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## Adapting Crash Modification Factors for the Connected and Autonomous Vehicle Environment

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Dr. Timothy Taylor, Director of Graduate Studies

ADAPTING CRASH MODIFICATION FACTORS FOR THE CONNECTED  
AND AUTONOMOUS VEHICLE ENVIRONMENT

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THESIS

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A thesis submitted in partial fulfillment of the  
requirements for the degree of Master of Science  
in Civil Engineering in the College of Engineering  
at the University of Kentucky

By

Federico Valentin Lause, iii

Lexington, Kentucky

Director: Dr. Reginald R. Souleyrette, Professor of Civil Engineering

Lexington, Kentucky

2019

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## ABSTRACT OF THESIS

### ADAPTING CRASH MODIFICATION FACTORS FOR THE CONNECTED AND AUTONOMOUS VEHICLE ENVIRONMENT

The Crash Modification Factor (CMF) clearinghouse can be used to estimate benefits for specific highway safety countermeasures. It assists safety professionals in the allocation of investments. The clearinghouse contains over 7000 entries of which only 446 are categorized as intelligent transportation systems or advanced technology, but none directly address connected or autonomous vehicles (CAVs). Further, the effectiveness of highway safety countermeasures is assumed to remain constant over time, an assumption that is particularly problematic as new technologies are introduced. For example, for the existing fleet of human driven vehicles, installation of rumble strip can potentially reduce “run off road” crashes by 40%. If specific CAV technologies, e.g., lane-tracking, can work without rumble strips, and say, half of all cars are so equipped, only half of the fleet will benefit, reducing the benefits of rumble strips by a commensurate amount. Benefits of the two improvements, e.g., rumble strips and automated vehicles, should not be double-counted. As there will still be human driven and/or non-connected vehicles in the fleet, conventional countermeasures are still necessary, although returns on conventional safety investments may be significantly overestimated. This is important as safety investments should be optimized and geared to future, not past fleets. Moreover, as CMFs are based on historical events, the types of crashes experienced by human-driven, un-connected cars are likely to be much different in the future. This research presents methods to estimate the safety benefits that autonomous vehicles have to offer and the changes needed in CMFs as a result of their adoption. This will primarily be achieved by modifying and enhancing a tool co-developed by the Fellow that estimates safety benefits of different levels of autonomy. This tool, ddSAFCAT, estimates CAV safety benefits using real-world data for crashes, market penetration, and effectiveness.

KEYWORDS: Connected Vehicles, Autonomous Vehicles, Crash Modification Factors,  
Highway Safety Analysis.

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07/18/2019

Date

ADAPTING CRASH MODIFICATION FACTORS FOR THE CONNECTED  
AND AUTONOMOUS VEHICLE ENVIRONMENT

By  
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## CHAPTER 1. INTRODUCTION

### 1.1 Background and Motivation

Although highway crashes and their attendant human and economic losses remain problematic in the United States (US) and around the world, there has been a downward trend in the number of crashes and fatalities over the past 30 years — especially in developed countries. However, after a sustained period of decline, vehicle fatalities have remained steady over the past 10 years (NHTSA 2019). Officials at transportation agencies are engaged in a concerted effort to improve safety further, chiefly by adopting *substantive safety* practices by using tools such as the *Highway Safety Manual* (HSM) and Interactive Highway Safety Design Model (IHSDM). These tools allow for greater flexibility in highway design and account for many factors that affect highway safety (FHWA 2009).

Stakeholders throughout the transportation industry believe that connected and automated vehicles (CAVs) hold the greatest promise to significantly reduce highway crashes. CAVs is a broad term that encompasses both connected vehicles and automated vehicles. Connected vehicles (CVs) have onboard equipment allowing them to communicate with other vehicles (vehicle-to-vehicle [V2V]); infrastructure (vehicle-to-infrastructure [V2I]); or other vehicles, infrastructure, pedestrians, data centers, and the cloud (vehicle-to-everything [V2X]). Depending on the level of automation, an automated vehicle (AV) performs some or all driving functions with limited input or entirely without input from human drivers (vehicles that do not require inputs from humans to execute driving maneuvers are classified as self-driving or autonomous) (Kalra and Paddock 2016). Vehicles can have connected *and* automated functions, so the classifications should not be viewed as mutually exclusive. Despite the promise of CAVs, these new *substantive*

*safety* approaches do not account for evolutions in vehicle technology. New analytical procedures are needed.

Given the potential for CAVs to significantly improve highway safety, some researchers have suggested that funding must be adequately allocated to the geographic locations that are most likely to experience an increase in market penetration of CAVs (Zhao and Kockelman 2017). Investment decisions must be guided by reliable estimates of costs and benefits. While current safety analytics can effectively estimate the benefits of various safety countermeasures, if they are insensitive to technological changes, they cannot be used to estimate future benefits.

## 1.2 Problem Statement and Objectives

The proliferation of CAVs will require changes in many aspects of highway infrastructure management, from policy to planning, design, operations, maintenance, and renewal. Major changes are likewise needed in highway safety analytics, particularly given that countermeasures DOTs currently deploy to mitigate crashes are designed with non-automated vehicles in mind. Safety countermeasures that are effective in the current transportation environment may require dramatic transformations as CAV technologies are adopted more widely. CAVs are likely to have safety benefits similar to conventional countermeasures. Benefits of the two improvements, e.g., rumble strips and automated vehicles, should not be double-counted. As there will still be human driven and/or non-connected vehicles in the fleet, conventional countermeasures are still necessary, although returns on conventional safety investments may be significantly overestimated. This is important as safety investments should be optimized and geared to future, not past fleets.

Several scenarios can be envisioned that could make these countermeasures more effective or less effective when taking CAVs into account.

This thesis develops a framework to analyze safety countermeasures in the context of vehicle fleets with varying levels of automation. A spreadsheet-based tool — ddSAFCAT — is introduced to demonstrate the utility and application of the framework. The tool’s main function is to estimate safety gains (i.e., reductions in fatalities) but it can also be used to estimate changes in countermeasure effectiveness. State departments of transportation (DOTs) can use ddSAFCAT to make more informed investment decisions when selecting countermeasures use for projects or include in lists.

### 1.3 Outline

Extensive literature reviews in Chapters 2 and 3 focus on two areas: 1) current safety practices and how countermeasures are managed, and 2) CAV capabilities and their relationship to overall safety. Assumptions are made of how these countermeasures and their parts might evolve with these technologies.

Chapter 2 discusses the literature on safety practices, focusing in particular on material the *Highway Safety Manual*. Countermeasures are defined and a method for quantifying their effectiveness is outlined. Because a large number of countermeasures may be considered, and the effectiveness of each countermeasure can be calculated differently, state DOTs often collect the most appropriate or frequently used countermeasures into a short list to examine in lieu of larger database.

Chapter 3 provides background on CAV technologies and methodologies for evaluating them over time. The potential benefits of these technologies must be quantified in some way. Previous studies have tended to categorize benefits according to the type of

technology available. After establishing the potential benefits of CAVs, many studies indicate they are closely linked to market penetration, and attempt to forecast it. The influence of CAVs on countermeasures is explored before presenting a unique forecasting tool.

Chapter 4 demonstrates the use of ddSAFCAT to assess the effectiveness of countermeasure for mixed vehicles fleets — those with both automated and non-automated vehicles. While the effectiveness of some countermeasures may increase over time, others may lose effectiveness; both possibilities must be considered when evaluating countermeasures for a project or short list. Chapter 5 summarizes techniques for assessing the effectiveness of countermeasures, presents future research topics, and offers concluding remarks.

## CHAPTER 2. CURRENT PRACTICE

### 2.1 Introduction

Methods for evaluating countermeasures may require adjustment to properly account for the expanded presence of CAVs on highway networks. Short-term changes are often accounted for since these countermeasures can yield different results based on variability in environmental conditions (e.g. day/night, seasonality, weather conditions). Although DOT officials frequently discuss the lifespan of a countermeasure When it is considered for a project, long-term changes of its effectiveness are not. While a number of studies have examined the positive safety impacts of CAVs, these improvements will only materialize if the physical infrastructure is sufficient enough to support them. As such, a change in the current safety practices should be made to reflect the increase of CAVs and changes in infrastructure.

### 2.2 The Crash Modification Factor

Before identifying potential modifications to how countermeasures are currently approached, it is important understand what countermeasures are and the tools used to gauge their effectiveness. A safety countermeasure is treatment designed to influence the crash characteristics of a site. Examples of countermeasures include road diets, the installation of median barriers, and the construction of roundabouts, among others (the Federal Highway Administration [FHWA] has identified 20 proven countermeasures. Typically, a transportation agency adopts a countermeasure to reduce the number and/or severity of crashes (HSM 2010). The effectiveness of a countermeasure is quantified using a crash modification factor (CMF). According to the FHWA, a “CMF estimates a safety

countermeasure’s ability to reduce crashes and crash severity” (FHWA 2017). A CMF is a multiplicative factor applied to either historical crash data or the forecasted output of a safety performance function (SPF) to estimate a countermeasure’s potential safety benefit. Many portions of the HSM invoke the term accident modification factors (AMF), which are essentially the same as CMFs. SPFs are equations used to predict crash frequency. Part C of the HSM explains how SPFs are developed; generally, their development requires more data than can be supplied by historical crash data (AASHTO 2010). An SPF is typically some function of exposure (e.g., AADT, segment length, time) and crash characteristics. Using forecasted changes in AADT, an SPF can be used to predict crash frequency at a given point in the future. An example of an SPF curve can be seen below (FHWA 2009):

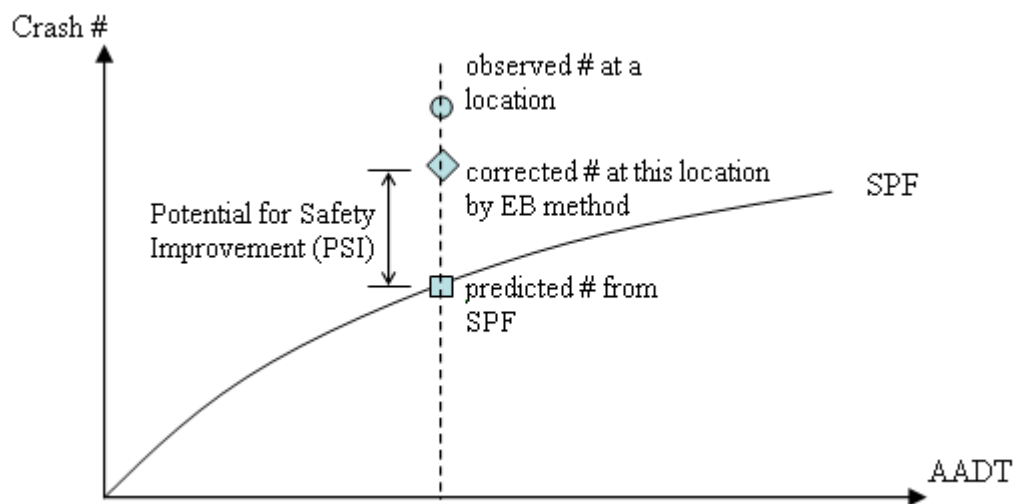


Figure 2-1 Potential for Safety Improvement Graphical Definition

SPFs are developed through statistical regression modeling of crash data. SPFs can be corrected using the Empirical Bayes (EB) method to account for regression to the mean bias as well as any random fluctuations in the data.



### 2.3 Calculating CMFs

CMFs are frequently used by transportation officials when conducting cost-benefit analysis to identify countermeasures with the greatest safety benefits (Gan et al. 2005). HSM Equation 3-5 is typically used to calculate a CMF. It is used to determine the ratio between the expected average crash frequencies of a site under two conditions (HSM 2010):

$$CMF = \frac{\textit{Expected Average Crash Frequency with Site Condition B}}{\textit{Expected Average Crash Frequency with Site Condition A}}$$

Often, a countermeasure has more than one CMF associated with it because its effectiveness varies based on contextual factors. For this reason, some state DOTs create lists of CMF values to use on their projects. CMFs are often confused with crash reduction factors (CRFs). The two terms are very similar and mathematically related to one another, as captured in the following equation:

$$CRF = (1 - CMF) * 100$$

In many cases, the safety benefit of a countermeasure is quantified using a crash modification function (CMFunction), which is an equation that calculates a CMF based on the characteristics of the site to which it will be applied (CMF Clearinghouse). These are often used to determine the effects of countermeasures which subtly or incrementally alter site characteristics (e.g., increasing retroreflectivity of striping by a certain amount, increasing lane width by a specified distance).

