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Impacts of Autonomous Vehicle Technology on Transportation Systems

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Department of
**Civil,
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Environmental
ENGINEERING**

Impacts of Autonomous Vehicle Technology on Transportation Systems

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16. Abstract Connectivity and automation technologies are expected to fundamentally alter transportation by significantly improving safety, increasing the efficiency of freight operations, and providing new mobility options for some population groups, such as the elderly and individuals with disabilities. Despite these expected benefits, it remains uncertain how the adoption of these technologies is going to affect other important aspects of transportation systems, including individual and network demand and the capacity of various transportation facilities. This research estimates the impacts of connected and autonomous vehicles on transportation systems using analytical and simulation methods. We focus on impacts related to transportation capacity, demand, land use, freight, energy use, and vehicle emissions. Despite the multiple uncertainties, we attempt to provide reliable predictions, to the extent possible, by utilizing assumptions informed from extensive literature review and expert opinion. The research team is comprised of a group of seven engineering faculty members and six graduate research assistants who worked collaboratively during the project duration. The North Carolina Department of Transportation (NCDOT) and specifically, NCDOT's Transportation Planning Branch can use the results of this research to inform decision making related to autonomous and connected vehicle regulation, pilot design, and long-range transportation plans. The results of this research will enable transportation planners at NCDOT as well as at the regional and local level to consider the effects of these emerging vehicle technologies when evaluating policy and planning decisions and prevent, to the extent that is possible, any negative externalities.			
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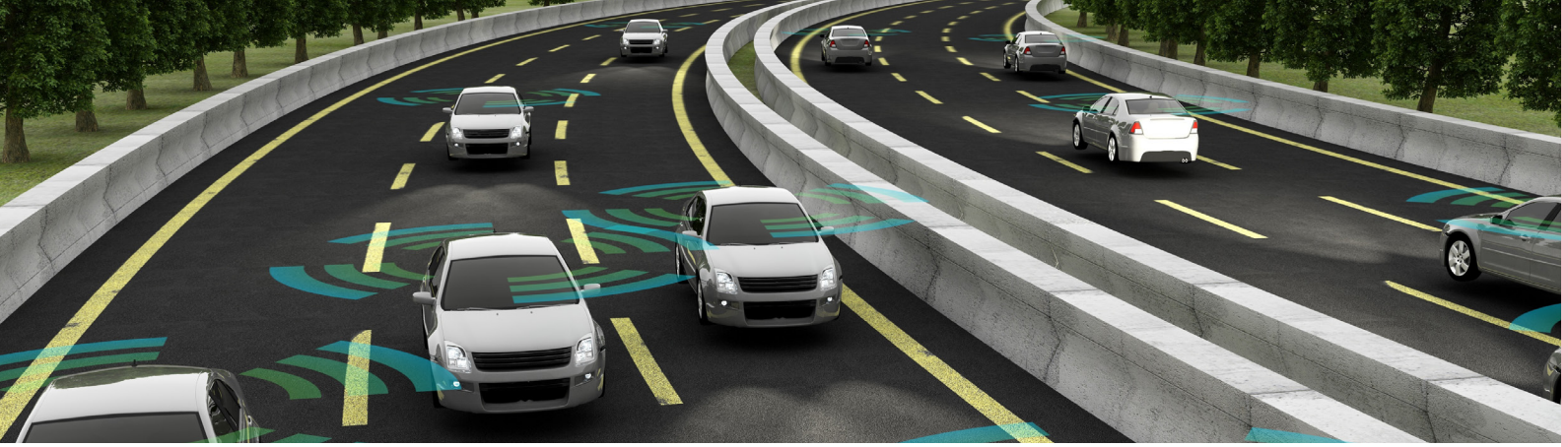
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Chapter 1

Introduction

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1.1 Introduction

Connectivity and automation technologies are expected to fundamentally alter transportation by significantly improving safety, increasing the efficiency of freight operations, and providing new mobility options for some population groups, such as the elderly and individuals with disabilities. Despite these expected benefits, it remains uncertain how the adoption of these technologies is going to affect other important aspects of transportation systems, including individual and network demand and the capacity of various transportation facilities. This uncertainty stems from a plethora of unknowns. First, the timing of adoption and market penetration rate of vehicles with different levels of automation and connectivity is highly unclear. This challenges studies that attempt to predict future impacts and advise public agencies on how to prepare for this new era. Second, the algorithms that define the movement of vehicles with automation and communication technologies are not available to the public and, in many cases, are still under development. For this reason, estimating how the adoption of connected and autonomous vehicles

will impact traffic operations is complex and typically based on multiple assumptions. Third, although stated preference surveys have provided an initial understanding of user perception and preferences related to vehicles with self-driving or communication capabilities, because these vehicles are not generally available, the behavior of individuals with respect to vehicle adoption and use remains uncertain.

This research estimates the impacts of connected and autonomous vehicles on transportation systems using analytical and simulation methods. We focus on impacts related to transportation capacity, demand, land use, freight, energy use, and vehicle emissions. Despite the multiple uncertainties, we attempt to provide reliable predictions, to the extent possible, by utilizing assumptions informed from extensive literature review and expert opinion. The research team is comprised of a group of seven engineering faculty members and six graduate research assistants who worked collaboratively during the project duration.

1.2 Report Organization

The research products are structured in four reports:

This report constitutes the **Main Report**, and it includes the research summary, conclusions, and recommendations (Chapter 4). This report also summarizes information related to concepts of operation of connected and autonomous vehicles (Chapter 2) and an industry update for these emerging technologies (Chapter 3), both led by Professor Missy Cummings.

Volume 1 contains three chapters that describe the research on connected and autonomous vehicles impacts on transportation demand and land use, led by Professor Eleni Bardaka. This research includes case studies for the Triangle Region, NC.

Volume 2 is comprised of two chapters that discuss simulations conducted to predict the potential capacity changes for freeways and signalized intersections due to connected and autonomous vehicle adoption. The research focused on freeways (Chapter 1) was led by Professors Nagui Rouphail and Billy Williams. The research focused on signalized intersections (Chapter 2) was led by Professor Ali Hajbabaie.

Volume 3 includes two chapters on the impacts of vehicle automation on freight, led by Professor George List, as well as a chapter on fuel use and emission rates reduction potential due to eco-driving, led by Professor Chris Frey.

The North Carolina Department of Transportation (NCDOT) and specifically, NCDOT's Transportation Planning Branch can use the results of this research to inform decision making related to autonomous and connected vehicle regulation, pilot design, and long-range transportation plans. The results of this research will enable transportation planners at NCDOT as well as at the regional and local level to consider the effects of these emerging vehicle technologies when evaluating policy and planning decisions and prevent, to the extent that is possible, any negative externalities.

Chapter 2

Concept of Operations for Autonomous and Connected Vehicles

Missy Cummings, Professor
Duke University



2.1 Introduction

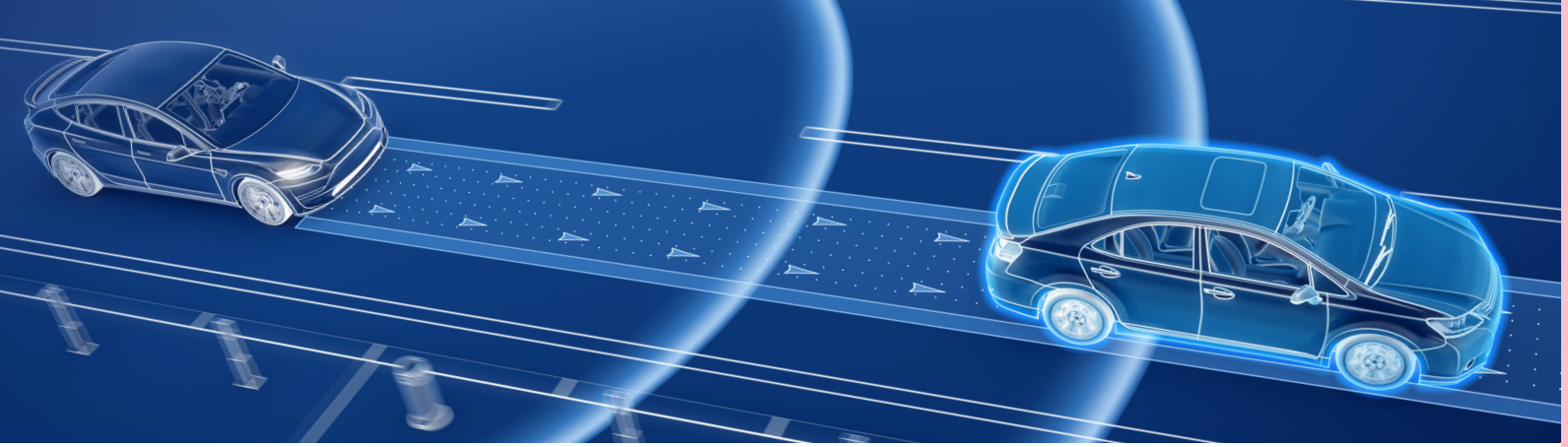
A concept of operations, otherwise known as CONOPS, generally describes how operations could and should occur in order to meet some common goal. This document will describe a set of CONOPs that address how self-driving capabilities could occur in highway settings.

Self-driving cars assume a human driver can take over operations while the term driverless car assumes no steering wheel and pedals exist for human control, and thus the car is fully autonomous. One application of self-driving cars that has been discussed is the ability of these cars to engage in fully automated driving on a highway with controlled access, aka, an interstate, freeway, motorway, or expressway. This is often suggested because, in theory, these settings reduce uncertainty by only allowing vehicles to move in more predictable manners, while restricting access to pedestrians, bicyclists, and other motorized or non-motorized vehicles not allowed in such environments.

In order to understand the various possible CONOPS that could emerge given this application of autonomous vehicles, it is important to first understand the Society of Automotive Engineers (SAE) levels of automation. The SAE has detailed a framework to describe the different levels of automation that could occur for various instantiations of self-driving cars. These levels have been widely adapted across industry and government, most notably NHTSA, and their adaptation can be seen in Table 2.1 (adapted from SAEJ3016).

As illustrated in Table 2.1, elements of self-driving do not formally occur until Level 3 where in addition to executing driving tasks, the underlying autonomy is also responsible for monitoring the dynamic driving environment. This shift in monitoring responsibility is important because it means that drivers are not expected to always have their eyes on the road. The next section discusses Level 3 CONOPs in more detail, followed by a discussion of Levels 4 and 5 CONOPS.

