. Meyer and S. Beiker, eds.), Springer International Publishing, Switzerland.
- Mallett, W., Jones, C., Sedor, J., and Short, J. (2006). *Freight Performance Measurement: Travel Time in Freight-Significant Corridors*. Washington, D.C.
- Margiotta, R., Eisele, B., and Short, J. (2015). *Freight Performance Measure Approaches for Bottlenecks, Arterials, and Linking Volumes to Congestion Report*. Washington, D.C.
- Menzies, J. (2016). “Daimler demonstrates autonomously driven truck platoon.” *trucknews.com*.
- Miller, G. (2014). “Autonomous Cars Will Require a Totally New Kind of Map.” *Wired*, Boone, IA.
- Myllymaki, J. (2016). “Autonomous Delivery Platform.” USA.
- National Conference of State Legislatures. (2016). “Autonomous, Self-Driving Vehicles Legislation.”
- National Highway Traffic Safety Administration. (2013a). “U.S. Department of Transportation Releases Policy on Automated Vehicle Development.” <http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development>.
- National Highway Traffic Safety Administration. (2013b). *Preliminary Statement of Policy Concerning Automated Vehicles*.
- National Highway Traffic Safety Administration. (2014). *Federal Motor Vehicle Safety Standards: Vehicle-to-Vehicle Safety (V2V) Communications*. *Federal Register*, 49270–49278.
- Nevada Department of Motor Vehicles. (2016). “Autonomous Vehicles.” <http://www.dmvnv.com/autonomous.htm> (Feb. 20, 2016).
- Office of the Under Secretary for Policy. (n.d.). “The FAST Act: Freight Provisions.” *U.S. Department of Transportation*, <https://www.transportation.gov/fastact/freight-factsheet> (Jun. 7, 2016).
- Padilla, A. (2012). *Senate Bill No. 1298*. The Florida Senate, 1–4.
- Piesing, M. (2014). “Autonomous vehicles: How safe are trucks without human drivers?” *The Independent*, <http://www.independent.co.uk/life-style/gadgets-and->

- tech/features/autonomous-vehicles-how-safe-are-trucks-without-human-drivers-9047546.html> (Feb. 10, 2015).
- Roeth, M. (2013). *CR England Peloton Technology Platooning Test Nov 2013 CR England Peloton Technology Platooning Test Nov 2013*.
- Ronald Berger. (2016). “Automated Trucks: The Next Big Disruptor in the Automotive Industry?” 1–23.
- Schneider, G., and Fish, C. (2008). *Interstate 80 Freight Corridor Analysis*. Cheyenne, WY.
- Shladover, S. (2004). *Assessment of the Applicability of Cooperative Vehicle-Highway Automation Systems (CVHAS) to Bus Transit and Intermodal Freight: Case Study Feasibility Analyses in the Metropolitan Chicago Region*. Richmond, CA.
- Slavin, H., Ricotta, P., Brandon, J., Rabinowicz, A., and Sundaram, S. (2010). *A New Traffic Assignment Method for Small and Medium Communities*. Newton, MA.
- Smith, S. A. (1999). *NCHRP Report 435 Guidebook for Transportation Corridor Studies: A Process for Effective Decision-Making*. Washington, D.C.
- Southworth, F. (2016). *A Review of Truck Freight Value of Travel Time and Travel Time Reliability Studies*. Atlanta, GA.
- Southworth, F., and Gillett, J. (2011). *Trucking in Georgia: Freight Performance Measures*. Georgia DOT Research Project No. 10-16. Final Report. Atlanta, GA.
- Southworth, F., and Smith, D. A. (2016). *Estimating the Monetary Benefits of Reducing Delays on a Heavily Trafficked Truck Freight Corridor*. National Center for Transportation Systems Productivity and Management. Atlanta, GA.
- State of Michigan 97th Legislature. (2014). *Enrolled Senate Bill No. 169*. 1–4.
- Strange, A. (2014). “Mercedes-Benz Unveils Self-Driving ‘Future Truck’ on Germany’s Autobahn.” <<http://mashable.com/2014/07/06/mercedes-benz-self-driving-truck/>>.
- Torrey, W. F., and Murray, D. (2015). *An Analysis of the Operational Costs of Trucking: 2015 Update*. Arlington, VA.
- Transmetric America Inc. (2015). “Traffic Counts in Georgia.” *Geocounts*, <<http://geocounts.com/gdot/>> (May 31, 2016).
- Transport Business. (2014). “Autonomous truck convoys: the question is when, not if.” *Transport Business*.

- Tsao, H. J., Zhang, L., Lin, L., and Batni, D. (2004). *Evaluation of Bus and Truck Automation Operations Concepts*.
- Tsugawa, S. (2013). "Final Report on an Automated Truck Platoon within Energy ITS Project." *International Task Force on Vehicle Highway Automation: 17th Annual Meeting*, Tokyo, Japan.
- Tsugawa, S., Kato, S., and Aoki, K. (2011). "An Automated Truck Platoon for Energy Saving." *IEEE International Conference on Intelligent Robots and Systems*, San Francisco, CA, 4109–4114.
- U.S. Census Bureau. (n.d.). "American FactFinder."
<<http://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t>>
(May 18, 2016).
- U.S. Energy Information Administration. (2016). "Petroleum and Other Liquids."
<http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_a.htm> (May 31, 2016).
- U.S. Environmental Protection Agency. (2014). "MOtor Vehicle Emission Simulator (MOVES)."
- United States Environmental Protection Agency Office of Transportation and Air Quality. (2008). *Average In-Use Emissions from Heavy-Duty Trucks*. Washington, D.C.
- USDOT Center for Climate Change and Environmental Forecasting, and Cambridge Systematics Inc. (2010). *Transportation's Role in Reducing U.S. Greenhouse Gas Emissions Volume 1: Synthesis Report*. Washington, D.C.
- Washburn, S. S., and Ozkul, S. (2013). *Heavy Vehicle Effects on Florida Freeways and Multilane Highways*. Gainesville, FL.
- Williams, K. M. (2013). *Transportation Planning Considerations for Autonomous Vehicles – A White Paper*. Tampa, FL.
- Wilson, A. (1971). "A Family of Spatial Interaction Models and Associated Developments." *Environment and Planning*, 3, 1–32.
- Wittwer, E., Adams, T., Gordon, T., Gupta, J., Kawamura, K., Lindquist, P., Vonderembse, M., and McNeil, S. (2005). *Upper Midwest Freight Corridor Study*. Columbus, OH.
- Wyrough, A. P. H. (2014). "A National Disaggregate Transportation Demand Model for

the Analysis of Autonomous Taxi Systems.” Princeton University.

Zabat, M., Stabile, N., Frascaroli, S., and Browand, F. (1995). *The Aerodynamic Performance of Platoons: Final Report*. Los Angeles, CA.

Zhang, W., Ma, X., and Jenelius, E. (2016). “Planning of heavy-duty vehicle platoon formulation: basic scheduling problem considering travel time variance.” *TRB 2016 Annual Meeting*, Washington, D.C., 1–12.