Countermeasure benefits vary according to weather type, day/night cycle, crash type, or other factors; the influence of these variables — specifically, the likelihood they will affect site conditions — should be examined when choosing countermeasures for a project (Harkey et al.). The number of potential CMFs is overwhelming, numbering into

the thousands. Fortunately, resources are available that compile and categorize CMFs. For example, the HSM contains numerous CMFs and describes processes on for their application. However, the most abundant source is the CMF Clearinghouse, an online tool which contains over 7,000 entries.

## 2.4 CMF Selection Processes

While the CMF Clearinghouse has excellent tools to search for CMFs, selecting one from the over 7,000 entries can be a daunting challenge. Because multiple CMFs are often associated with a given countermeasure, some DOTs develop lists of suggested CMFs to use on agency projects. The structure of these lists vary by state. CMFs can be organized by crash type, benefit-cost ratio, jurisdiction, functional class, design type, quality rating, appropriateness for project funding source, or another factor. To prepare a short list of CMFs for Kentucky, this research looked at practices in seven states. Practices were not studied in a particular order, and the examination of these practices relied mainly on documentation that is available publicly online (with some exceptions).

Readers should be note that some previous work has been done in Kentucky to develop a list of CMFs. In 2018, the VHB company produced a list of 94 CMFs to use in the state for planning purposes (Read 2015). The methodology used to develop this list is unknown. The Kentucky Transportation Center (KTC) also developed a list 1996, however, the purpose of this list was only to associate CRFs with types of highway improvement (Agent et al.1996).

The Oregon DOT categorizes CMFs according to countermeasures in its CRF appendix. Countermeasures are grouped into two categories: 1) those eligible for *hotspot* funding, and 2) those eligible for *systemic* or *hotspot* funding. The systemic category can

be subdivided even further, but for informational purposes only. The appendix contains relevant information on each countermeasure, and it references the CMF Clearinghouse, HSM, and the older FHWA's *Desktop Reference for CRFs* (McDaniel-Wilson).

The Washington State DOT has adopted a more traditional breakdown for its CMF Short List. Countermeasures are grouped in a manner similar to the CMF Clearinghouse, which is the only reference used. Multiple CMFs are presented for each countermeasure, and entries contain all relevant information that would be found in the CMF Clearinghouse. Before a countermeasure is added to the list, a CMF Review Form must be filled out by an engineer and reviewed by a committee. The CMF short list is not exhaustive and users have the option to explore CMFs from external sources, such as the FHWA's *Desktop Reference for CRFs* or HSM (*WSDOT Crash Modification Factor (CMF) "Short List"*).

The North Carolina DOT established a Crash Reduction Factor Committee (CRFC) to oversee the development and maintenance of the agency's CMF short list. If multiple CMFs are associated with a countermeasure, the committee generally selects the CMF with the highest star rating and lowest standard error. Particular CMFs are put to a vote as needed. The CRFC is also responsible for deciding when to use values not found in the CMF clearinghouse. When this occurs, a CMF is calculated in-house using the state's crash data and project history until additional research is conducted. Countermeasures are evaluated by performing a before/after Empirical Bayes analysis on similar projects in the state; this is done in conjunction with a typical cost-benefit analysis. Specific examples can be found in short list (Smith and Scopatz 2016).

The Wisconsin DOT maintains a table of CMFs organized by countermeasure in an Excel-based tool. With the tool, users can filter countermeasure categories to identify a CMF best suited to their project. It contains notes on when and how to properly consider a CMF. The agency's tool only includes CMFs for countermeasures frequently used in the state. If more than one CMF can be used to quantify the effect of a particular treatment, the agency selects one by matching the CMF characteristics to the roadway features and crash profiles of the most common sites under evaluation (*Traffic Engineering, Operations & Safety Manual* 2005).

The Florida DOT has developed a method to update the agency's existing list of CRFs as well as to automate updates to the short list when new improvement projects become available. The agency has also built a web-based application called the Crash Reduction Analysis System Hub (CRASH). The system catalogues safety improvement projects throughout the state and updates CRFs using a before/after analysis of Florida-specific crash data. CRASH is also equipped to undertake cost-benefit analysis for project evaluations. When developing its short list and building CRASH, agency personnel gathered information on best practices used by other state DOTs to manage CRFs (Gan et al. 2005).

Prepared by the Larson Transportation Institute, the Pennsylvania DOT's guidance on the proper application of CMFs outlines methods for transportation officials to integrate CMFs into their safety plans. Development of this guidance motivated the preparation of a list of CMFs relevant to the state of Pennsylvania. Along with the CMF list, the guidance outlines a training protocol for the proper utilization of CMFs. Only *high quality* CMFs were considered; criteria such as star rating and standard error were used to determine

which CMFs are high quality (Donnell and Gayah 2014). After the initial development of guidance, the agency narrowed its search criteria for CMFs. It first developed state-specific SPFs for rural two-lane roads, and then adjusted its CMF list accordingly. The Pennsylvania DOT privileged CMFs in the CMF Clearinghouse which rely on data unique to the state or other states with similar characteristics. If CMFs meeting these criteria were not available, the agency selected CMFs with star ratings of 5. If more than one CMF had high ratings, stakeholders reviewed each in the Clearinghouse (Scopatz and Smith 2016).

No state DOT reviewed as part of this research has established protocols to understand the influence of proliferating CAV technologies on how countermeasures — as well as CMFs and CRFs — are selected. As vehicles equipped with CAV technologies become more numerous and exert significant influence on both traffic dynamics and infrastructure management, it is probable that agency officials will need to rethink their approach to countermeasure selection. New methodologies are therefore needed to analyze the implications of CAVs for the efficacy of various countermeasures and their associated CMFs and CRFs.

## CHAPTER 3. METHODOLOGY

### 3.1 CAV Measures of Effectiveness

Before exploring how countermeasures might change in response to CAVs, it is important to grasp the capabilities of CAV technologies. A common assumption is that CAV technologies will enable vehicles to operate more safely than those helmed by human drivers alone (Kalra and Groves 2017). While this is likely the case, this argument is often supported by misleading evidence about the influence of human error on crashes. One persistent misconception is that 94% of all crashes are due to human error, which is true to some degree (NHTSA 2017). In reality, the 94% encompasses all people involved in a crash, not necessarily the driver (Koopman 2018). Another enduring myth is that most fatal crashes are the product of cell phone distraction — but impairment, not wearing seatbelts, and speeding are also common contributing factors. National crash statistics from 2016 indicate that distraction-affected fatalities decreased by 2.2%, while alcohol impairment and speeding related fatalities increased by 1.7% and 4% respectively (NHTSA 2017). Potential improvements in vehicle operations from CAV technologies can help reduce human error; it is possible their use will reduce fatal crashes by half over the long-term (Koopman 2018).

To gauge the potential benefits of CAVs, researchers have employed a measures of effectiveness (MOE) framework. An MOE framework includes up to five dimensions: safety, efficiency, environmental impacts, land use, and user experience (Tian et al. n.d.). The first three elements are performance-oriented facets of the taxonomy. Bolstering highway safety is a primary goal of most CAV technologies. Examples of available CAV technologies intended to enhance safety are numerous — collision warning systems, lane

assist, emergency breaking, and adaptive headlights, among others. Mobility applications of CAV technologies seek improvements in operational efficiency (e.g., increasing roadway capacity, decreasing travel time). Examples of emerging mobility applications are truck platooning and advanced traffic signal coordination facilitated by CVs (Tian et al.).

Interactions between the three performance-oriented MOEs can be represented with a Venn diagram (Figure 1) that classifies CAV applications into infrastructure-centric, traveler-centric, and vehicle-centric applications (Tian et al.). Environmental impacts are not generally a priority when assessing the benefits of a countermeasure. A good portion of Tian et al.'s study merely groups CAV applications into the categories shown in the diagram.

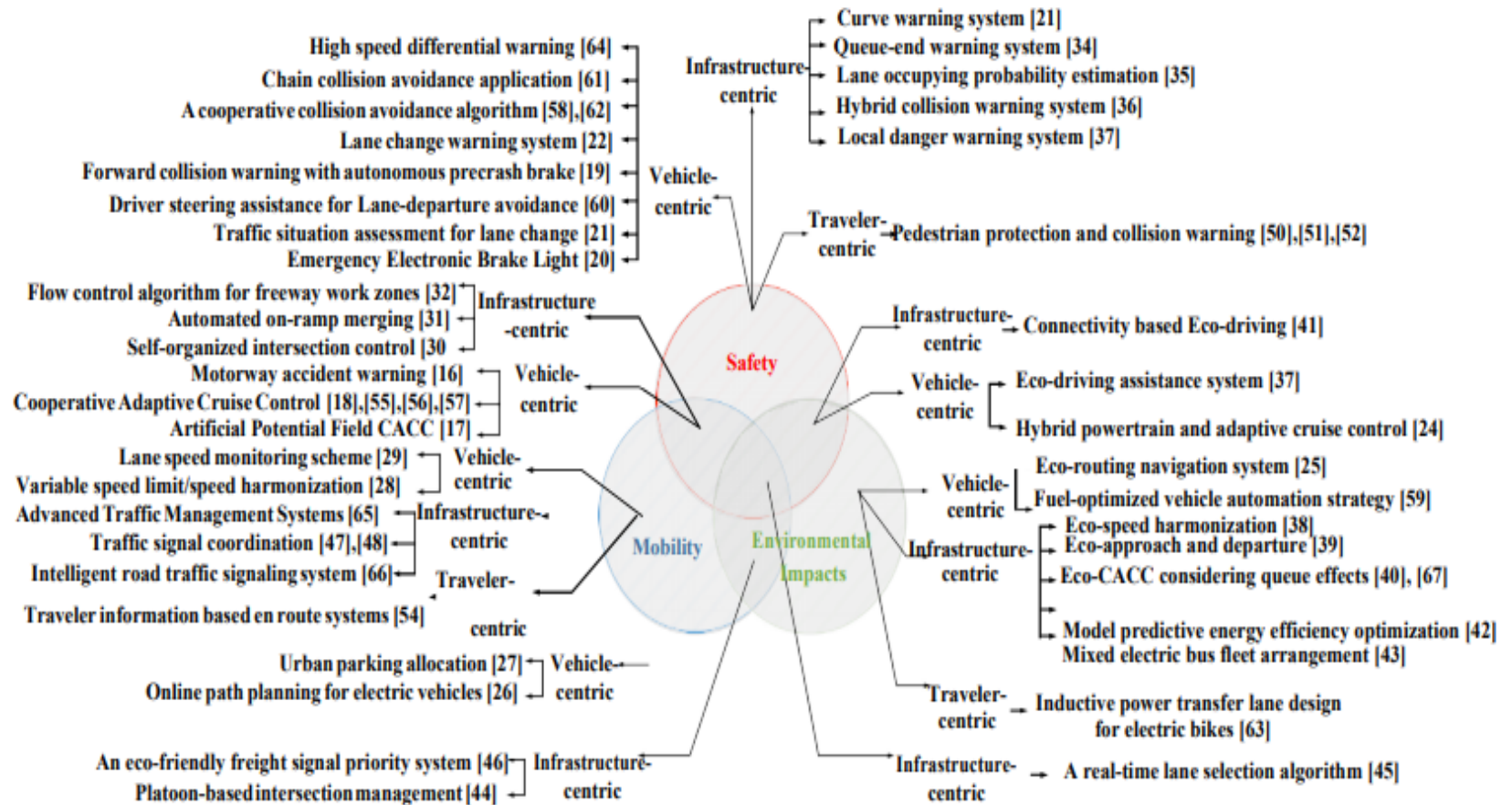


Figure 3-1 CAV Taxonomy



With respect to Focusing on the infrastructure-centric CAV applications focused on safety and mobility, it is probable urban locations will experience the greatest benefits. Dedicated short range communications (DSRC) and similar CV technologies will play a critical role by facilitating better intersection coordination. In decentralized locations, sophisticated ramp-merging systems hold great promise for improving safety and mobility by leveraging a distance decision algorithm and a fuzzy controller which use information acquired from V2I technology. Similarly, a lane merging system derived from a flow control algorithm lets CAVs better navigate work zones.