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2.2 Level 3 Vehicles

A Level 3 version of automated highway driving means that a driver would be expected to drive the car to a restricted access highway and then engage the automated mode, for example when merging with traffic on an established on-ramp. At this point, the driver could expect that the car would be responsible for maintaining proper lane position, accelerating, braking, maintaining appropriate stopping distances from cars in front of it, passing other vehicles, and then exiting the selected off ramp. At that point in time, the driver would take over.

The Level 3 assignment of autonomy assumes that while the car is responsible for motion control and navigation, the human driver is alert behind the wheel and ready to take over for any situation the autonomy deems itself unable to handle. Such scenarios could include:

- Camera vision systems lose the ability to localize due to problems such as missing or faded white lane lines, moisture and/or precipitation in the air, low sun angles and resulting shadows, etc.
 - Human drivers would need to potentially

respond on time scales of seconds.

- Failure of navigation systems like an inoperable or degraded GPS.
 - Human drivers would need to potentially respond on time scales of seconds to minutes.
- Missed obstacle detection. All autonomous vehicle sensors have regions of limited capability. For example, radars cannot detect parked vehicles on highways. Another example is known as the 'sudden reveal', which occurs when one car is following another, and the lead car suddenly shifts lanes revealing an obstacle in the path ahead. This problem has been illustrated by several Tesla incidents, resulting in both fatal and non-fatal accidents.
 - Human drivers would need to potentially respond on time scales of seconds, or even in less than a second.
- Erroneous obstacle detection. Sensors in autonomous vehicles are not perfect and can often experience false alarms for both individual sensors as well as fused data. For example, a LIDAR could detect an artificial obstacle, which could just be a plastic bag

floating in the air, causing the car to abruptly engage the brakes at high speeds.

- Human drivers would need to potentially need to override such an event on time scales of seconds. In addition, other following cars, which could be driven by humans, would need to respond to erroneous emergency braking by the lead vehicle, which could cause an accordion effect in high density traffic.

The most critical issue with Level 3 operation is the reliance on the human to resolve those situations listed above in the required times. Moreover, there is ambiguity concerning who is responsible for safe operation of the vehicle. While in Level 3, human drivers are assigned responsibility for overall safe operation of the vehicle but in some limited applications, they are also not required to maintain attention. Recently Honda announced it was employing a Level 3 traffic jam pilot, where automation drives in slow traffic jams up to 50km/hr (31 mph), and human drivers are not expected to have their eyes on the road during the traffic jam. Audi attempted a similar mode but eventually halted production due to liability concerns. This mode requiring human drivers be responsible for overall safety but allowing them to multitask presents a conundrum for human drivers, which is likely not going to be clear to them.

There have been a number of studies that have shown that having a driver monitor an automated system and then having the car "handover," aka, hand back control, to a human who may not be paying perfect attention will likely lead to accidents [1, 2]. Several Tesla fatalities in the United States

and in the pedestrian death in Tempe, Arizona have all demonstrated how fragile human driver attention is during critical automation handovers or failures. Thus, to be a viable CONOP, any level 3 system should effectively address the human role in dealing with those problems listed above, including establishing effective interventions for the timescales listed.

Additional Areas of Concern

Given the current state of technology, there are areas of operation that are especially problematic in highway settings for autonomous technologies, regardless of the level. The first of these are construction zones. Because of the relative unstructured and highly variable nature of construction zones in highway environments, cars equipped with both Level 2 and Level 3 technologies as outlined in Table 2.1 cannot currently safely operate in these areas. These problems are driven by the weaknesses in the perception system's inability to correctly detect and classify the surroundings.

	Name	Narrative		Agent executing steering & acceleration/deceleration	Agent monitoring the driving environment	Ultimate responsible agent	System driving modes
0	No Automation	Human driver performs all aspects of the dynamic driving task, even with enhanced warning or intervention systems		Human driver	Human driver	Human driver	N/A
1	Driver Assistance	Human driver assisted with either automated steering or acceleration/deceleration	Human driver performs all remaining aspects of the dynamic driving task	Human driver & system			Some driving modes
2	Partial Automation	Human driver assisted with both automated steering and acceleration/deceleration		System			
3	Conditional Automation	Automated driving system performs all aspects of the dynamic driving task for specified driving modes	Human driver will respond appropriately to any request to intervene	System	System	Human driver	Some driving modes
4	High Automation		Even if a human driver does not respond appropriately to an intervention request, the car pulls over safely			System	Many driving modes
5	Full Automation		Human driver not expected to take over				All driving modes

Table 2.1 Levels of automation in self-driving and driverless cars, as set forth by SAEJ3016



2.3 Level 4 Vehicles

If the assumption holds that the sensors in the car, perhaps aided by technology embedded in the infrastructure, perform sufficiently well such that a human driver is not expected to take over any active driving task (Level 4 in Table 2.1), then this introduces another CONOP layer for automated highway driving. In this CONOP, cars move at posted highway speeds which could range from 55-80 mph and the cars, not the drivers, are responsible for all driving tasks.

In self-driving settings that assume only limited-access highways can support such advanced autonomy, human drivers would drive their car to the highway or interstate, engage the autonomous mode, and then theoretically divert their attention as they desire. Such tasks could include checking email on a phone or laptop, watching movies, talking on the phone, eating, playing games with a passenger, etc.

In the case of any problems, whether caused internally by system problems (such as a sensor detecting that it has a problem) or an external situation arises where the car recognizes it does not know what to do (such as detecting a construction zone), the

car is expected to pull itself onto the highway shoulder and communicate to the driver (or perhaps a remote dispatch center which will be discussed in a subsequent section) what the problem is, giving the driver the option to take over driving.

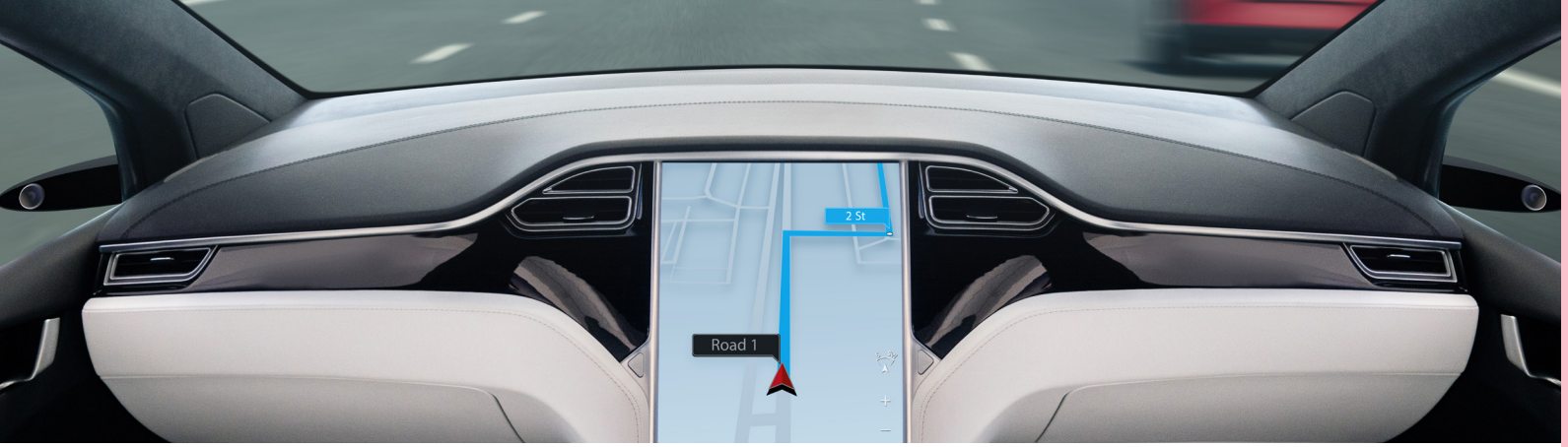
Currently, public transportation ridesharing and shuttles that have an attendant on board technically qualify as Level 4 technologies. While such self-driving shuttle generally drive on local routes and not on interstates, it is possible that these could eventually transition to limited access roads. However, all of the previous issues with time-critical responses apply to these systems as well.



Areas of Concern

Assuming L4 vehicles can operate reliably, one area of concern is how to ensure drivers in passenger cars maintain safe body positions in the event of a crash. Currently all restraint and crash protection systems assume that occupants are seated and facing forward (if not in an infant car seat). The risk of human injury and death in the case of a collision increase dramatically at highway speeds so once Level 4 is achieved, ensuring people maintain safe positions will be of significant concern. In such settings, drivers and passengers could adopt problematic risk homeostasis and begin moving between seats while the car is in motion, sleeping in various positions, and other likely unsafe and untested postures. There is a need for the research community to begin examining these issues now, before the cars are in widespread use.





2.4 Level 5 Vehicles

The highest level of vehicle automation in Table 2.1 is Level 5 where humans essentially remain as passengers instead of drivers and the automation is fully responsible for driving, monitoring and overall safety. Level 5 is commensurate with the term driverless. It is widely accepted that in Level 5 operations, cars will have no brake and acceleration pedals or steering wheel. In this CONOP, the only input a human has is giving the vehicle a destination. Shuttles could operate in Level 5 without an attendant once the technology is deemed safe enough for deployment on public roads.

A popular Level 5 CONOP is that of Robo-Taxis, where fleets of driverless cars provide ridesharing services, much like Uber and Lyft do today with human drivers. However, Robo-Taxi CONOPs assume local driving on all access roads, which is substantially more difficult than on just highways. There is no industry consensus on if or when such capabilities, embedded either in personal cars or fleets of vehicles, can be realistically achieved.

One new function that will need to accompany any Level 5 CONOP is the need

for communication with passengers. Because passengers in Level 5 cars will not understand urgent or emergent situations, like an AV pulling off to the side of the road because a flat is detected, someone in a remote center will need to communicate with them. As AVs become more commonplace, services like GM's OnStar® could be adapted to focus on passengers instead of drivers and they will likely also need to coordinate with other public safety dispatchers. Waymo has already developed such a capability for passengers riding in its experimental self-driving service, these dispatchers fall into their "Rider Support Division". Their primary job is to monitor and interface with customers who need help.

Areas of Concern

Some autonomous driving companies have suggested that they will rely on remote drivers connected via a remote operation center to take over control of a car in Level 5 operations (and possibly Level 4) if there are problems that the vehicle cannot resolve on its own. In this CONOP, remote drivers literally take over full control, including steering and speed and brake control.



2.5 Other Related CONOPS

Level 1-4 + Level 5 for Trucking

One hybrid CONOP unique to limited-access roads is related to optional-driver trucks. Waymo, Aurora and TuSimple have discussed the CONOP of having tractor trailers and other large commercial trucks be driven by humans to special interstate access points, which could occur across Levels 1-4 in Table 2.1. These hubs would then serve as the on- and off-ramps for driverless trucks (Level 5). In this hybrid CONOP, humans handle the difficulties of driving in unstructured settings, while autonomy operates the trucks on limited access roads. While there is significant demand for such services, the technology has yet to be deployed for all the difficulties presented in the other sections of this report.