The MOE framework presented by Koopman and Fratrick (2019) contains four dimensions: operational design domain (ODD), object and event detection and response (OEDR), maneuvers, and fault management. ODD limits the operational needs of an automated system by constraining the operational environment to a subset of all possible situations. Examples include geometric road designs, environmental/weather conditions, and infrastructure characteristics (e.g., traffic lights, signage). OEDR describes an operation within a defined ODD — it generally refers to the proper handling of external situations. Two subcategories fall under OEDR: object factors and event factors. Object factors include static or dynamic obstacles (e.g., pedestrians, guardrail, trees) and the system's ability to detect them. Event factors account for the behaviors of object factors as well as the system/operator's interactions with them (i.e., the Haddon matrix described in the HSM). Maneuvers are the actions taken to move from one point in space to another while avoiding obstacles; they are typically guided by some form of navigation. Lastly, fault management is a multilayered dimension of validation that includes system limitations, which specify what the system is capable of; system faults, which detail system

errors; and fault responses, which is how the system manages and corrects errors (Koopman and Fratrick 2019).

### 3.2 CAV Market penetration

The consensus among transportation researchers is that the magnitude of safety, mobility, and environmental benefits realized through the adoption of CAV technologies will be contingent upon how rapid and widespread their proliferation is (Bansal and Kockelman 2017, Lavasani et al. 2016, Kalra and Groves 2017). But market penetration is likely to be uneven in the US due to demographic variability. Purchasing vehicles equipped with CAV technologies is a function of age, sex, income, population density, health, and many other factors. While these technologies are gradually filtering into less expensive vehicles, the most sophisticated CAV systems tend to be found on vehicles in the high-end market segment. Additionally, the use of AVs — once they become available — will probably vary by trip types and travel purposes (Bansal and Kockelman 2017).

Researchers have been turning more and more of their attention to the safety implications of AVs. Because AVs are not currently available to consumers and are only present in small numbers on roadways, models for estimating the safety benefits of these vehicles are generally constructed using historical data on vehicle safety. For example, the Rand Model of Autonomous Vehicle Safety (MAVS) estimates the safety benefits of AVs by comparing the rate of market penetration to the time at which penetration begins. Market penetration is thus a primary model input and is treated as an assumed value that the user inputs. The model suggests that introducing AVs to market sooner and more gradually will yield greater safety benefits than delaying their introduction and ramping up production and sales at a much faster pace (Kalra and Groves 2017).

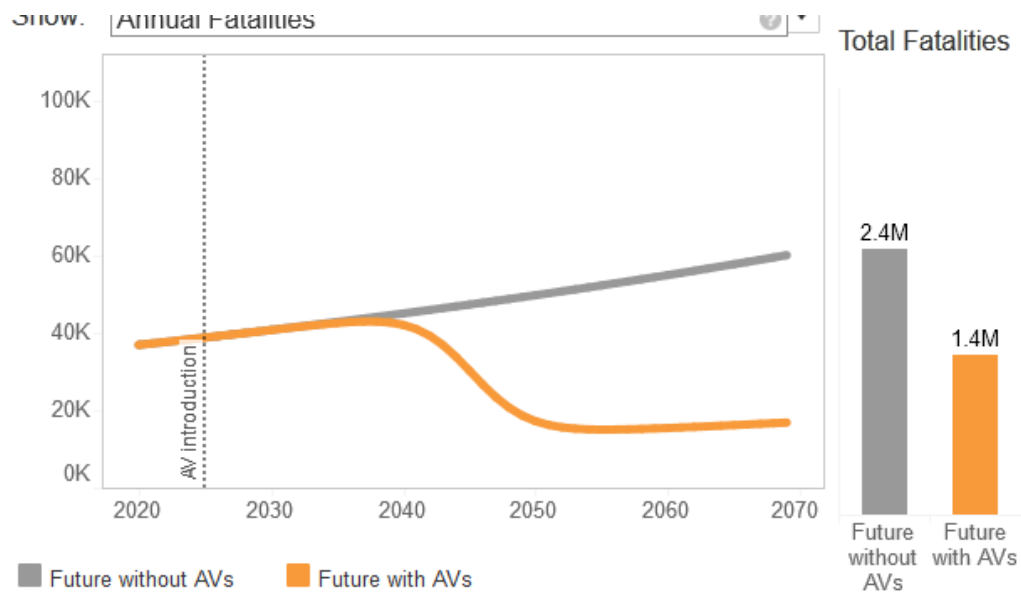


Figure 3-2 Rand MAVS

Estimating market penetration is difficult; the rate of adoption will ultimately be influenced by the affordability and public acceptance of AV technologies. Statistically analyzing population demographics is critical, as the likelihood of AV adoption varies by age, income (and average vehicle cost/maintenance), and vehicle performance (Bansal and Kockelman 2018). Although forecasting the rate at which fully autonomous vehicles will penetrate the market is difficult, researchers are attempting to generate predications based on the current availability of advanced driver assistance systems (ADAS) (Koopman 2017). Lavasani et al. (2016) developed a Bass diffusion model to analyze national market trends in hybrid-electric vehicles and cell phones to derive parameters for an S-curve model. (Lavasani et al. 2016).

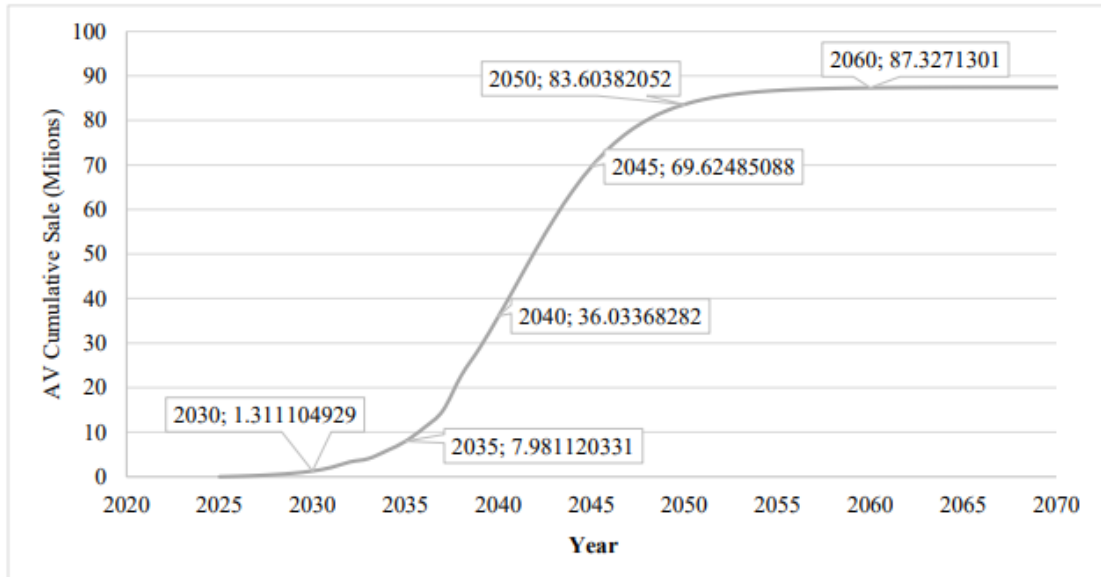


Figure 3-3 Bass Diffusion Market Penetration of CAVs

Figure 3-3 illustrates trends in the cumulative number of adopters predicted by Lavasani et al.'s (2016) Bass diffusion model. Sales are expected to increase rapidly beginning in the mid-2030s. The MAVS developed by Kalra and Groves (2017) used an interval regression model to forecast market penetration several assumptions fill the gaps between an estimated maximum and minimum adoption, one being that AVs are safer than humans and that. Bansal and Kockelman (2018) adopted a similar approach but narrowed this technique down to specific pieces of CAV technology to fill the gaps. This was done by taking descriptive survey data from the state of Texas to develop various forecast scenarios.

Because CAV technologies are geared toward improving highway safety (NHTSA 2010), it is possible to infer engineering countermeasures will undergo transformations based on the degree to which the public accepts individual components of technology. Kockelman's (2017) paper on long-term adoption of CAVs outlines many scenarios in which the public will gradually accept the suite of technologies. Although broken down

by level to some degree, the paper generally retains a focus on evaluating each piece of technology over time. Table 1 summarizes crash types (using CMF Clearinghouse designations) individual aspects of CAV technologies are expected to mitigate.

Table 3-1 Kockelmen Surveyed Technology by Crash Type Effectiveness

<b>TECHNOLOGY</b>	<b>(AS</b>	<b>CRASH TYPE</b>
<b>FORECASTED BY KOCKELMAN ET AL.)</b>		
<b>ELECTRONIC CONTROL</b>	<b>STABILITY</b>	Wet road
<b>LANE CENTERING</b>		Run off road, cross median, head on
<b>LEFT TURN ASSIST</b>		Left Turn
<b>CROSS TRAFFIC SENSOR</b>		Sideswipe, rear end
<b>ADAPTIVE HEADLIGHTS</b>		Nighttime
<b>PEDESTRIAN DETECTION</b>		Vehicle/Pedestrian
<b>ADAPTIVE CRUISE CONTROL</b>		Rear end, speed related
<b>BLIND-SPOT MONITORING</b>		Sideswipe
<b>TRAFFIC SIGN RECOGNITION</b>		Multiple vehicle, fixed object
<b>EMERGENCY BRAKING</b>	<b>AUTOMATIC</b>	Rear end
<b>CONNECTIVITY</b>		Multiple vehicle,
<b>SELF-PARKING VALET</b>		Parking Related
<b>LEVEL 3 AUTOMATION</b>		Varies by road types and weather condition
<b>LEVEL 4 AUTOMATION</b>		Varies by weather condition

Kockelman forecasted market penetration by projecting the public's willingness to pay (WTP) for each type of technology over time. Baseline WTP data were collected using a national survey. A multinomial logit model was developed to project future WTP for multiple scenarios. Bansal and Kockelman (2018) later developed another model for the state of Texas, utilizing data collected from a large-scale survey.

### 3.3 A Tool for Estimating Safety in a CAV Mixed Fleet

Knowing that the effects of countermeasures will change over time as CAVs become more numerous, it is important to have a reliable forecasting tool to evaluate the benefits of countermeasures under as CAVs proliferate. This section describes the data-driven. UK's data driven Safety Assessment for Connected Autonomous Transportation (ddSAFCAT) breaks down the safety benefit by specific levels of autonomy and facility type in which each level is effective. The Society of Automotive Engineers (SAE) has developed a system to classify different levels of automation. **Figure 3-4 SAE Levels of Automation** summarizes the main features of vehicles in each category. Level 2 technologies (e.g., lane assist, self-parking) are currently available — although they are most often seen on pricier vehicles. While vehicles with more advanced automation are in testing, it is unclear when consumers will be able to purchase them. Upon their initial release, it is probable that vehicles with Levels 3–5 automations will add \$10,000 to the price of a vehicle, narrowing the window of consumers able to afford them. As prices fall, it is reasonable to presume AVs will become more ubiquitous, but it remains unclear when vehicles with high levels of automation will make up a significant proportion of vehicles on US roadways.