Platooning

The previous discussed Level 3 and 4 CONOPs broadly apply to both passenger and freight vehicles, although the handover

concerns for commercial freight trucks are especially important to address given their mass and potential for significant damage. For such trucks, an additional CONOP has been proposed, which is that of platooning. In this CONOP, a lead truck which has a human driver (who could be operating a level 2, 3, or 4 truck on the highway), is then closely followed by one or more other trucks. These following trucks may have a driver supervising a level 4 truck, or the truck may be unmanned with no driver in it. The motivation for such close following, also called drafting, is to take advantage of reduced drag and improved fuel efficiency [6]. Such close operations would require intense focus of human drivers in the following trucks and would be fatiguing, so such precise position maintenance is far more suited to computers.

While such operations have clear logic for utility, there are many practical limitations that need to be considered for such CONOPs. If sensors and the associated perception systems are

not highly reliable, any of the problems discussed previously have the potential to be even more catastrophic due to the high speeds and weights of the trucks, as well as close distances. Moreover, the reliability of the vehicle-to-vehicle communications network will need to be extremely high, and contingency plans for graceful system degradation will be critical.

Remote Fleet Management

Once reliable vehicle-to-vehicle (V-to-V) and vehicle-to-everything (V-to-E) networks are established, such capabilities could enable remote dispatch and fleet management services to aid in improved flow of traffic as well as managing emergent situations that arise such as crashed or disabled vehicles. Such dispatch services would include an operations center staffed by personnel that resemble freight dispatchers today, but these operators could have significantly more responsibilities.

Assuming some level of connectivity exists in vehicles and/or the infrastructure, remote dispatchers of the future could monitor real-time traffic flows of all levels of cars in Table 2.1, including platooning trucks. In highway settings, dispatchers could ensure that disabled or crashed vehicles receive assistance, while also potentially redirecting traffic away from the emergent events. Because these futuristic operators will have the ability to directly communicate with some, but not all, cars, they may be able to communicate through the V-to-V network to help ease congestion. Moreover, they may be able to change signs and signals in order to communicate with non-equipped vehicles.



Cybersecurity Concerns

All of the CONOPs discussed previously assumed that the vehicles and the remote operations center are not subject to active or passive hacking or other cybersecurity threats. GPS-spoofing is a known problem for self-driving cars [7, 8], as well as the ability to remotely access various controls in a car, even while it is moving. Recently, researchers have demonstrated that even if a car does not rely on any external signals that could be compromised, the computer vision systems can be passively hacked by manipulating the environment the car operates in, such as traffic signs [9, 10]. Thus, more work is needed in fundamental and applied research applications to ensure that all CONOPs previously discussed adequately address the various cybersecurity concerns associated with their unique elements.

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Chapter 3

Current and Forecasted Trends for the Autonomous and Connected Vehicle Industries

Missy Cummings, Professor
Duke University

3.1 Introduction

In order to understand the commercial and regulatory impact that connected, self-driving and driverless vehicle operations could have in North Carolina, it is first critical to understand who the primary companies are in this space, how close they are to commercial operations, and what the state and federal regulatory impacts currently are, as well as what could occur in the short and long term.

For the purpose of this analysis, the phrase Autonomous Vehicles (AVs) includes privately-owned personal cars, commercially-owned fleets of cars, aka robotaxis, commercial cargo-carrying trucks, and delivery vehicles with embedded autonomy. The phrase “self-driving” means vehicles that are capable of being driven by humans or onboard autonomy (see Chapter 2 for a more detailed discussion how these relate to SAE Levels), while “driverless” means a vehicle with no steering wheel or brake/acceleration pedals with onboard autonomy that controls all aspects of driving. This chapter focuses on Level 4 and 5 vehicles.

The first section details the primary companies that are conducting self-driving and driverless research and development, including those focus on privately-owned AVs, robotaxis, AV shuttles (like the experimental NCSU CASSI shuttle, Fig. 3.1), trucks and last-mile delivery vehicles. The second section discusses connectivity developments in the automotive industry. The third section discusses regulatory AV activity at the state and federal levels. The last section will discuss possible future developments and predictions.



3.2 Who are the Players and How Close to Commercial Operations are they?

There are a number of companies in the self-driving and driverless space, including those focused on system software development (like Waymo) and original equipment manufacturers (OEMs, like Ford), but also relatively newer entrants like chip suppliers that claim to provide all needed capabilities through integrating sensor data on a single chip. One notable recent trend is the number of consolidations, mergers and partnerships between these entities as it has become clear that the timeline for commercialization is much longer than originally speculated and the costs are much higher than anticipated¹. These major players are discussed below including recent mergers.

Privately-Owned AVs, Shuttles and Robotaxis

System Software Developers

This group of companies are those that focus primarily on the development of the software that enable self-driving capabilities. While they may team with others, they are the prime movers for technology development.

- Waymo is generally considered the lead company in self-driving passenger vehicles, including robotaxis, with its core product known as Waymo Driver. This product has two spinoffs called Waymo One², its ridesharing application and Waymo Via³, an extension focused on autonomous trucking, discussed in more detail in a subsequent section.
- Waymo One announced in October 2020 that it will provide true self-driving robotaxi services to paying customers in limited areas in Arizona via a smartphone-based

Figure 3.1 NCSU CASSI Experimental Driverless Shuttle



app with no safety drivers in the cars⁴. Waymo is currently the only US company to achieve this capability. This service has demonstrated that such operations require extensive external support and the profitability of such operations has been questioned⁵. A recent video from a rider in AZ demonstrated that orange construction cones can cause significant problems, requiring a human to physically take over⁶. While it was valued at \$175B in 2018, Waymo is now valued at \$30B⁷. Waymo's CEO, John Krafcik, unexpectedly stepped down in April 2021.

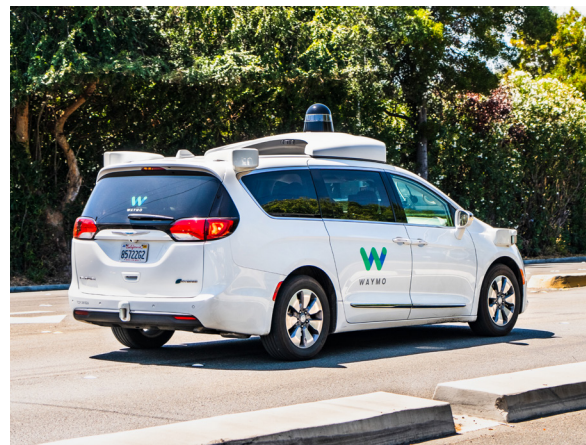
- Cruise is a self-driving majority-owned subsidiary of General Motors (GM) and headquartered in San Francisco, where the bulk of their operations take place. Cruise has not yet conducted operations without a safety driver behind the wheel but recently applied for a permit to conduct commercial self-driving operations in the city⁸.
- Argo AI is a start-up out of Pittsburgh with financial backing from Ford and VW. While they have tested self-driving cars, they recently announced development of a Level 4 microbus that could be self-driving in some limited areas⁹.
- Aptiv acquired Nutonomy in 2017, an MIT self-driving spin-off, and then created Motional, a joint venture with Hyundai. While they have demonstrated limited self-driving capabilities¹⁰, they have not yet commercialized any services.

Original Equipment Manufacturers (OEMS)

The companies listed below are those with established self-driving programs that have demonstrated significant investments and progress in Level 4 and 5 technology

development.

- General Motors (GM): As mentioned previously, GM's self-driving capabilities exist vis-a-vis Cruise, and while they have demonstrated Level 4 cars, they have not achieved any commercialization.
- Ford: Argo AI is Ford's partnership in the self-driving space, and while they also have demonstrated Level 4 capabilities, they have not yet demonstrated the ability to operate without a safety driver.
- Toyota: Headquartered in Tokyo, Toyota created a new company in 2018 called Toyota Research Institute-Advanced Development (TRI-AD) to focus on Autonomous Driving. While they have not yet demonstrated any Level 4 capability publicly, they are now building a new test facility called the Woven City¹¹. Scheduled to open in 2024, this facility



is supposed to be a city replica that allows Toyota the ability to explore not only vehicle, but also necessary infrastructure technology.

- VW: Because of their partnership with Argo AI, VW has also not demonstrated any capability beyond Level 4 with a safety driver.
- Tesla: While Tesla currently sells cars with advanced driving assist systems (ADAS), the CEO, Elon Musk, stated that it is possible

that in the future, owners may be able to have their cars independently conduct robotaxi operations, i.e., Level 4, and thus create additional value for owners¹². However, Tesla has experienced many high-visibility crashes and problems with some self-driving technologies like its Smart Summon system and it is not clear if and when robotaxi capabilities will be achieved. Recently, Tesla released a document to the Securities Exchange Commission that stated it may not ever be able to achieve such capabilities.

- Hyundai: Through its joint venture with Aptiv discussed above, Hyundai is currently testing Level 4 vehicles in Las Vegas. While they do not have a safety driver, they instead have a safety steward in the right front passenger seat¹³. They have not achieved any commercial operations.

Chip Suppliers

- NVIDIA has developed a self-driving “system-on-a-chip” that purports to provide self-driving capabilities based on fused information from computer vision, LIDAR, and RADAR¹⁴. Current partners include Audi, Tesla, Mercedes-Benz, BMW, Volvo and Honda.
- Mobileye is an Intel company that also claims that it can support self-driving capabilities on a single chip¹⁵. Mobileye differentiates itself from its competitors by claiming that it only needs computer vision and does not need radar and lidar. There is no industry consensus on whether this is possible.

Outside the US

The dominant area of self-driving research and development is occurring in China. While there are many European and Japanese car companies

investigating self-driving technologies, they are doing so in partnership with the companies as listed above.

- Pony.ai is a Chinese company with strong links to Silicon Valley. They are developing Level 4 cars with integrated LIDARs (instead of mounting them on the car)¹⁶. However, they have not demonstrated any ability to conduct sustained operations without safety drivers.
- Baidu is thought by many to be the leading Chinese company developing self-driving technology and reportedly is testing self-driving passenger vehicles as well as shuttles and buses¹⁷. However, to date, there are no commercial operations.
- WeRide is a Chinese company that purports to have Level 4 robotaxi vehicles and driverless shuttle buses, but beyond a handful of video demonstrations¹⁸, there are no commercial operations.
- AutoX is another Chinese company developing Level 4 cars, and claims to have started commercial operations in Shenzhen in January of 2021¹⁹, but there has been no independent verification.
- Xpeng is a Chinese competitor to Tesla for ADAS-equipped electric vehicles, but also like Tesla is developing some self-driving capability²⁰. Unlike Tesla, Xpeng vehicles include LIDAR.
- Scania is a Swedish company working with TuSimple in Sweden for Level 4 trucking operations²¹.