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	You are driving whenever these driver support features are engaged - even if your feet are off the pedals and you are not steering			You are <b>not</b> driving when these automated driving features are engaged - even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
What do these features do?	These are driver support features			These are automated driving features		
	These features are limited to providing warnings and momentary assistance	These features provide steering OR brake/acceleration support to the driver	These features provide steering AND brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met	This feature can drive the vehicle under all conditions	
Example Features	<ul style="list-style-type: none"> <li>• automatic emergency braking</li> <li>• blind spot warning</li> <li>• lane departure warning</li> </ul>	<ul style="list-style-type: none"> <li>• lane centering OR</li> <li>• adaptive cruise control</li> </ul>	<ul style="list-style-type: none"> <li>• lane centering AND</li> <li>• adaptive cruise control at the same time</li> </ul>	<ul style="list-style-type: none"> <li>• traffic jam chauffeur</li> </ul>	<ul style="list-style-type: none"> <li>• local driverless taxi</li> <li>• pedals/steering wheel may or may not be installed</li> </ul>	<ul style="list-style-type: none"> <li>• same as level 4, but feature can drive everywhere in all conditions</li> </ul>

Figure 3-4 SAE Levels of Automation

Like the Rand MAVS, ddSAFCAT is tool that can forecast reduction in fatalities from safer driving habits of CAVs. The goal of this tool is to provide a more data driven approach to the forecast. ddSAFCAT uses an S-curve function model safety. An S-curve is selected because safety is expected to be a function of market penetration, where the public acceptance of the technology will be low at first, and then a drastic increase, finally followed by a slow increase to the maximum, determined by the user. Therefore, an S-curve function with potential for flexibility is required. The generalized logistic function (also known as Richard's curve) was selected. Equations are as followed for the tool (:

$$Y(t) = A + \frac{K - A}{1 + e^{-B(t-M)}}$$

$$B = \frac{2 * \ln(9)}{t_{90} - t_{10}}$$

$$M = \frac{(Years\ until\ t_{10}) + Growth\ Rate}{2}$$

Where  $Y(t)$ , is the market penetration,  $A$  is the lower limit (user input),  $K$  is the upper limit (user input),  $B$  is the growth rate,  $t$  represents the current year,  $M$  represents the year of 50% market penetration,  $t_{90}$  is the time until market penetration reaches 90%, and  $t_{10}$  is the time until market penetration reaches 10%.

These equations are applied to each level of autonomy. There are 6 levels of autonomy defined by the Society of Automotive Engineers (SAE) ranging from 0 to 5. The values for Levels 5 and 0 control the market penetration for the rest of the tool because level 5 vehicles are likely not to be replaced once deployed, and level 0s are already on the roadway (there likely always be some number of non-automated vehicles). The value in the second equation  $t_{90} - t_{10}$  represents the turnover rate of the fleet which is about 15 years for the average automobile (though this is could change from new technologies). In ddSAFCAT, these equations are used to calculate market penetration of each level, then a series of if statements are in place such that whenever a new level has sufficiently penetrated the market, the previous level will decline.

The next step after establishing market penetration is to determine how effective the vehicles will be at reducing crashes. The tool makes the assumption that automated vehicles will be safer on the roadway than human drivers. Each level of autonomy will have varying degrees of effectiveness. Level 5 vehicles are considered to be the most effective at reducing crashes, and the effectiveness of a level 5 vehicle is determined by how reliable its software is. Each other level is considered to be *as effective as* a level 5 vehicle when under the right conditions, and for eliminating certain crash types. Level 4 vehicles are considered to be *as effective as* level 5 vehicles when the weather conditions



are clear. A new level introduced into the tool, level 3.5, is considered to be effective for all weather conditions, but only on certain roads. Levels 2 and 3 are only effective in clear weather conditions on arterial roadways. And finally, level 1 vehicles are only as effective as level 5 vehicles on arterial roadways, and when the human driver is not distracted and using the vehicle's features properly.

Crash data unique to Kentucky was then analyzed to account for the number of crashes that happened in these conditions, the data was provided by the Kentucky Transportation Center.

KABCO		K																				
Count of MasterFile		Column Labels																				
City street		City street Total					US					US Total					FALSE		FALSE Total		Grand Total	
Row Labels	16-19	20-25	26-65	over 65	U	16-19	20-25	26-65	over 65	U	16-19	20-25	26-65	over 65	U	16-19	20-25	26-65	over 65	U	FALSE Total	Grand Total
2013	4	2	12	5	8	31	10	16	82	30	14	152	38	58	249	60	15	420	603			
Poor	2	1	4	1	4	12	4	7	22	7	5	45	13	28	85	14	3	143	200			
Angle	1			1		2	1		1	3		5		1	7	1			9	16		
Fixed Object			2			2		2	8	2		12	5	6	20	4			35	49		
Non-Fixed object				1	3	4		1	7	5		13	3	7	15	1	3		29	46		
Other	1	1	1		1	4		4	6	1		11	4	12	40	6			62	77		
Rear End							1			1		2	1	1	3	2			7	9		
Sideswipe							2					2		1					1	3		
Clear	2	1	8	4	4	19	6	9	60	23	9	107	25	30	164	46	12	277	403			
2014	3	6	9	8	4	30	8	27	85	24	14	158	31	68	255	63	15	432	620			
Poor	3	1	3	5	1	13	5	10	36	6	6	63	8	35	69	22	7	141	217			
Angle	1		1	2		4			4	3		7		2	4	2			8	19		
Fixed Object	2		2	1		5	1	5	9			15	5	9	25	11			50	70		
Non-Fixed object			1	1	1	3		3	12	2	6	23	1	8	11	1	6		27	53		
Other				1		1	4	2	8	1		15	2	14	25	7	1		49	65		
Rear End									3			3		2	1	1			4	7		
Sideswipe															3				3	3		
Clear		5	6	3	3	17	3	17	49	18	8	95	23	33	186	41	8	291	403			
2015	1	4	14	3	5	27	13	28	107	32	12	192	30	82	294	50	34	490	709			
Poor		4	2	2	2	10	5	10	47	8	7	77	13	29	107	18	12	179	266			
Angle		2	2			4	1	3	4	2		10		1	3	1			5	19		
Fixed Object		1		1		2	2	1	4	1	1	9	4	6	28	1	1		40	51		
Non-Fixed object					2	2		4	15		6	25	3	2	23	5	8		41	68		
Other		1		1		2	1	1	18	2		22	6	17	42	11	3		79	103		
Rear End									3	1		4		3	9				12	16		
Sideswipe							1	1	3	2		7			2				2	9		
Clear	1		12	1	3	17	8	18	60	24	5	115	17	53	187	32	22	311	443			
2016	2	2	20	3	6	33	8	25	112	39	21	205	43	76	318	73	27	537	775			
Poor	1	1	8		3	13	1	7	41	14	5	68	9	27	103	14	9	162	243			
Angle	1		1			2			4	8		12	1	2	3				6	20		

Figure 3-5 Snapshot of crash data used as input for ddSAFCAT

The above figure actually displays an excel pivot table to summarize the isolated crash data. This was done for simplicity in creating the tool, as there are over 785,000 crash entries. Only fatal crashes were observed in the data. The table can be used to filter out any crashes that occurred on major roads (US or interstate), as well as any crashes that occurred in poor weather. Poor weather conditions are considered to be anything that is not “clear.” Driver age may also be filtered out, though this has no input into the tool yet. The data only contains of crashes from 2013 to 2017.

In addition to crash data, vehicle miles traveled (VMT) data is also used. This is to account for the increasing travel trends. A dataset obtained from (Volpe, 2017), a growth rate formula was then used to forecast VMT out to 2050. This data can then be broken down to roadway type, such as arterial, interstate, etc., and area type, such as rural or urban. Connected and autonomous vehicles however are extremely likely to change travel habits in the long term and VMT may increase dramatically each year (Kalra and Paddock 2016). Combining all of these elements: market penetration, effectiveness, crash data, and VMT growth, a total number of fatalities can be estimated each year, weighted by the levels. The resulting equation is as follows:

$$Fatalities = Base Fatalities * VMT Growth$$

$$* \sum_{n=1}^5 ((1 - Effectiveness_{Level\ n}) * Market Penetration_{Level\ n})$$

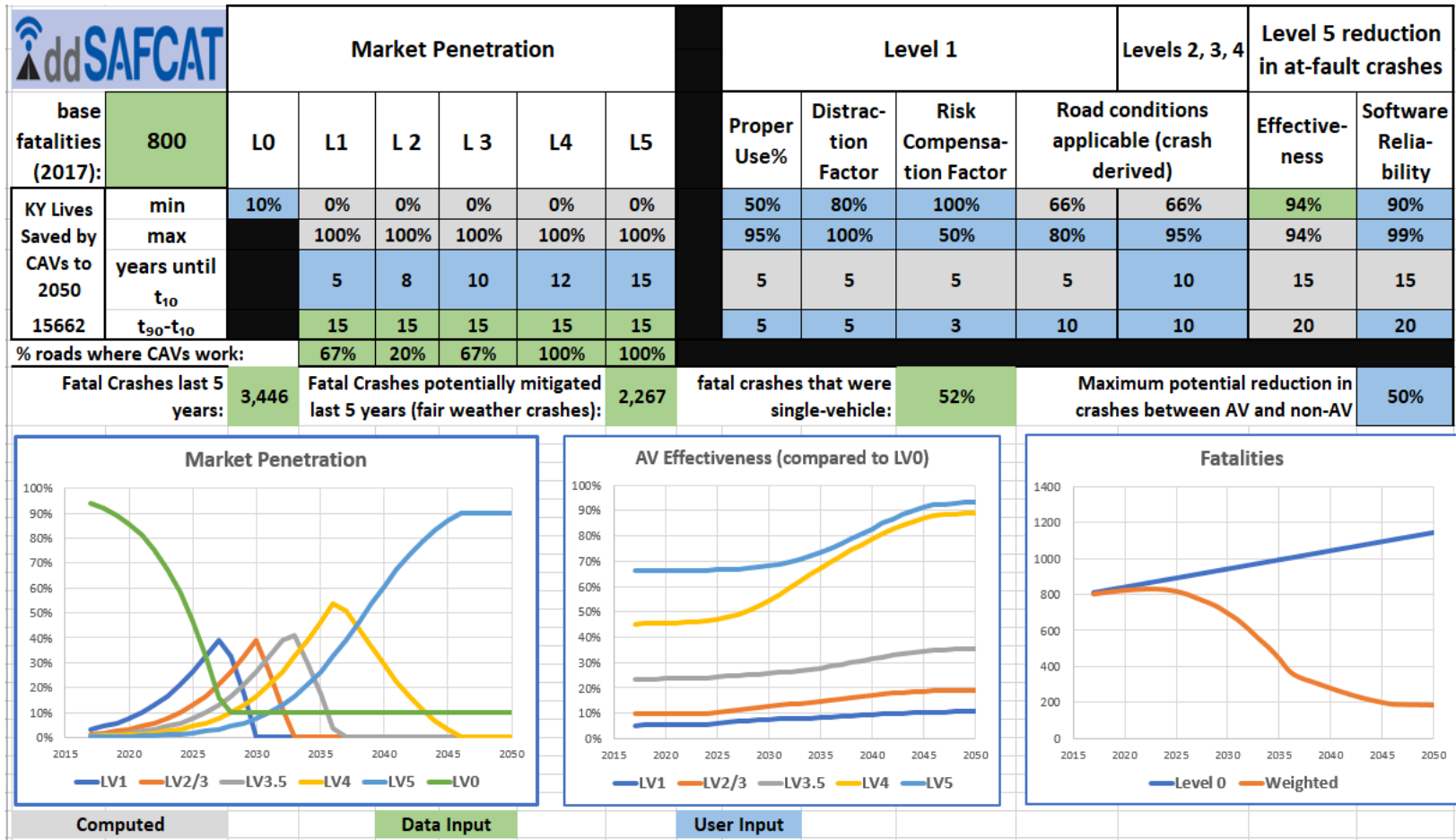


Figure 3-6 ddSAFCAT user interface

Figure 3-6 illustrates the ddSAFCAT user interface. Green cells contain elements derived from historical data, while blue cells contain user-specified values. Grey cells are computed by the tool. Three graphs sit below the table. The first captures the market penetration of vehicles with different levels of automation, while the second graph looks at how effective each level of automation is compared to Level 0. The graph on the right side contains two trend lines: the upper line projects the number of crash-related fatalities under a baseline scenario with only Level 0 vehicles, while the bottom line forecasts the anticipated number of fatalities based on the market penetration and effectiveness of AVs throughout time.

#### 3.4 The Dynamics of Countermeasure Effectiveness

Assessments of a countermeasure's effectiveness can reveal temporal fluctuations in performance, both over the short- and long-terms (Le et al. 2018). According to Mannering (2017), "virtually every statistical analysis of highway safety data is predicated on the assumption that the estimated model parameters are temporally stable. (2)" Often, when a CMF is derived it is based on observations of how a countermeasure's benefits vary in different conditions (e.g., day/night, dry/wet weather). Many studies establish this distinction by categorizing these different conditions as crash types. They can even be filtered in the CMF Clearinghouse.

The performance of a countermeasure generally does not change significantly through time. However, if changes are observed a new CMF is developed to forecast the benefits of a countermeasure (Donnell and Gayah 2014). The nature of long-term changes varies by countermeasure (Abdel-Aty et al. n.d.). Each countermeasure and conditions

where they may change provides keen insight into how their respective CMFs can be calculated. It is typical to examine the compound effect of all of these conditions where countermeasures might be used and look these changes as a whole to simply examine an overall forecast. Since many of these factors change over time, the many scenarios should be observed separately and then compounded.

The charts presented in this section demonstrate possible trends in crash rates following the introduction of a countermeasure. Each chart indicates crash rates before installing a countermeasure (BCR) and crash rates following implantation (PCCR). Vertical green lines delineate the point at which a countermeasure is adopted. Crash rates are represented as wavy lines to indicate their stochastic nature. Over short periods of time crash rates can fluctuate unpredictably. The charts are for illustrative purposes only, but they do capture long-term trends in crash frequencies before and after the introduction of a countermeasure.

### Scenario 1 – Constant BCR, ConstantPCCR

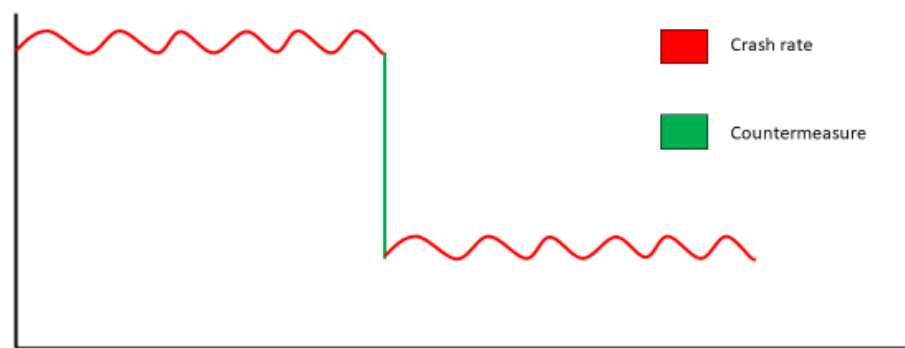


Figure 3-7 Scenario 1: Countermeasure reduces overall Crash rates

Scenario 1 (Figure 3-7) depicts trends along a problematic roadway segment that initially suffers from high crash rates. These frequencies oscillate over time, but on average remain high. Introducing a countermeasure significantly lowers crash rates. Again, there is natural variability in the rates, but on average they are much lower than prior to adoption of the countermeasure.

### Scenario 2 – Increasing BCR, Increasing PCCR

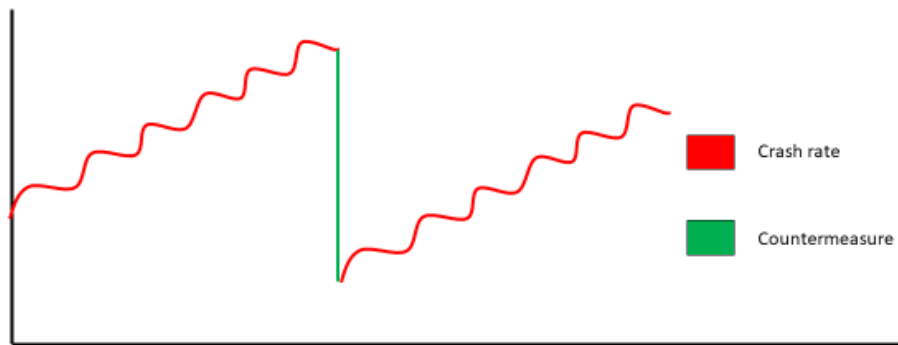


Figure 3-8 Scenario 2: Countermeasure reduces overall crash rates, but increasing trends persist

With Scenario 2 (Figure 3-8) the crash rate before installation of a countermeasure increases over time, suggesting the roadway is growing more hazardous. Installing a countermeasure initially causes a dramatic fall in crash rates, but the countermeasure's efficacy wanes over time and crashes increase, eventually nearing levels observed prior to the countermeasure's adoption. An example of where this scenario might play out in the real world is an area where a guardrail is constructed to reduce frequent run-off-the-road crashes. While the guardrail may initially reduce crash frequency, crash rates climb after motorists begin crashing into the guardrail.

### Scenario 3 – Increasing BCR, Constant PCCR

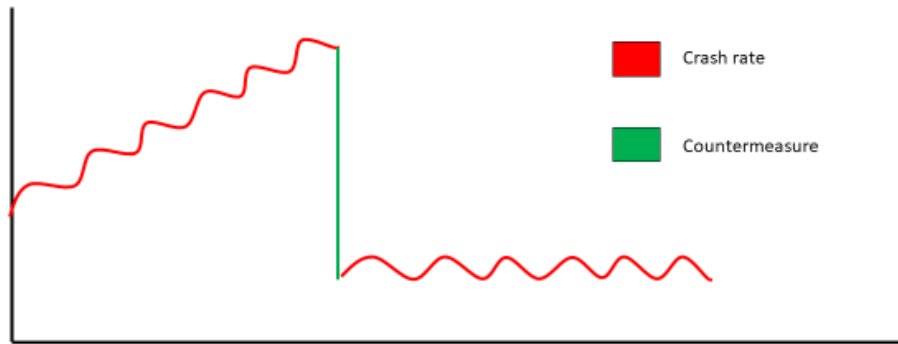


Figure 3-9 Increasing crash trends are fixed after countermeasure is taken

The initial crash frequency trends observed in Scenario 3 mirror those in Scenario 2, with rates going up over time. Unlike Scenario 2, in this one countermeasure installation lowers the crash rates, which then fluctuate around a steady average, suggesting the underlying issue has been corrected. An example of where this trend could be expected is optimizing signals at problem intersections.

The goal however is to indicate how the effectiveness of countermeasure may change over time with the inclusion of autonomous vehicles in the fleet. There are two possibilities. The first that the countermeasure will become less effective over time. In this case the countermeasure itself is not really becoming less effective per se, but more accurately they will no longer be needed in light of the changing fleet. The net benefit that the countermeasure would yield will be reduced.



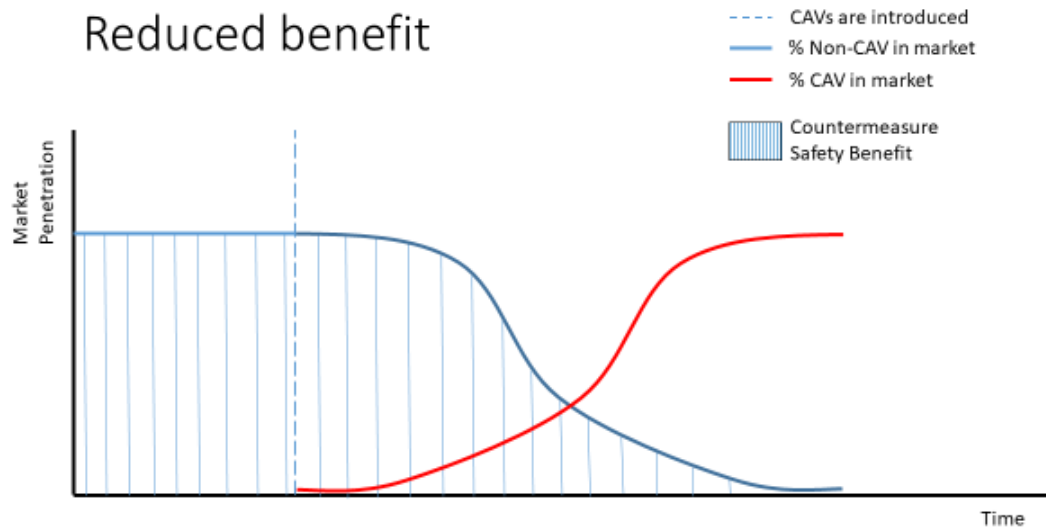


Figure 3-10 Countermeasure with reduced benefits

Figure 3-10 shows an example scenario. The safety benefit of the countermeasure is represented by the areas under the curves. All vehicles to start with are considered to be non-CAV. After some time CAVs enter the market and begin to overturn the non-automated vehicles. Since CAVs are able to perform driving tasks that could be safer than what a human driver is capable of, then the benefit of some countermeasures will not be acquired for the amount of CAVs in the market.

On the other hand, some countermeasures are likely to become more effective over time. In this case *more effective* can translate to *more important*. The primary example used in this paper is with striping. Many automated vehicles rely on adequate striping in order to stay in the correct lane or change lanes (Ballingall and Walsh 2017). In this case, when the countermeasure of high-quality striping is available, the automated vehicle will reduce crashes in addition to the crash reduction of the countermeasure. Consider the conceptualized data in the table below:

Table 3-2 Sample CMFs for striping

	POOR	MEDIUM	GOOD
<b>LEVEL 0</b>	100	90	80
<b>LEVEL 1&amp;2</b>	94	84	74
<b>LEVEL 3</b>	88	78	68
<b>LEVEL 3.5</b>	82	72	62
<b>LEVEL 4</b>	76	66	56
<b>LEVEL 5</b>	70	60	50

The table shows several CMFs expressed as a percentage. Three scenarios are considered for the case of striping. There is poor, medium, and good quality of striping. Each level of autonomy is reducing the CMF of the striping quality by some amount. As the quality of striping improves, the CMF is reduced even further. The values from the table can be expressed in the form of a chart:

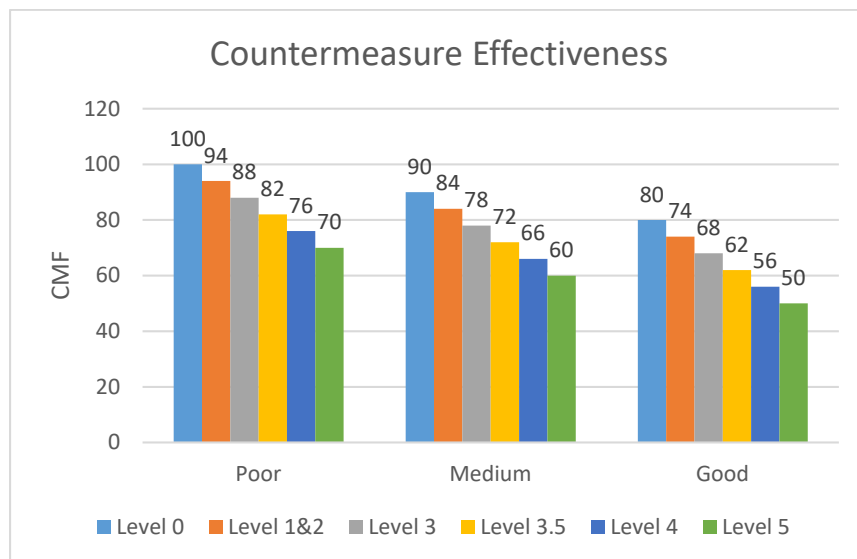


Figure 3-11 CMF Decline by level of autonomy and Striping quality.