Who is no longer in this space

In 2020 Uber sold its AV program (called the Advanced Technologies Group) to Aurora, a Silicon Valley startup who now focuses on self-driving trucks, discussed more in a later section.

In 2021, Lyft sold its driverless car program to a Toyota subsidiary²².

- Zoox was sold to Amazon in 2020 and while a press buzz was generated in December of 2020 over the design of a bi-directional driverless shuttle²³, there has been no demonstration of any self-driving capability with no safety driver in the car.
- Voyage, a company that focused on low-speed AVs in limited areas like retirement communities was acquired by Cruise in 2021²⁴.
- In 2020, Mercedes said it would no longer attempt to develop self-driving cars, although it has partnered with Waymo for self-driving trucks²⁵.

Trucking

There is growing speculation that commercial truck autonomy will better scale and be more profitable than passenger-vehicle autonomy²⁶, so there is increasing activity in this space, including some companies shifting their priorities away from passenger-vehicle autonomy. Some believe that application of autonomy may be more straightforward in limited-access settings like interstates and freeways where pedestrians, bicyclists, etc. are not a factor, and this technology would also protect against fatigued truck drivers, a long-recognized human problem.

- Waymo Via is Waymo's application of its Waymo Driver software to trucks. To date, the technology requires a safety driver, works only on freeways and interstates and does not work on surface streets²⁷.
- TuSimple is a China-backed company that focuses on self-driving long-haul tractor trailers, and recently had a Nasdaq initial-public offering (IPO). While they currently require a safety driver and also are only

designed to work on limited-access roads, they have stated that they will be able to drive these trucks with no one in the cab in 2021²⁸.

- Aurora, a Silicon Valley startup, is headed by Chris Urmson (formerly the head of Waymo), Sterling Anderson (formerly an autonomy engineer at Tesla), and Drew Bagnell (from Carnegie Mellon and Uber). In 2017, it originally focused on self-driving technology for passenger cars and possibly robotaxis, but the company recently pivoted to the self-driving trucking industry. Aurora recently partnered with PACCAR, maker of medium- and heavy-duty trucks, and they also have backing from Amazon. They currently require safety drivers in the cab.
- Plus is another autonomous trucking company who will soon be publicly traded through a special purpose acquisition company²⁹. They claim that they will be the first company to start mass scale production for Level 4 systems, which means that the driver does not always have to be paying attention and the car will take full responsibility in limited access settings (see Chapter 2 for a longer discussion about Level 4). However, Plus has not presently demonstrated that it can remove safety drivers.

Who is no longer in this space

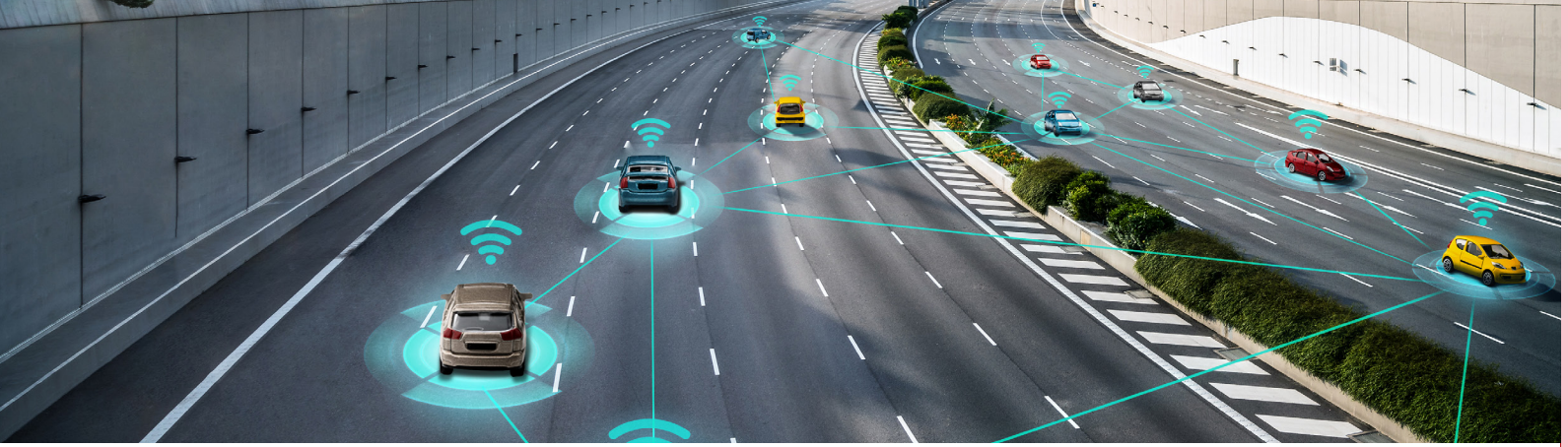
Starsky Robotics was a start-up founded in 2015 focused on autonomous trucking. In 2020, the company closed its doors and the CEO was very clear in a public blog³⁰ that he thinks the underlying machine learning algorithms are not sufficient to enable systems to drive on their own. He also warned that other companies in this business were ignoring safety engineering in a rush to impress investors.



Last-mile Delivery

While the trucking industry is primarily focused on the use of self-driving technologies to drive trucks across long distances, there is increasing interest in providing last-mile autonomous delivery. Such operations have the advantage of smaller, better-mapped areas with vehicles operating at slow speeds, which is helpful for obstacle detection, especially pedestrians and bicyclists. While there are many companies focused on sidewalk-based delivery (e.g., Starship and Amazon's Scout robot), this section will only focus on companies that intend to deploy their technologies on public roads.

- Nuro focuses on driverless last-mile delivery, and their specially-designed vehicles are the size of small mini-vans. They recently started a pilot service under a US Department of Transportation exemption in Houston, TX delivering pizza³¹.
- Walmart made a recent large investment in Cruise for local deliveries³², although it is not clear if the final intended vehicle design is a passenger vehicle or whether there are plans to design a more-tailored cargo vehicle like that of Nuro.
- Amazon's recent acquisition of Zoox in combination with its significant backing of Rivian³³, who makes electric delivery vans, could signal its intent to integrate Zoox's software with Rivian vehicles.



3.3 Connectivity

Often the word connectivity is attached to AV (i.e., CAV) to imply that these cars are in communication with an external party, either human- or computer-based. Any company like Waymo or Nuro that requires interaction with some kind of remote operations center is inherently connected, so even though there is no C in many mentions of AVs, the connectivity is implied.

One important point of confusion that routinely is revealed in articles and surveys about AVs is that many people believe that connectivity must exist for AVs to function, which is simply not the case. Because of inherent communication delays and possible loss of data packets, no AV

will ever be able to safely operate if it must rely on connectivity to safely actuate and navigate. Thus, AVs should never need any connectivity to safely operate, but such connections improve efficiencies of operation. For example, connected vehicles can share information about unexpected construction areas that can improve navigation, and even possibly warn of nearby collisions, but an AV can never rely on external information to determine whether an emergency stop is warranted.

While connectivity is often conflated with AVs, it is important to recognize that it can and does exist completely apart from the notion of AVs. For example, GM's OnStar® remote monitoring and call center is a form of centralized connectivity available in the world today. Moving forward, current research and development efforts in connectivity are attempting to link vehicles together in a decentralized fashion so that they can "talk" to one another, and even roadway infrastructure to mitigate congestion, provide additional safety protections and improve efficiency in the overall travel experience. All of these advantages can happen regardless of when

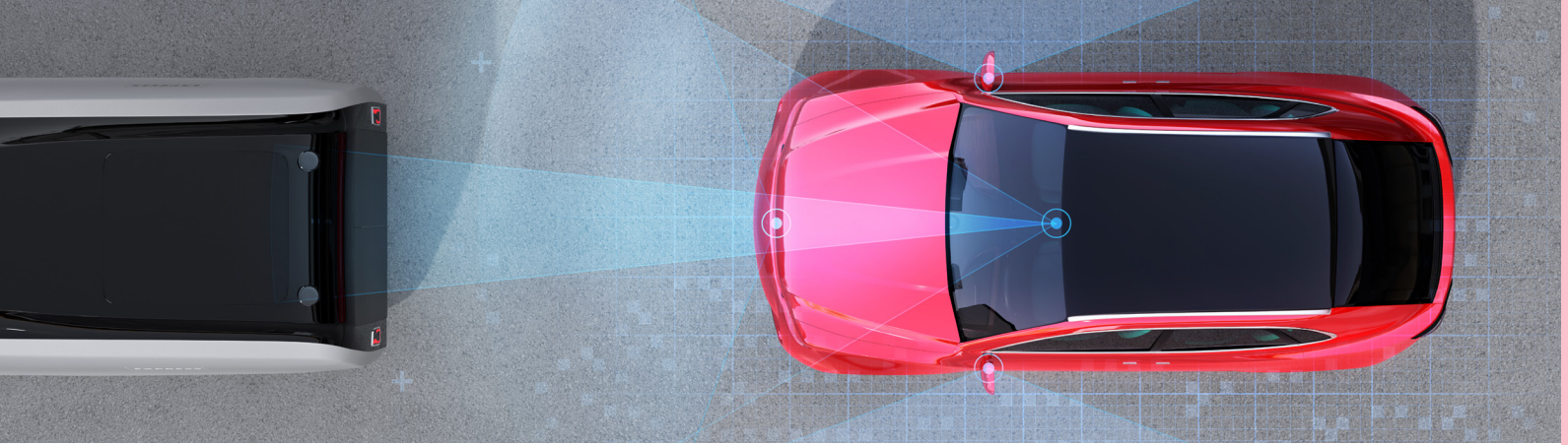




and to what degree AVs are integrated into the travel landscape.

Dedicated short range communication (DSRC) has been considered the defacto architecture for vehicle-to-everything (V2X) communication since 1999 but lack of commitment on both the part of the US government and vehicle manufacturers has stalled any meaningful rollout of this technology³⁴. Support has generally moved from DSRC to cellular vehicle-to-everything (CV2X) communications, with the thinking that 5G in cellular communications is the key enabler. 5G networks, in theory, provide faster movement of more data but such technology operates at short ranges so there is likely significant infrastructure cost when developing such networks.

The automotive industry recognizes that 5G could become the industry standard for connectivity and all manufacturers are developing strategic plans for future development. China is expected to take the lead in vehicle integration (traditional and AV) but the US and Europe are also expected to have significant capability in this space, with significant growth starting between 2022-2023²⁵. One significant caveat to the use of these technologies is cybersecurity concerns. The more connected a car is, the more vulnerable it is to hacking. Significantly more work is needed at the chip and vehicle levels to thwart such events.



3.4 Regulatory Landscape

In terms of regulation and connectivity, while generally everyone in the automotive industry including federal and state governments is supportive of increased vehicle connectivity, the US federal approach to 5G is seen as one in disarray, with no coherent plan³⁷. As stated earlier, vehicle manufacturers are publicly embracing 5G connectivity so it will be important to monitor how such technologies evolve on the commercial front, as these developments could then influence policy. It is also critical to monitor any regulatory actions regarding 5G and cybersecurity. Regardless of how 5G is rolled out from a vehicle perspective, it is currently available in cell phones.



Thus, there is data available about people's use of 5G phones in cars and so many lessons can theoretically be learned now if an agency has access to such data.

When looking at regulation and AVs, Table 3.1 outlines the overarching responsibilities of federal and state agencies³⁸ for how all vehicles should be regulated. Most AV oversight activity is currently occurring at the state level, but there is some movement at the federal level. For example, in February 2020, NHTSA approved its first AV exemptions to Nuro, which allows their robot cars to not have mirrors and a windshield³⁹. Such devices are moot given there is no driver in the vehicles.

While there has been some progress at the federal level, for the most part any major initiatives have failed. The SELF DRIVE Act passed in 2017 in the House of Representatives, but the complementary Senate AV START Act died by 2019. A recent Congressional Research Service report cited the following reasons for the lack of progress of these efforts, which include:

- How should the responsibilities in Table 3.1 be

Federal Responsibilities	State Responsibilities
Communicate with and educate the public about motor vehicle safety issues.	Regulate motor vehicle insurance and liability.
Enforce established safety standards compliance.	Enact and enforce traffic laws and regulations.
Investigate and manage the recall and remedy of non-compliance and defects nationwide.	Conduct safety inspections, when necessary.
Set safety standards for new motor vehicles and motor vehicle equipment.	License human drivers and register motor vehicles in assigned jurisdictions.
When necessary, issue guidance to achieve national safety goals.	

Table 3.1 Federal and State Regulatory Responsibilities

distributed? For example, it is not clear who should be, in effect, licensing AVs since there are no humans. Moreover, there are clear safety implications because the vehicles will require new forms of inspection, but it is not clear how and who would be responsible for conducting these.

- How many AVs should be allowed to be tested on public roads through the current exemption process and how should current safety standards be relaxed or removed for these tests?
- How will cybersecurity threats be addressed as well as privacy concerns?
- Who has access to data generated by the AVs, as well as who has the rights to sell vehicle-related data to others?⁴⁰

As of May 2021, there has been renewed interest in attaching self-driving legislation to other bills, but currently such efforts have not gained any traction⁴¹. Competition with China is often cited as the urgent driver for opening up the market⁴², but high-profile crashes like recent multiple Autopilot-related Tesla crashes and the pedestrian death in Tempe, AZ in 2018 during

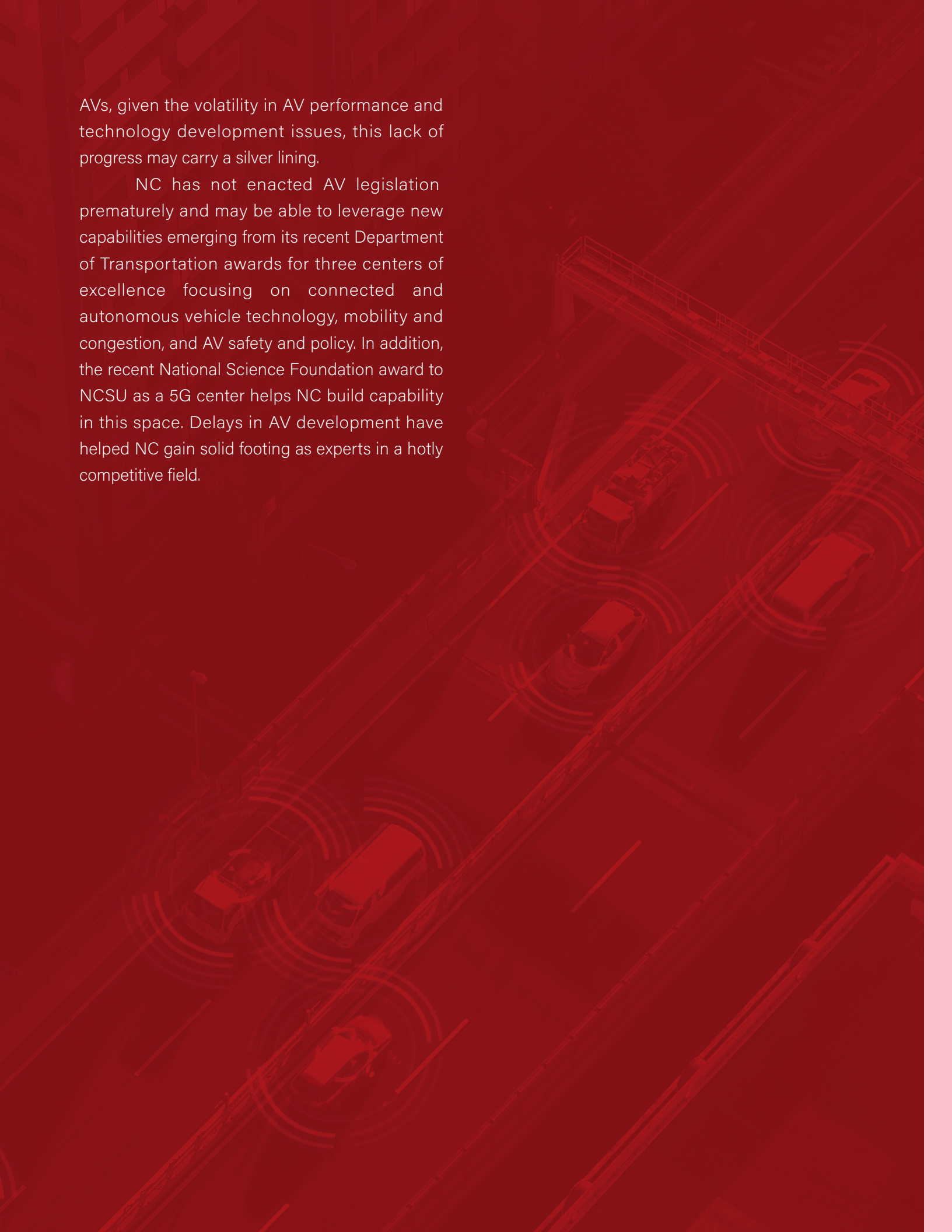
Uber self-driving testing have raised awareness about the nascent and unproven nature of this technology.

In looking at what state legislatures have done, the National Conference of State Legislatures (NCSL) provides a website that tracks autonomous vehicle bills introduced across the USA⁴³. Overall, 29 states have enacted some kind of legislation that address AV operations, and 14 states have failed or pending legislation. Arizona has favorable AV policies, and it was the first state to allow commercial AV operations, conducted by Waymo. Both Waymo and Cruise have applied for commercial self-driving permits in California⁴⁴, but these are still pending. Nevada, Michigan, Texas and Massachusetts have all approved AV testing on public roads. Florida recently passed legislation supportive of autonomous delivery vehicles.

North Carolina is similar to many states in that there have been some legislative actions, specifically regarding AV operations and platooning⁴⁵, but there have been no significant regulatory actions since 2018. While NC has not been a leader in policy and legislation surrounding

AVs, given the volatility in AV performance and technology development issues, this lack of progress may carry a silver lining.

NC has not enacted AV legislation prematurely and may be able to leverage new capabilities emerging from its recent Department of Transportation awards for three centers of excellence focusing on connected and autonomous vehicle technology, mobility and congestion, and AV safety and policy. In addition, the recent National Science Foundation award to NCSU as a 5G center helps NC build capability in this space. Delays in AV development have helped NC gain solid footing as experts in a hotly competitive field.





3.5 Looking to the Future

While some claim that the AV industry is gaining momentum⁴⁶, the recent mergers and acquisitions (and outright failures) of many companies in the self-driving space clearly signal that the industry is not progressing at the rate it would like. Indeed, Waymo, Ford and Tesla have all previously claimed that they would have widespread commercial self-driving operations by 2021 but this has not happened.

Despite the technical obstacles, many companies still promise AV self-driving in the next few years. The more companies have invested in self-driving technology including investors, the more likely they will fall into a sunk-cost bias trap. The sunk cost fallacy is a well-known psychological decision bias that occurs when, despite evidence that a current decision or plan (including investments) is not reaping expected rewards, people elect to continue with the sub-optimal decision or plan because so much effort/money/time have already been spent.

Despite the possible occurrence of sunk-cost bias in regards to AV deployment, there are likely some derivative technologies that will

emerge with viable and scalable business models. Understanding that forecasting is fraught with error and uncertainties, the following events related to AVs and connected vehicles are predicted to occur under the specified time frames:

- Given recent NHTSA exemptions and the investment of Amazon into Aurora, Zoox and Rivian, it is likely that significant advances in slow-speed self-driving last-mile delivery in relatively small, geo-fenced and well-mapped areas will be made in the next few years. The development of this technology will also need to occur in parallel with advances in dispatch services (see Chapter 2), so it is not yet clear whether such services can ultimately be profitable.
- There are a number of autonomous shuttle experiments happening in the US⁴⁷, China⁴⁸, Singapore⁴⁹ and Europe⁵⁰. CASSI in Fig. 3.1 is just such an example. Such services represent improved economies of scale over passenger vehicles, but none of the experimental trials have yet transitioned into actual operations.

Results from these trials are still pending but it is possible that with additional infrastructure investment (i.e., dispatch services, sensors in the roads or dedicated/marked AV lanes), such services could become profitable in the next 5-10 years but more data is needed.

- Fleets of robotaxis and long-haul trucks that operate under limited-access and/or geo-fenced areas may occur in the next 10+ years in very small markets. However, these will require significant investment in infrastructure to operate safely. It is not clear whether such operations will be profitable.
- Individually-owned passenger cars or trucks that can operate on any road under any set of conditions will not likely occur for at least 20-30 years.
- The scale and pace of increased vehicle connectivity is still yet to be determined, as well as the hacking vulnerabilities introduced into vehicles as connectivity is increased. NCSU's 5G center will be critical in helping NC determine how to position itself. However, it is also important to recognize that historically, for more than 20 years many people in the transportation industry thought DSRC was going to be the standard. Closely monitoring industry, other government actions, and any new US federal 5G policies will be critical in the next few years.