Note that the levels of autonomy are expressed in the similarly to what is shown in ddSAFCAT for consistency. The net effectiveness in crash reduction can then be calculated by either level of autonomy or striping quality. To forecast how this may change over time, one should look back to market penetration. Consider the market penetration of ddSAFCAT:

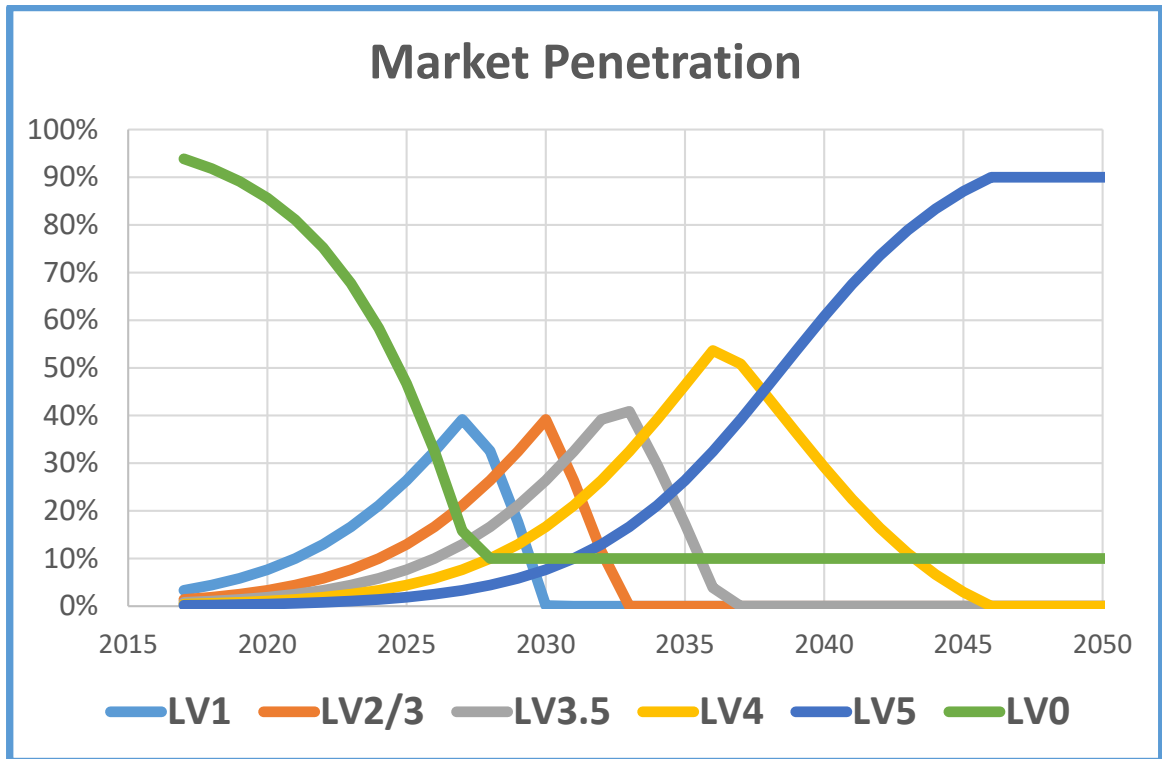


Figure 3-12 ddSAFCAT market penetration

The curves for market penetration shown in Figure 13 use the assumption that there are very few autonomous vehicles in the market currently and that market will always have at least 10% of non-automated vehicles. A weighted average can then be calculated using the market penetration curves and the sample CMF values to estimate a net effectiveness by striping quality (similarly to how fatalities are calculated in ddSAFCAT).

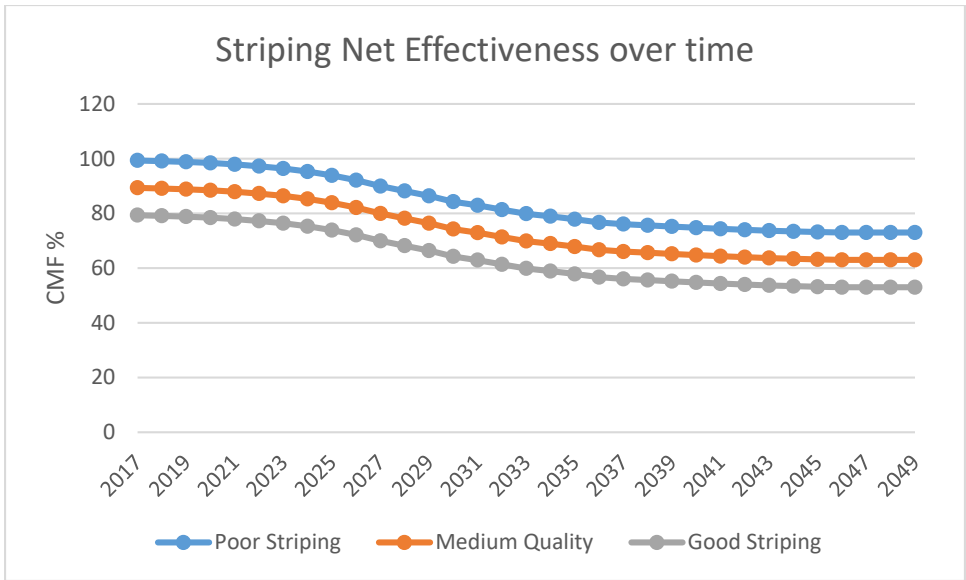


Figure 3-13 Sample net effectiveness of striping

The issue with this method however is establishing a CMF for levels of autonomy that are not in the market for specific countermeasures. Collecting data for this method of analysis in reality is likely to be resource intensive and tedious.

## CHAPTER 4. CASE STUDIES

### 4.1 Introduction: Using ddSAFCAT to Adapt Countermeasure CMFs

Determining how CMFs should be adjusted to account for the influence of CAVs is challenging. Most of the promised safety benefits of CAVs will fail to materialize unless the infrastructure is there to support their presence on roadways (e.g., adequate striping and lighting). Tools like ddSAFCAT can be used to guide decisions in infrastructure investments.

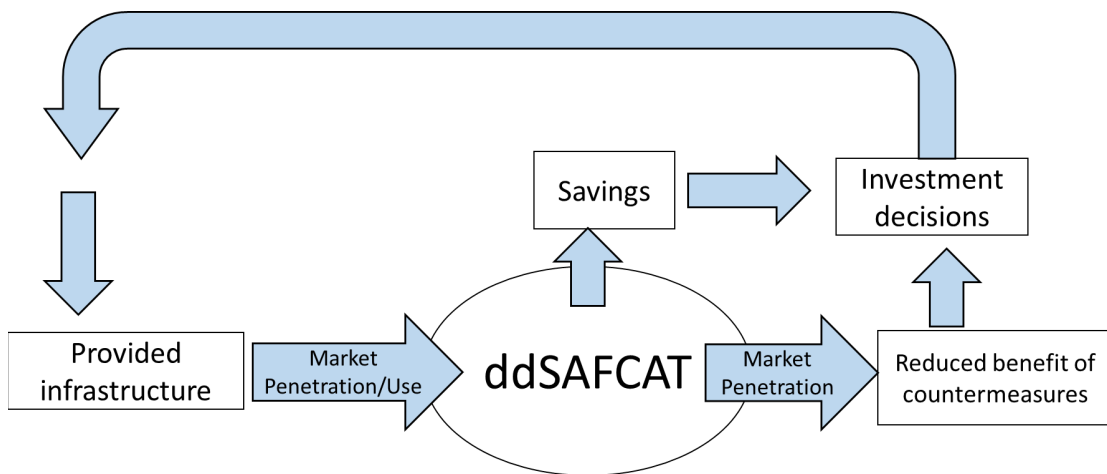


Figure 4-1 Flow of infrastructure decisions based on CAV evaluation tools

Figure 4-1 is a flow chart that represents how DOTs can adopt a data-driven approach to understand the benefits of CAVs and make judicious investment decisions. Agencies have the option of calculating how many fatalities will be prevented by CAVs or gauging changes in the performance of countermeasures based on the market penetration of CAVs. For the analysis presented here, it is assumed countermeasure's effectiveness is proportionate to the market penetration of each level of automation (i.e.,

SAE Levels 0–5), similar to how other researchers have tied future safety benefits to market penetration.

#### 4.2 Case 1: Reduced Benefit Countermeasures

For most countermeasures that have a single CMF, adjustments to the CMF depend on the proliferation of CAVs. Given the familiarity with the ddSAFCAT model, a countermeasure that is expected to become less effective over time will follow the same trends as the tool's market penetration equations. The model multiplies the percentage of automated vehicles in the market by the CMF (i.e., the number of crashes reduced). A search of the CMF Clearinghouse returns 700 results for rumble strips. Most of these exclusively address mitigation of run-off-road crashes. It is likely that fewer vehicles will run off the road as more vehicles with higher levels of automation are incorporated into existing fleets, because human reactions and decision making, which may result in a vehicle being steered off a road, will be progressively eliminated from driving. As such, rumble strips are likely to become less critical for maintaining highway safety, and their effectiveness — as measured using a CMF — will decline.

As more AVs increasingly populate the roads, CMFs for rumble strip treatments will also increase. This is not to suggest the installation of rumble strips will increase crashes — a CMF for rumble strips will never exceed 1.0. A basic example will clarify this dynamic. Suppose the CMF for a particular rumble strip treatment is currently 0.85. This indicates that installing a rumble strip will lower crash rates by 15 percent. With a different vehicle fleet composition, one that includes more vehicles with varying levels of automation, that CMF is recalculated for the rumble strip and it increases to 0.95, suggesting that rumble strip installation will reduce crash rates by 5 percent. What this

information tells a practitioner is that the expected benefits of rumble strip installation are lower under when a greater share of the vehicle fleet is automated, potentially leading agency personnel to conclude investments should be directed toward safety treatments that will yield greater benefits. The problem is not that the rumble strips no longer performs its intended function. What is at issue is that fewer vehicles will benefit from the rumble strip's function because they have automated systems designed to prevent them from departing the roadway. And the successful operation of those systems does not hinge on whether a rumble strip is present.

The bounds for these changes are kept in check through a short series of if-statements. When plotting the CMF over time, it will likely assume the shape of an S-curve, mirroring market penetration. The basic equation for each level and each year is:

$$CMF_{New} = (1 + MP_{By\ Level}) * CMF_{Old}$$

This equation will only be applied to the levels where the countermeasure will lose effect over time (levels 3, 4 and 5).

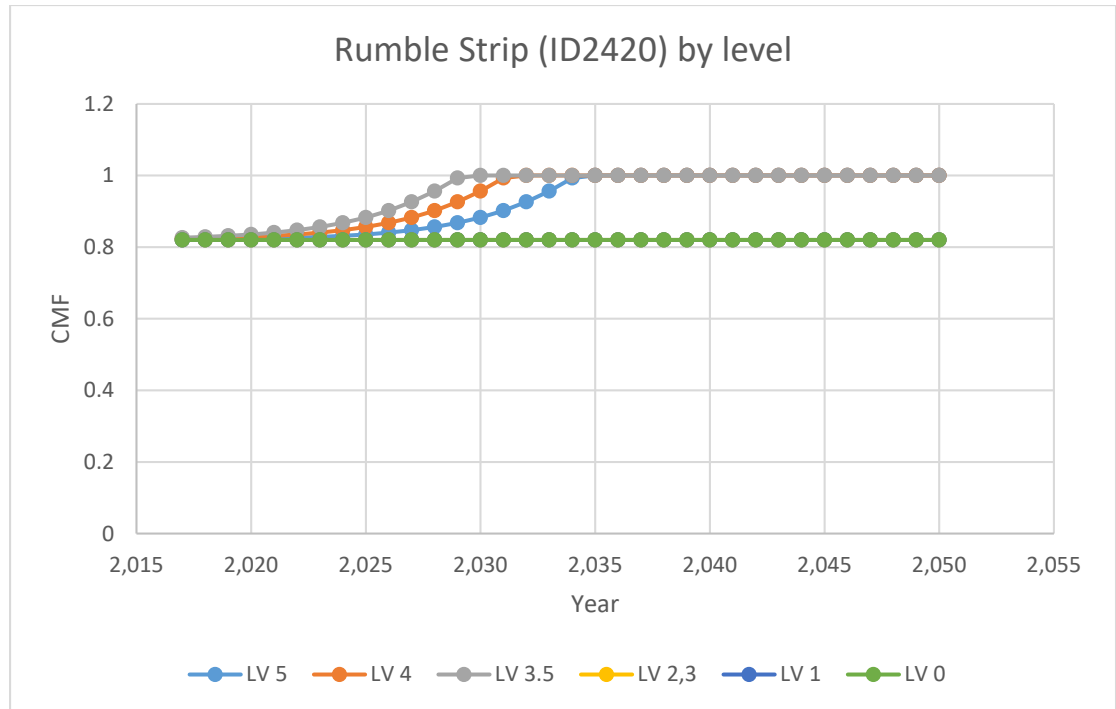


Figure 4-2 Change in rumble strip CMF by level of autonomy

Vehicles with Levels 3–5 of automation can prevent all run-off-road crashes. But Level 3 vehicles are only effective on interstates and major arterials. Thus, CMF trends for the rumble strip documented in Figure 15 (ID 2420; CMF = 0.82) follow a logit model that closely resembles the market penetration trends for these levels of automation. Net CMF is calculated for each year using a weighted average. The CMF gradually increases beginning around 2025; its increase accelerates over the next 6–7 years, before leveling out in 2023.