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Chapter 4

Research Summary, Conclusions, and Recommendations



1. Recommendations for connected and autonomous vehicle research and pilot programs in North Carolina

Given that the timeline of deployment of self-driving vehicles for widespread use is unclear, it is paramount that NCDOT be attuned to the constantly changing landscape of AV development and deployment. Moreover, it is important that NCDOT continue investigations into connectivity and traditional transportation opportunities separate from the connected and autonomous vehicle opportunities since the timeline of AV development is likely much longer than anticipated and much more uncertain. To this end, the following recommendations are made:

- Develop a formal system for tracking AV legislation at both the federal and state levels. Special emphasis should be placed on monitoring developments in Arizona, Michigan, Massachusetts, California, Texas and Florida. The goal of such an effort is to understand when new legislation is proposed, what recommendations, laws, and guidelines result, and what the tangible outcomes

are. For example, in San Francisco, Cruise- and Waymo have had permission for some time to operate AV robo-taxis, but neither company has yet to do so. This suggests that the companies do not feel their technology is mature enough for deployment, and that there are underlying safety concerns that need to be monitored.

- Develop a formal system for tracking current AV developments to include:
 - a. Robo-taxis
 - b. Last-mile delivery AVs
 - c. AV shuttles
 - d. AV trucking applications
 - e. Personal AVs

The goal in such an effort will be to track progress of these technologies, including testing and certification, in order to forecast when the technologies could achieve sufficient maturity to move out of testing into small scale deployment. This effort should occur in conjunction with the Economic Development Partnership of North Carolina in order to identify opportunities to bring business to NC, including sandbox types

of testbeds including possible candidate communities, which could provide substantial benefit to the numerous companies developing these technologies.

- Develop a simulation capability to explore different concepts of operation for various connectivity applications independent of AVs to determine possible impact on safety and traffic flow for high impact regions.
 - This could be developed in conjunction with academic partners and could be used to develop competitions for students. For example, such a simulation could be used to explore different uses of 5G for light timing, dynamic routing, or new kinds of mapping apps.
 - This effort could be linked to the current NSF-funded 5G center at NCSU.
- NCDOT should develop a comprehensive research roadmap that addresses connected and autonomous vehicles and determine which areas of applied research it needs to support internally for more near-term needs, and then determine what are the more basic and futuristic areas of research that academics in NC should be addressing.
 - This roadmap should explicitly address the role of test and certification of advanced transportation technologies. NHTSA has recently mandated that both AVs and also more traditional ADAS-equipped cars adhere to more strict accident reporting rules, so it is clear that such vehicles are undergoing increasing regulatory scrutiny. There may be economic opportunities for NC in terms of developing testing and certification facilities and expertise given related work in the various universities and also the North Carolina Center

for Automotive Research (NCCAR) in Garysburg, NC. It is possible that robust test facilities and qualified personnel could bring businesses to NC.

- Continue supporting NC academic institutions for both research into AVs and connectivity.
 - Currently NCDOT is sponsoring two academic centers of excellence, the NC A&T Center of Excellence in Connected and Autonomous Vehicle Technology (NC-CAV), and the NCSU Center of Excellence for Traffic Congestion and Mobility. These initial efforts are critical for establishing research capabilities but these centers should be specifically expanded to support the needs outlined in the research roadmap.

2. Impacts of connected and autonomous vehicles on transportation demand

2.1 Research summary and conclusions

Autonomous and connected vehicle technologies have the potential to bring profound changes in travel behavior and transportation network performance with moderate to significant market penetration rates (MPR) within the next few decades. To better understand the long-term impacts of these technologies, this study predicts the network-level effects of privately-owned autonomous vehicles (AVs) and connected and autonomous vehicles (CAVs) for the Triangle Region, North Carolina, in the year 2045. Market penetration scenarios of personal AVs and CAVs along with results from microscopic mixed-traffic simulations and travel behavior assumptions are incorporated into the Triangle Regional Model.

Overall, the results indicate that with induced travel demand, capacity adjustments,

and reduced value of travel time, people will make more and longer trips by personal vehicles, resulting in up to a 3.6% increase in daily VKT in the Triangle Region. The findings significantly vary by the rates of AV and CAV adoption. Most importantly, the estimated impacts due to AV adoption are notably different from the impacts of CAV adoption. A 75% MPR of personal AVs is found to deteriorate the network's performance, resulting in a 5.4% increase in daily VHT, and a 17.2% increase in daily hours of delay. The opposite holds for CAV adoption, which is shown to lead to lower peak period link speed and less congestion. (See full research description and results in Volume 1, Chapter 1.)

2.2 Practical conclusions and recommendations

Our research findings support the following conclusions and recommendations:

- If privately-owned AVs dominate the market in the near future, the impacts on network performance are going to be negative. Lower speeds and higher delays are expected.
- Assuming private ownership, positive impacts on network performance are expected only after the widespread adoption of private CAVs. However, there is significant uncertainty related to the development and manufacturing of CAVs, which leads us to conclude that improvements in network performance may take more than two to three decades to materialize.
- NCDOT should also expect that the network conditions may deteriorate during the period of transition from traditional vehicles to AVs and CAVs if the market penetration of AVs is higher compared to CAVs.
- The negative and the positive impacts

identified through our study are higher in areas with initially higher travel demand (e.g., Wake County). This emphasizes the need for drawing adequate attention to those areas.

- Because private ownership will not lead to system-wide benefits unless there is a substantial CAV adoption rate, we suggest that NCDOT considers policies and shared mobility pilots that will lead to reduced vehicle ownership in the near future.

This study is limited by the lack of mode choice models with personal AV or CAV options for the Triangle Region and the lack of necessary household survey data for developing such models. For this reason, the market penetration of AV and CAV is simulated assuming higher-income households as potential adopters. Future studies should focus on collecting data from households in the Triangle Regions and other regions in NC. Information on households' willingness to adopt and pay for connected and autonomous vehicle technologies should be collected in order to develop mode choice models; these models should later be incorporated in regional travel demand models to allow researchers and NCDOT staff to consider AVs and CAVs in transportation planning scenarios and future decisions.

3. Parking Policies for Private Connected and Autonomous Vehicles and their Effect on Transportation Network Performance

3.1 Research summary and conclusions

Access to connected-autonomous vehicles (CAVs) could provide several parking options to the owners, for instance, sending the vehicle back home, finding cheaper or free parking spots, or relocating somewhere outside the busy central business district (CBD) areas. This study

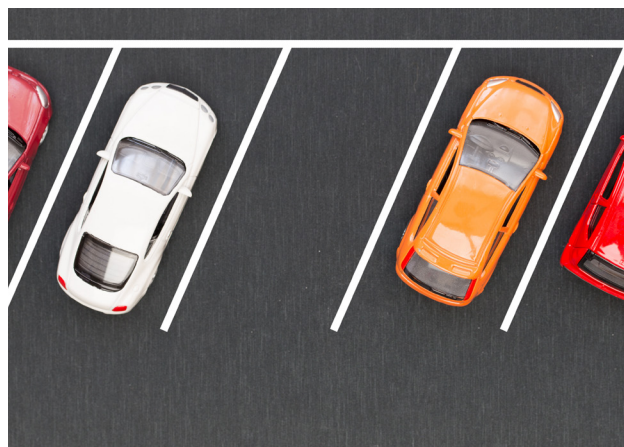
explores a number of parking policies and vehicle relocation scenarios to better understand their regional and local impacts on travel demand. The study focuses on the Triangle Region, NC, which includes three major employment centers (Raleigh, Durham, and Chapel Hill). We use the Triangle Regional Model (TRM), which is the four-step travel demand forecasting model for the Triangle Region, to simulate parking scenarios with 75% market penetration rate of privately owned CAVs for the year 2045. Our results indicate that a single CAV could travel as much as 10.5 miles back to home if the areas outside the CBD do not allow on-street parking of non-resident vehicles, leading to an increase of daily vehicle-miles traveled (VMT), vehicle-hours traveled (VHT) and delay by 3.6%, 10.2% and 43.6%, respectively. On the contrary, providing subsidized parking facilities outside the CBD areas could provide parking for 145,927 vehicles and result in an increase of 1.6%, 7.2%, and 35.3% in daily VMT, VHT, and delays. (See full research description and results in Volume 1, Chapter 2.)

3.2 Practical conclusions and recommendations

- On-street parking fees coupled with time-based fees on empty CAV trips lead to better network performance than other parking policies.
- If employer provided free or subsidized parking facilities are not available inside CBD areas, empty CAV trips to home result in 3.6%, 10.2%, 43.6% and 3.2% increase in daily VMT, VHT, delay, and average travel time to work, respectively.
- Removing parking from the CBD and installing peripheral parking facilities at subsidized parking rates may not be a realistic

solution. It is found that, about 41 peripheral parking facilities, each with parking capacity for 4000 CAVs would be required in order to house all the peak-period parking demand from CAV home-based trips to work.

- Methods and findings of this study will help NCDOT to have a better perspective about the wide range of possible outcomes accompanied by mass adoption of personal CAVs. This will help in forming new and innovative parking policies to avert or alleviate potential adverse impacts of empty self-driving vehicle trips.



Outputs of this study provide useful insights for future downtown parking and land-use policies. This study is limited to home-based work trips while other trip purposes (shopping and other trips) will be considered in future research. Single pricing scenarios are analyzed for on-street parking fees, and for time-based and distance-based empty CAV fees. Future studies should also look into the social impact of empty parking trips which can be revealed by analyzing the distribution of the parking trips into different neighborhoods.

4. Impacts of connected and autonomous vehicles on land use

4.1 Research summary and conclusions

Mass adoption of self-driving vehicle technologies is expected to significantly impact transportation system performance and mobility, which are vital factors of residential location decisions for households. This study investigates and compares the long-term effects of moderate to high market penetration rates of personal AVs and CAVs on the distribution of households within a metropolitan area. First, this study estimates a Mixed Multinomial Logit model to capture the existing residential location choice preferences of households living in the Triangle Region of North Carolina and commuting to work by personal vehicle. Then, the region's transportation network performance for several AV and CAV-related scenarios for the year 2045 is simulated using the Triangle Region four-step travel demand model. The outputs from the travel demand model along with predicted sociodemographic variables for 2045 are used to forecast the future residential location of the studied household population by AV and CAV scenario. The analysis encompasses a wide range of scenarios, including conservative and optimistic levels of market penetration, self-driving vehicles with and without vehicle connectivity components, and fuel types associated with different operating costs, providing a broader spectrum of the potential effects of driverless vehicle technologies.

High market penetration of AVs is characterized by reduced highway capacity, which adversely impacts transportation network speeds, travel time, and delays. Our results indicate that extensive adoption of electric AVs is associated with up to a 1.3 percentage point decrease in the share of households residing in urban

areas compared to the 2045 base scenario. This translates to a 2% decrease in urban households that commute to work by personal vehicle. Adoption of CAVs is expected to enhance highway throughput compared to AVs and human driven vehicles. These conditions motivate households to reside further away from their work location in search of preferable neighborhood amenities and other characteristics without increasing their commute time compared to the 2045 base scenario. For a 75% MPR of electric CAVs, the average commute distance of households with personal CAVs increases by 5.6% compared to the 2045 base scenario. This leads to a 2.0 percentage point increase in the share of households residing in suburban or rural areas within the Triangle Region. This suburbanization trend constitutes the highest impact identified in this study. It reflects an approximately 7% increase in this region's suburban and rural population who commute by personal vehicle through shifts from urban zones. (See full research description and results in Volume 1, Chapter 3)



4.2 Practical conclusions and recommendations

Our research findings support the following conclusions and recommendations:

- Given a transportation network where there are no dedicated lanes for AVs or CAVs in most of the roadway segments, the improved or deteriorated network conditions due to mixed traffic will be experienced by all commuters and may lead to different location decisions even for households that do not own AVs or CAVs.
- Our study suggests that substantial impacts will be experienced mainly for high market penetration of self-driving technologies in combination with vehicle electrification. Therefore, it is likely that it will take more than three decades to realize such impacts.
- CAV adoption is expected to lead to population shifting from urban to suburban and rural areas. NCDOT should carefully consider the forecasted suburbanization trends and promptly explore policies, programs, and investments that discourage private vehicle ownership.



This research investigates the impacts of AVs and CAVs on transportation demand and land use by making assumptions about

people's behavior with respect to adopting, purchasing, and using AVs and CAVs. Although such assumptions are necessary due to lack of household survey data from NC, they could lead to overestimation or underestimation of the estimated effects. It is important to conduct surveys and collect information on household preferences and potential behavior in several hypothetical scenarios to produce more realistic estimates of the transportation and land-use impacts of AVs and CAVs. This will help NCDOT better understand the perceptions of NC households, their willingness to adopt emerging vehicle technologies, and how these technologies will affect commuting and residence location decisions and will shape the NC land uses in the future. In addition, future research should consider the impacts of shared AV and CAV services as well as other trip types and non-working households to provide a more complete picture of the anticipated changes.

5. Impacts of connected and autonomous vehicles on freeway capacity

5.1 Research summary and conclusions

This research explored the mobility effects of connected-autonomous vehicles (CAVs) operating on freeways (both at segment level such as merge, diverge, and basic, and facility-level) in a mixed traffic environment and in platoons on a dedicated freeway lane. In the first instance, CAVs operate along with autonomous (AV) and traditional (TV) vehicles in general-purpose lanes. A microscopic simulation capable of distinguishing between vehicle technologies and employing state-of-the-art, vehicle type-dependent car following and lane changing models to capture the interaction of those vehicles

in the traffic stream was used for this analysis.

Findings of the microsimulation work have indicated that CAVs, in most cases, will yield significant improvements in freeway capacity, whether they operate in mixed flow, but more dramatically when using a dedicated lane. Under mixed flow, the level of improvements is highly dependent on the CAV MPR since platooning is only feasible when multiple CAVs are in proximity of each other. We also found that the introduction of AVs into the traffic stream will reduce capacity. Part of the potential negative impacts on capacity may be due to the OEM policies to put a premium on crash avoidance in the early AV pilot studies, to the detriment of enhanced mobility considerations.

Freeway segment throughput results indicated that for segments with three lanes per direction, reserving a lane for CAVs is beneficial when their market penetration rate is within 20%-60% and optimally at 40%. Outside of this range, throughput degrades significantly due to congestion on either the dedicated or general-purpose lanes. Furthermore, mandating CAVs to operate exclusively in the dedicated lane negatively impacted the throughput at the medium and high feasible ranges (40%-60%), but proved beneficial at the low CAV MPR of 20%. The fundamental diagram and travel rate distribution analyses showed that ramp volumes and access/egress lengths have a significant impact on the freeway facility's performance – the higher the ramp volume and/or the lower the access/egress length, the worse the effect.

The planning level calculator analysis has shown that CAV's capacity contribution is not proportional to their market share in the fleet when operating in mixed traffic. Platooning – a pivotal contributor to capacity increases requires multiple CAV vehicles to be in proximity of

each other, which is not guaranteed in the case of mixed traffic. When CAV demand makes it feasible, a dedicated lane will yield significant capacity improvements to the freeway facility. (See full research description and results in Volume 2, Chapter 1)

5.2 Practical conclusions and recommendations

This research supports the following conclusions and recommendations:

- In general, CAVs yield significant improvements in freeway capacity, whether they operate in mixed flow, but more significantly when operating in a dedicated lane.
- Literature regarding the impact of AVs on capacity is conflicting. This research found that the introduction of AVs to the traffic stream will reduce throughput. This reduction can be attributed to the conservative gap settings needed for safe operations of AVs and the problematic nature of the interaction between AVs and TVs.
- Lane reservation for equipped vehicles depends on a number of factors such as demand, ramp volume, access/egress lengths,



and market penetration rates. For a three-lane per direction freeway segment, reserving a lane for CAVs is only beneficial when the market penetration rate is within 20%-60%.

This study investigated the impact of CAVs and AVs on freeway throughput and reserving lanes for equipped vehicles. Further research is needed to generate additional speed flow relationships from microsimulation, covering a range of market penetrations of vehicle technologies, with the possible objective of generating passenger car (or TV) equivalencies for mixed traffic flow. Another important direction is to model the heterogeneity in car-following and lane-changing behavior which will be available to OEM clients in the future and which will impact the capacity estimates. Thirdly, an analysis of lane width requirements for CAVs to operate is recommended. The literature provided some evidence that, because of automation and connectivity, seven or eight or feet lanes may be sufficient, raising the prospect of retrofitting existing freeway cross-sections to serve CAVs without taking out any GP lanes. Finally, the team recommends using real-world pilot test data of CAVs and AVs to assist in developing and testing surrogate safety measures in a microscopic simulation environment.

6. The effects of connectivity and automation on traffic operations at signalized intersections

6.1 Research summary and conclusions

This research evaluated the potential effect of different connectivity and automation levels on saturation headway and several mobility performance measures at signalized intersections. The research team considered four vehicle types in this project as (I) human-driven vehicles, (II)

connected vehicles, (III) automated vehicles, and (IV) connected and automated vehicles. Vissim was used as a testbed to simulate the movement of vehicles with different driving behaviors and study their potential effects on mobility when they interact with each other and traffic signal controllers under various market penetration rates.

The result of this study showed that CAVs provide the most efficient mobility. CVs also improve mobility due to receiving advance information about the future signal timing plans. As a result, CVs will adjust their speed upstream of the intersection and arrive during the green traffic light. In contrast with CVs and CAVs, AVs drive more cautiously and yield longer saturation headways and delays. (See full research description and results in Volume 2, Chapter 2)

6.2 Practical conclusions and recommendations

Our research findings support the following conclusions and recommendations:

- Connectivity of vehicles to traffic signal controllers leads to reductions in saturation headway and consequently to increase in capacity of lane groups at signalized intersections. This trend is consistent for both connected human-driven and automated vehicles.
- Automated vehicles with no connectivity did not present a positive influence on traffic operations in signalized intersections and increased saturation headway.
- Connected automated vehicles on the other hand, yielded the highest improvement in traffic operations at signalized intersections and reduced the saturation headway by 80%.

This study determined saturation headway for different lane groups under various CV, AV,

and CAV market penetration rates. These values could be used to calculate the saturation flow rate and capacity of various lane groups in the presence of CAVs. The results of this study are based on making changes in certain parameters of car-following and lane-changing models of Vissim, which were originally designed to represent human driving behavior. Further studies are required to replace the car following and lane changing logics of existing simulation packages with logics specifically designed for CVs, AVs, and CAVs.

7. Impacts of Connected and Autonomous Trucks on Urban Network Performance

7.1 Research summary

The travel demand modeling study done is focused on autonomous freight trips in an urban area, the Triangle region of North Carolina to be specific. The Triangle Regional Model (TRM), which is a planning model employed by the Capital Area Metropolitan Planning Organization (CAMPO), was used as the analysis tool. The analysis year was chosen to be 2045 simply because the TRM is presently validated for that horizon year. We study autonomy levels 4 and 5 as specified by the Society of Automotive Engineers (SAE). For level 4, we assume the AVs can operate autonomously on controlled access facilities like freeways; they will be more amenable to AV operation than “lower class” facilities. For level 5, we assume they can use any link although we encourage them, through preferential weights, to use “higher-type” facilities where possible. We do not distinguish between AVs with and without communication/connection capabilities. We assume all of the AVs are connected as well as autonomous. The three main questions we

address are: 1) to what extent can AVs reduce the peak period levels of congestion, 2) what operational changes will be needed, and 3) what if any special facilities might be needed to accommodate these flows. There are different treatments done for AV trips depending on the level of automation. In the case of level 4, we assume a probability that traditional truck (TV) trips will be converted to blended conventional-automated trips (TAVs); and for level 5 we assume a likelihood that all TV trips will become AV trips. In order to have safe “mode transitions” between AV and TV modes, TAZs were flagged as “mode change lots” (MCLs). A TV can enter an MCL to shift from TV to AV mode, letting the driver disembark (the driver also might stay with the vehicle). At the end of the AV segment of the trip, the truck would enter a second MCL and undergo a similar mode change, in reverse. (See full research description and results in Volume 3, Chapter 1)

7.2 Practical conclusions and recommendations

The level 4 study findings are as follows:

- Because the changes only pertain to single unit trucks (SUTs) and multiple unit trucks (MUTs), and those flows are such a small portion of the overall trip table, it was not possible to see significant changes in aggregate measures. This is a significant finding. Thus, it should not be expected that a shift from TVs to a mixture of TVs and TAVs will not have a profound impact on the way in which the urban network functions during the peak hours.
- The various treatments applied like shifting TV trips to TAV trips, rerouting the TAV trips, with greater circuitry, so that they made use of the

freeways, and shifting the AV trips out of the peak, created mixed impacts. The shift toward longer trips for the TAVs increased VMTs and VHTs in some facilities while reduced the VMTs and VHTs in others.