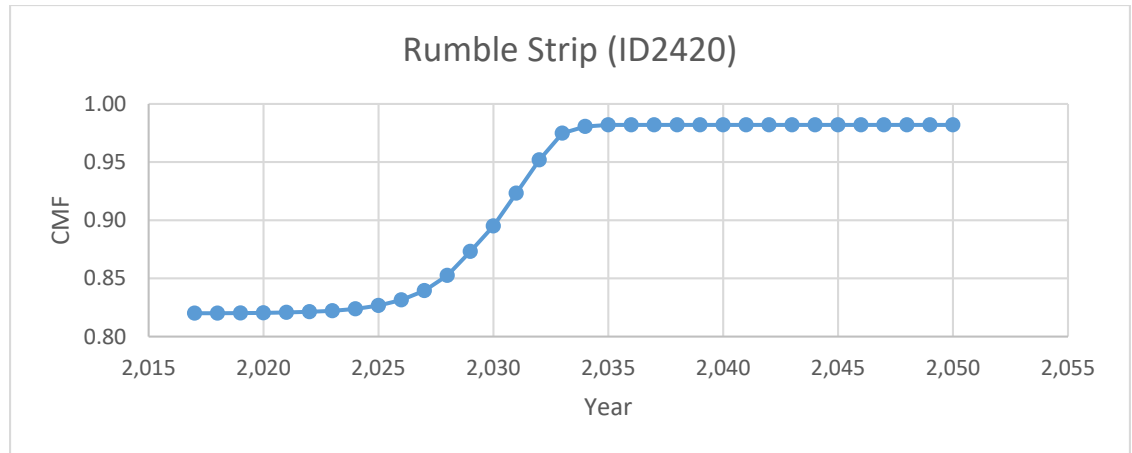


Figure 4-3 Weighted change in rumble strip CMF

#### 4.3 Case 2: Increased Benefit Countermeasures

Some countermeasures will likely take on greater importance as CAV deployment increases. Rather than focusing purely on which countermeasures will lose effectiveness, it is useful to explore which countermeasures are likely to warrant greater investment to improve the safety of a more CAV-saturated vehicle fleet. One countermeasure whose value will probably grow is improved striping. Good striping is critical for the operation of many CAV systems. The CMFunction for a striping treatment may change in response to increasing retroreflectivity or altering lane width.

This case study focuses on countermeasure listed as ID 2374 in the CMF Clearinghouse. It increases retroreflectivity from some value,  $X$ , under 200 mcd/m<sup>2</sup>/lx to another value,  $Y$ , which is set to 200 or more (Smadi et al. 2008). In general, the minimum requirement for the operation of lane-keeping systems on roadways is 150 mcd/m<sup>2</sup>/lx and a stripe width of 150 mm (Ballingall and Walsh 2017). As an extreme case, consider the effects of increasing striping retroreflectivity from 50 mcd/m<sup>2</sup>/lx to 200 mcd/m<sup>2</sup>/lx:

$$CMF = e^{-0.0021*(X-Y)} = e^{-0.0021*(200-50)} = 0.73$$

After deriving a CMF from the CMFunction, a process similar to the one employed in the first case study (see Equation 4.1) can be used to estimate striping effectiveness. Assuming that changes in the CMF are proportional to the market penetration of each level of automation, Equation 4.3 is adjusted based on year and automation level. Because this countermeasure is expected become more effective as CAVs proliferate, instead of adding market penetration to one (1) in the first term as is done in Equation 4.1, the value for market penetration is subtracted from one (1) (Figure 16). The result is then multiplied by a weighted average (Figure 17).

$$CMF_{New} = (1 - MP_{By\ Level}) * CMF_{old}$$

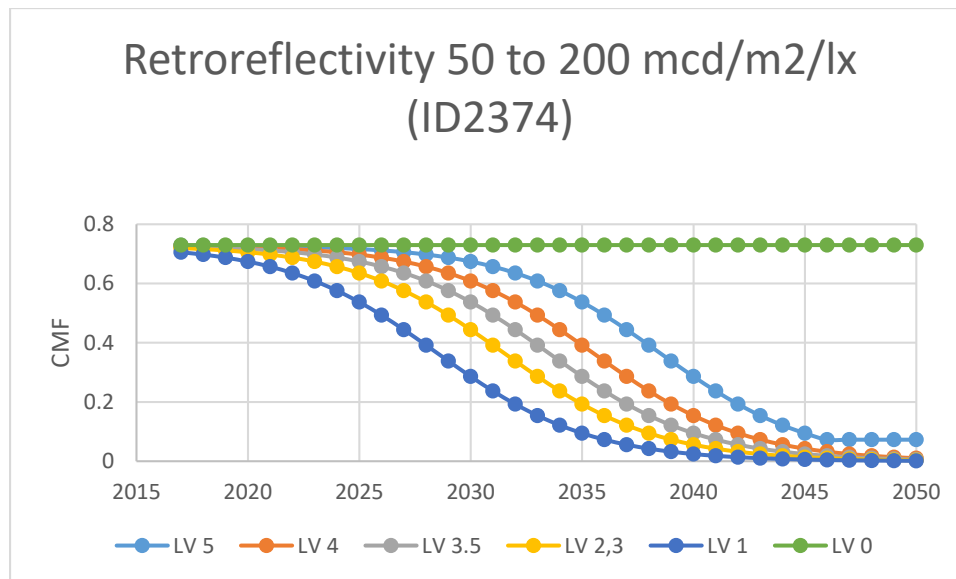


Figure 4-4 Change in striping CMF by level of autonomy

This of course can be compounded with a weighted average such as before.

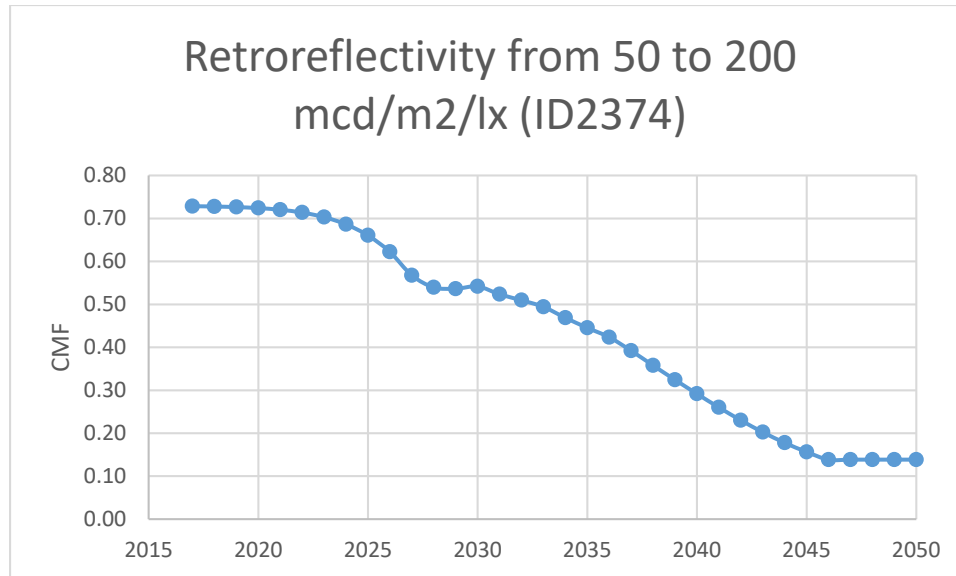


Figure 4-5 Weighted change in striping CMF

In reality, the curves will assume a different shape because other factors, which are omitted here, must be considered. Bounds are required for a more realistic approach. The upper bound of each countermeasure with potential for improvement is represented by the original CMF. A potential source for lower bounds remains unexplored.

#### 4.4 Case 3: Countermeasures and Capacity

A major appeal of CAVs lies in their potential to bring about operational improvements. Research has already looked at the safety – capacity tradeoffs of CVs. One study (Dominique et al. 2006) performed analysis using a brick wall scenario, in which a disaster interrupts a vehicle string’s flow. The authors devised new equations for capacity and developed a safety index, eventually concluding that reaction times associated with each vehicle in the string increase due to connected technologies. These will also vary with the market penetration of each technology. Figure 18 expresses safety (derived from number of crashes and safety distances) as a function of vehicle capacity. While the study

considered equations of both the *Highway Capacity Manual* (HCM) and the HSM, it does not discuss specific countermeasures or infrastructure.

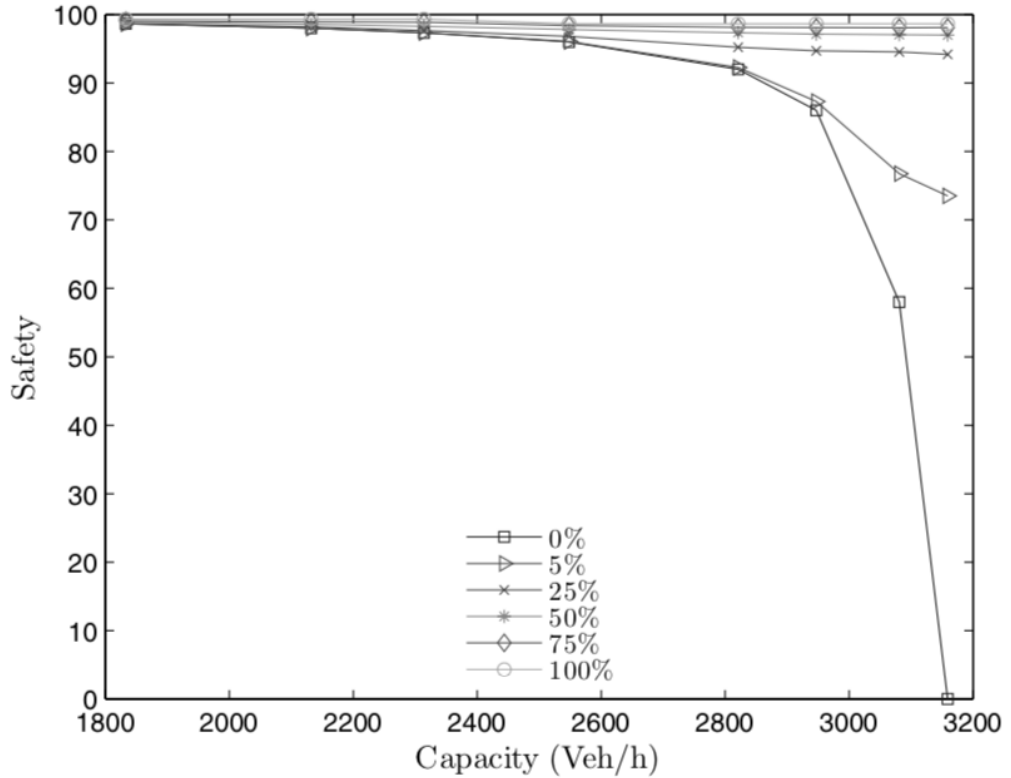


Figure 4-6 Safety-capacity tradeoff of CV technology

In the first two case studies, the countermeasures (rumble strips, striping) will not directly affect highway capacity. Some countermeasures, such as modifying lane width or speed limits, can influence highway capacity. Examples of countermeasures that could affect highway capacity can be deduced by examining a standard capacity equation from the HCM:

Basic freeway Segment (HCM Equation 12-6)

$$c = 2200 + 10 * (FFS_{adj} - 50)$$

Multilane Highway Segment (HCM Equation 12-7)

$$c = 1900 + 20 * (FFS_{adj} - 45)$$

Where, (Equations 12-3 and 12-5 in HCM)

$$FFS_{adj} = FFS * SAF = (BFFS - f_{lw} - f_{TLC} - f_M - f_A) * SAF$$

and where:

$c$  = capacity and is a function of an adjusted free flow speed.