- The clearest picture was obtained by examining change in total VMT and VHT, splayed out for all the links in the network. This representation of results showed that there was a decrease in VMTs and VHTs on urban freeways, urban and rural interstate, but an increase in other facilities like urban & rural collector-distributors and urban & rural arterials. This trend was observed for both 30% and 100% AV diversion rates and also for their respective sub-scenarios where circuitry was 15% and 25%.

In the level 5 analysis, the same trends in cumulative VMT and VHT as level 4 were observed. The decrease in VMTs and VHTs was more substantial as compared to level 4 which is understandable given the assumptions associated with the level-5 vehicles.

8. Impacts of Connected and Autonomous Trucks on Freeway Operations

8.1 Research summary

Our main objective was to explore the extent to which highway operations, especially on freeways, might be affected by the presence of the Truck-CAVs (T-CAVs). We perceived that the best way to do this was to create a microscopic simulation model of this mixed vehicular environment and apply that model to typical freeway situations; namely, a basic freeway section and a typical urban setting that involved an on ramp followed by an off-ramp. We also wanted to explore the impacts of specifying which lanes could be

used by the T-CAVs, either all lanes or just the middle lane. SUMO, which is an open-source microsimulation software, was selected for this study. The simulation runs can be thought of as being of two types: 1) a basic freeway segment or 2) a “weaving” segment, technically an on-ramp followed by an off-ramp. The results from the analysis are both informative and reassuring. We explored truck percentages ranging from 10% to 40%, and percentages of T-CAVs ranging from 0% to 100%. A three-number scheme was used to identify the vehicle mix. For example, 20-0-80 indicates 20% T-CAVs, no conventional trucks, and 80% autos. Many traffic mixes and operating conditions were explored. (See full research description and results in Volume 3, Chapter 2.)



8.2 Practical conclusions and recommendations

The simulation study indicates the following:

- The effects of the T-CAVs are minor. Even when the percentage of T-CAVs is 40%, there is not a dramatic impact on the travel rates. There appears to be a minor change in the percentage of lane changes that occur, especially from the right-hand lane to the middle lane.

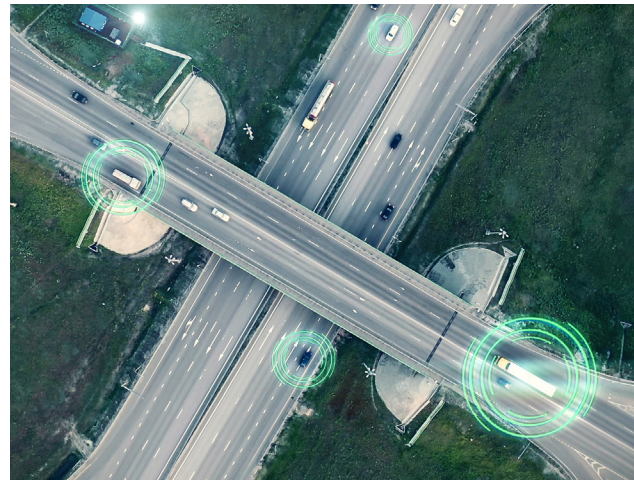
- Moreover, when use of the middle lane is mandated for the T-CAVs, there does not appear to be a major impact on either the travel rates or the lane changing behavior. This is good news in that, if a policy decision is made to require T-CAVs to use the middle lane, that decision will not have an adverse effect on freeway operations, at least for T-CAV percentages up to 40%.
- The travel rates were found to be somewhat higher than for the basic freeway section, which should be expected since weaving movements are taking place.
- The percentage of T-CAVs in the traffic stream, at least up to 20%, does not appear to have a significant impact on either the travel rates or the percentages of lane changes.
- Restricting the T-CAVs to use the middle lane does not appear to have a significant impact either.
- As was observed for the basic freeway section analysis, if there is desire to implement a policy where T-CAVs are “required” to use the center lane, this will not have an adverse impact on the performance of the weaving section.

9. The effects of vehicle automation on energy use and emissions

9.1 Research summary and conclusions

Eco-driving refers to economical or ecological driving depending on interest in reducing fuel use or air pollutant emissions, respectively. Eco-driving offers potential to reduce fuel use and emission rates (FUERs) of light-duty gasoline vehicles (LDGVs). AVs can include LDGVs. To quantify FUERs reduction potential via eco-driving, AVs were assumed to be operated similarly to those of the most efficient human driving with traditional

vehicles. Three million seconds of real-world speed trajectory data were analyzed based on predominantly naturalistic driving of 160 drivers on eight mesoscale routes in the Triangle Region. The routes, with a total length of 110 miles, were divided into 199 microscale segments. A Vehicle Specific Power (VSP) modal model was used to estimate trajectory-average FUERs of CO₂, CO, hydrocarbons (HC), NO_x, and particulate matter (PM) for over 200 trajectories per route and segment.



At mesoscale, eco-driving is an effective strategy to reduce LDGV fuel use and tailpipe emission rates of CO₂, CO, HC, NO_x, and PM. Depending on species, route, and vehicle type, mesoscale rate reduction potential ranges from 6% to 40%, compared to average rates estimated based on all trajectories. FUERs reduction potential varies by route and species. Compared to route-average rates, there are co-benefits of economical driving in reducing air pollutant emission rates, and, similarly, there are co-benefits of ecological driving in saving fuel. However, compared to route-minimum rates, there are inter-species tradeoffs in rates

associated with eco-driving due to different sensitivity to engine power demand among species.

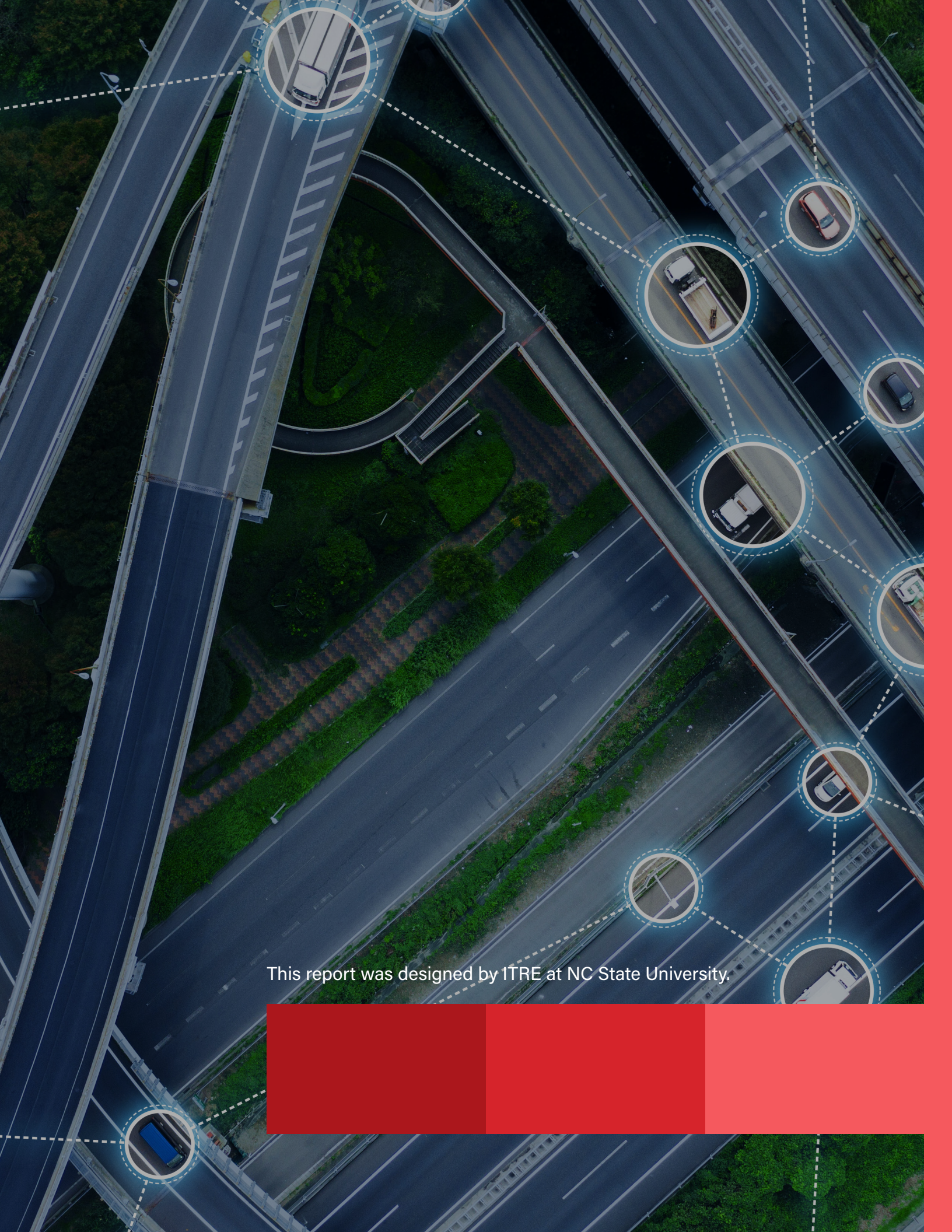
Mesoscale eco-driving typically leads to travel time tradeoffs, on average 20%, compared to the fastest trajectories. However, compared to the route-minimum rates, choosing the fastest trajectories would cause on average 18% tradeoffs for rates of fuel, CO₂, HC, NO_x, and PM and on average 151% tradeoffs for CO emission rates due to more high engine power demand episodes compared to eco-driving.

Real-world mesoscale eco-driving for a route typically has co-benefits in reducing microscale emissions, such as on average 24% FUERs reduction potential for 85% to 95% of the emission hotspots, but can exacerbate FUERs of the remaining emission hotspots by an average 15%. Eco-driving trajectories can be developed such that mesoscale and microscale FUERs are concurrently reduced. (See full research description and results in Volume 3, Chapter 3)

9.2 Practical conclusions and recommendations

- Based on LDGVs, eco-driving is expected to enable moderate FUERs reduction potential for individual AVs by improving speed trajectories.
- Eco-driving focused on fuel savings typically reduced air pollutant emissions and vice versa.
- AV eco-driving can moderately penalize travel time, whereas trajectories aimed at reducing travel time are expected to increase FUERs.
- Mesoscale eco-driving typically but not always concurrently reduces microscale emissions.

These results focus on individual vehicles. However, eco-driving of one vehicle may affect the eco-driving of other vehicles within a road network, such as due to conflicting movements of crossroads and main corridors. Thus, evaluation of the effectiveness of eco-driving in mitigating road network FUERs is recommended.



This report was designed by ITRE at NC State University.