FFS = free flow speed

$FFS_{adj}$  = adjusted free flow speed

BFFS = base free flow speed

SAF = speed adjustment factor

$f_{LW}$  = lane width adjustment factor

$f_{TLC}$  = lateral clearance adjustment factor

$f_M$  = median type adjustment factor

$f_A$  = access point density adjustment factor

The SAF is usually selected from a list of default values in HCM Exhibit 11-21.

The CMF Clearinghouse includes countermeasures with each variable of these capacity equations. While these countermeasures may not significantly impact safety in the context of CAV proliferation, when a greater share of vehicles on roadways are CAVs they may influence capacity. Consider the countermeasures for decreasing lane width, for which many CMFs have been developed. Most are expressed as a CMFunction. Reducing lane width tends to increase the frequency of run-off-road crashes (Gross et al. 2009). However, crashes overall may decrease by encouraging more careful driving habits (Abdel-Aty et al. n.d.). With respect to capacity, free flow speeds will decline as lane width shrinks. This is apparent from analyzing the equations listed above and the HCM Exhibit 12-20.

Table 4-1 HCM Exhibit 12-20

AVERAGE LANE WIDTH (FT)	REDUCTION IN FFS, $f_{lw}$ (mi/hr)
$\geq 12$	0.0
$\geq 11 - 12$	1.9
$\geq 10 - 11$	6.6

In general, reducing lane width will lower roadway capacity and increase safety by reducing crashes. This may not be the case when CAVs are mixed in the fleet. Consider the following figure:

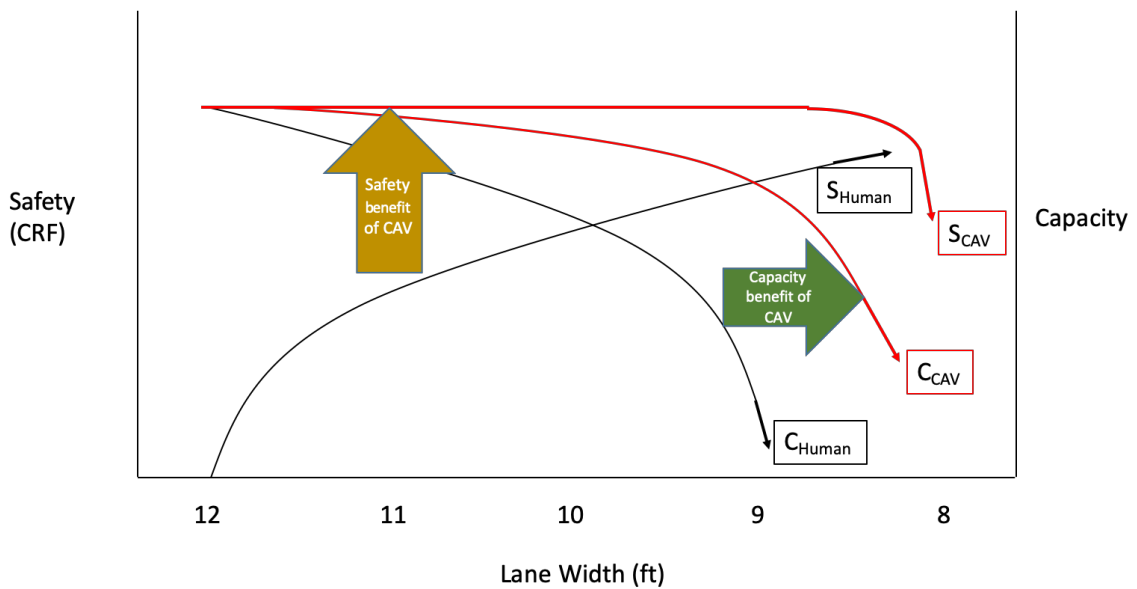


Figure 4-7 Safety-capacity tradeoff for change in lane width for CAVs

In Figure 4-7, black lines indicate safety (expressed as a CRF) and capacity with human drivers; red lines represent the safety and capacity of CAVs when lane width is modified. The logic underpinning this diagram presumes narrower lanes are safer for human drivers, even though this may not actually be the case for some crash types (e.g., run-off-road). But narrower lanes come with a tradeoff — safety for capacity. The large

arrows indicate the potential benefits (safety and capacity) of CAVs. The CRF for reducing lane width likely will not change (see Section 4.2). Instead it will be flat, until some width is reached at which a CAV cannot function properly. Thus, narrower lanes reduce the safety benefit of CAVs. Capacity benefits trend in the opposite directions, with narrower lanes yielding a greater benefit.

## CHAPTER 5. CONCLUSIONS

### 5.1 Summary

This document opened with a review of SPFs, which are equations used to predict the average number of crashes each year at a given location. To account for the effects of installing a countermeasure, SPFs are multiplied by a CMF. Agencies can select from many countermeasures, and often a single treatment will have several associated CMFs because the context into which a countermeasure is introduced influences its performance. Many DOTs compile countermeasures or CMFs into short lists that contain those they use most frequently. While abundant evidence attests to the benefits of countermeasures and the utility of CMFs for measuring their impacts on safety, with CAVs likely to proliferate in the next 20 to 30 years, agencies will need to rethink their approaches to countermeasures and identify those which are most likely to bring about the greatest safety benefits as CAVs are gradually integrated into vehicle fleets. Because CMFs are not tailored to estimate the implications of CAVs for the efficacy of various countermeasures, they will require modifications as well.

Researchers have catalogued many safety and operational benefits of CAVs. Typically, these benefits are analyzed using an MOE framework. Studies using MOE frameworks have routinely cited improved highway safety as a key virtue of CAVs. However, the magnitude of CAV safety benefits will be proportional to their market penetration. Most researchers have conceptualized market penetration as following an S-shaped curve. Building from previous work, a safety forecasting tool — ddSAFCAT — was presented. It was used to evaluate the future benefits of AVs according to level



automation by leveraging Kentucky crash data, VMT data, and CAV crash statistics. Currently, the tool expresses benefits as a total reduction in fatalities.

ddSAFCAT was then used to investigate how the effectiveness of countermeasures (rumble strips, striping, adjustments to lane widths) will change as more CAVs get added into the vehicle fleet. The underlying assumption of ddSAFCAT is that increases or decreases in safety benefits are proportional CAV market penetration. For example, while rumble strips might grow less effective over time, because automation systems do not rely on them to keep a vehicle on the road, the importance and effectiveness of striping will increase because those same systems require highly visible pavement markings to navigate roadways. Other countermeasures, such as adjustments to lane width, have the potential to affect capacity. Evaluating these countermeasures requires an approach rooted in the HCM's capacity equations, which can be used to estimate the *safety-capacity* tradeoff.

## 5.2 Limitations

ddSAFCAT has several limitations, most of which pertain to its assumed inputs. Although a model for market penetration was developed, current market data for CAVs are difficult to obtain and therefore incomplete or potentially unreliable. However, because the aim of this research was to establish a framework for analyzing CMFs in light of CAV proliferation, making assumptions was inevitable. As more empirical data on CAVs and the effectiveness of countermeasures in mixed vehicle fleets become available, the tool can be refined. Given the myriad countermeasures DOTs can select from, in examining just three this research only scratched the surface, and many more unique scenarios and idiosyncrasies remain to explore.

### 5.3 Future Work and Next Steps

The main deliverable of this thesis is to provide a framework of analysis for countermeasures in the presence of CAVs. This framework needs to be developed further to proper analysis and evaluation of countermeasures with more data. Work should continue on ddSAFCAT. Developing and then implementing a method to incorporate more data into the model will improve its forecasts. One strategy is to rework the equations and inputs for market penetration by following approaches similar to Zhao and Kockelman (2017) or Lavasani et al. (2016) — one requires data collection through extensive surveying, the other mines purchasing data on CAV-related technologies. Surveys are time-consuming and resource-intensive endeavors, while data mining is more feasible and economical. Accordingly, the next recommended step is to forecast CAV market penetration with the Bass diffusion model, rather than the S-curve ddSAFCAT currently uses, to eliminate assumed values for market penetration. Some historical precedent could be examined to better inform these forecasts, or perhaps the forecasts of specific countermeasure. Historically, manufacturers have also made substantial changes to safety (e.g. seatbelts, antilock brakes, airbags, etc.). Using the experience from these past innovations, a better forecast could be obtained.

ddSAFCAT should also be equipped with a full list of countermeasures to facilitate their direct evaluation. Lists of countermeasures are available for download in the CMF Clearinghouse, however, some are likely to require different treatment from those evaluated as part of this research. Also, CMFunctions are not included in this download and cannot be filtered out in the Clearinghouse; each CMFunction is unique as well. Therefore, CMFunctions must be handled differently when used as an input into analytical tools. A potentially useful course of action is to create a separate database

dedicated to CMFunctions, which can be used in analysis. Once a full list is developed and implemented into the tool, a fatality analysis could be performed with the intervention of countermeasure rather than the actual change in the CMF.

It is likely necessary to develop new CMFs for each technology type to allow for an improved analysis of Countermeasures with increased benefit as seen in section 3.4. While an assumption was made that vehicles of higher levels of autonomy will still reduce crashes in the presence of lower quality countermeasure conditions, actual data is required to confirm this assumption. These lower quality countermeasures could in fact *cause* more crashes since the infrastructure may not be capable of supporting the necessary technology. This could potentially be challenging as it requires collecting safety performance data of vehicles that are not in the market. This could be remedied by a more frequent exchange of information between original equipment manufacturers and local DOTs. However, these types of information exchange are few and infrequent since these manufacturers tend to withhold information for fear of their competitors acquiring it (Gibson 2017). Therefore, some policy change could be put into place to facilitate information exchange and improve the forecast of countermeasure change.

The effect of countermeasures on capacity demand more analytically intensive evaluations. Their analysis lies beyond the scope of ddSAFCAT and other safety analysis tools. If these tools are to be used, they will require dramatic adjustments. More likely, a new tool should be developed to consider the safety-capacity tradeoff of specific countermeasures, or tools currently available should be enhanced for this. In the example described for capacity analysis in chapter 4, a mixed fleet is not accounted for, only vehicles of full autonomy and vehicles with no autonomy. Mixed fleets should be

accounted for in this type of analysis. Furthermore, once the fleet is fully autonomous, allowing for narrower lanes as per the example, the non-CAV vehicles that still operate (for emergency and construction projects) will require some additional infrastructure to operate properly such as including shoulders, HOV lanes, or concrete aprons.

Finally, the discussion of discount rates should be included in future works. The purpose of this thesis is to evaluate the future safety benefit of countermeasures to inform investment decisions of agencies in a benefit-cost analysis. The purpose of discount rates is to put all present and future costs and benefits within the common metric of their present value. These discounts are applied to countermeasures to inform investment decisions. Performing a benefit-cost analysis using the techniques outlined would demonstrate a use of this framework. Evaluating costs by this framework and comparing to the base costs with the discount rates will show one of two outcomes. High discount rates advertise countermeasure investments over shorter periods of time. It is possible for a countermeasure may serve its useful life before the introduction of CAVs into the market.

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  - Date: 1/15/2019
  - Authors: Freddy Lause, Reginald Souleyrette, Austin Obenauf
- Automated Vehicles Symposium Poster
  - Title: A Data Driven Tool for Estimating Safety Benefits of CAV Deployment
  - Date: 7/9/2018
  - Authors: Reginald Souleyrette, Austin Obenauf, Freddy Lause