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# Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems

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ABSTRACT

The Connected Vehicle (CV) technologies together with other Driving Assistance (DA) technologies are believed to have great effects on traffic operation and safety, and they are expected to impact the future of our cities. However, few research has estimated the exact safety benefits when all vehicles are equipped with these technologies. This paper seeks to fill the gap by using a general crash avoidance effectiveness framework for major CV&DA technologies to make a comprehensive crash reduction estimation. Twenty technologies that were tested in recent studies are summarized and sensitivity analysis is used for estimating their total crash avoidance effectiveness. The results show that crash avoidance effectiveness of CV&DA technology is significantly affected by the vehicle type and the safety estimation methodology. A 70% crash avoidance rate seems to be the highest effectiveness for the CV&DA technologies operating in the real-world environment. Based on the 2005–2008 U.S. GES Crash Records, this research found that the CV&DA technologies could lead to the reduction of light vehicles' crashes and heavy trucks' crashes by at least 32.99% and 40.88%, respectively. The rear-end crashes for both light vehicles and heavy trucks have the most expected crash benefits from the technologies. The paper also studies the effectiveness of Forward Collision Warning technology (FCW) under fog conditions, and the results show that FCW could reduce 35% of the near-crash events under fog conditions.

## 1. Introduction

### 1.1. Background

The connected vehicle technology (CV) and driving assistance technology (DA) are believed to have a great effect on traffic safety. The CV&DA technologies would inform a vehicle about the traffic conditions from its surrounding environment, such as a nearby vehicle's position, speed, and braking behaviors, the signal status and other traffic information. The CV&DA technology could also support part of driving tasks like acceleration or deceleration without the driver interference. These functions would benefit a vehicle's safety substantially because it could help the driver be aware of the potential hazards, and the vehicle can even automatically take actions to avoid a hazard. The CV&DA technology has the ability to mitigate the negative effects of drivers' errors, which is considered a major culprit solely or in combination with other factors in more than 94% of public roadway crashes (Singh, 2015).

Many automobile manufacturers, as well as research organizations, are always on their way developing more functional and efficient CV&DA technologies. Up till now, there are over thirty types of CV&DA technologies and integrated systems, and over twenty-one types of them have been tested for safety effectiveness utilizing actual operation tracking or simulation methods (summarized by our research team). Toward these CV&DA technologies, there are some questions: How many crashes would be reduced if all vehicles are equipped with CV&DA? Would these CV&DA technologies really benefit safety as much as our expectation? The answers to these questions are meaningful because they could provide important guidance for the CV&DA technology development priority and promotion policy.

### 1.2. Objectives

Many previous studies have provided the effectiveness estimations of CV&DA technologies or integrated systems based on field tests or simulation experiments. For example, recently the Insurance Institute for Highway Safety (IIHS) has published several reports about the testing results of Forward Collision Warning (FCW) (Karush, 2016; Cicchino, 2017a), Autonomous Emergency Braking (AEB) (Cicchino, 2017a), Autobrake (Karush, 2016), Blind Spot Warning (BSW)

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**Table 1**
Tested CV&DA technologies and corresponding pre-crash scenarios.

| CV&DA Technology | Automation Level(SAE) | Target Pre-Crash Type and Pre-Cash Scenarios |
|---|---|---|
| NS: Forward Collision Warning (FCW) | 0 | Rear-End: |
| NS: Autonomous Emergency Braking (AEB) | 1 | 1 Lead Vehicle Stopped |
| NS: Collision Warning System (CWS) | 0 | 2 Following Vehicle Making a Maneuver |
| S: Forward Collision Warning (FCW) + Adaptive Cruise Control(ACC) | 1 | 3 Lead Vehicle Decelerating |
| S: Forward Collision Warning (FCW) + Autobrake | 1 | 4 Lead Vehicle Moving at Lower Constant Speed |
| S: Forward Collision Warning (FCW) + Autonomous Emergency Braking (AEB) | 1 | 5 Lead Vehicle Accelerating |
| S: Adaptive Cruise Control(ACC) + Advanced Braking System (AdvBS) | 1 | |
| S: Adaptive Cruise Control(ACC) + Advanced Braking System (AdvBS) + Collision Warning System (CWS) | 1 | |
| S: Collision Mitigation Brake System (CMBS) | 1 | |
| NS: Pedestrian Crash Avoidance and Mitigation System(PCAM) | 1 | Pedestrian:<br>1 Pedestrian Crash With Prior Vehicle Maneuver<br>2 Pedestrian Crash Without Prior Vehicle Maneuver |
| NS: Blind Spot Warning (BSW) | 0 | Lane Change: |
| NS: Lane Change Warning (LCW) | 0 | 1 Vehicle(s) Turning – Same Direction |
| S: Blind Spot Warning (BSW) + Lane Change Warning (LCW) | 0 | 2 Vehicle(s) Changing Lanes – Same Direction<br>3 Vehicle(s) Drifting – Same Direction |
| NS: Intersection Movement Assist (IMA) | 0 | Crossing Paths:<br>● Vehicle Turning Right at Signalized Junctions<br>● Vehicle Turning at Non-Signalized Junctions<br>● Straight Crossing Paths at Non-Signalized Junctions<br>● Running Stop Sign<br>● Running Red Light |
| NS-CV: Left Turn Assist(LTA) | 0 | Crossing Paths: |
| S: Collision Mitigation Brake System (CMBS) | 1 | ● Left Turn Across Path from Opposite Directions at Non-Signalized Junctions<br>● Left Turn Across Path from Opposite Directions at Signalized Junctions |
| NS: Lane Departure Warning(LDW) | 0 | Run-Off-Road: |
| S: Lane Departure Warning(LDW) + Curve Speed Warning(CSW) | 0 | ● Road Edge Departure With Prior Vehicle Maneuver<br>● Road Edge Departure Without Prior Vehicle Maneuver<br>● Road Edge Departure While Backing Up |
| NS: Electronic Stability Control (ESC) | 1 | Run-Off-Road:<br>● Control Loss without Prior Vehicle Action<br>● Control Loss with Prior Vehicle Action |
| NS: Backup Collision Intervention (BCI) | 1 | Backing: |
| NS: Rearview Cameras (RCA) | 0 | ● Backing Up into Another Vehicle |

*Note:*S stands for the integrated system, while NS stands for non-syste.

(Cicchino, 2017b), Lane Departure Warning (LCW) (Cicchino, 2017c) and Rearview Cameras (RCA) (Cicchino, 2017d). A complete summary of these studies is needed to answer the proposed questions in subsection 1.1, and it could provide us a clearer picture of the overall effectiveness of the CV&DA technologies. Some efforts have been made so far toward the summarization work. Jermakian (2011) estimated the maximum potential crash reduction of the CV technologies for U.S. passenger cars, which include: Side View Asist (SVA), Forward Collision Warning (FCW), Lane Departure Warning (LDW), and Adaptive Headlight (AdHd). Kockelman and Li (2016) provided a combined benefit estimation of 15 CV&DA technologies for light vehicles. Chang (Chang, 2016) summarized the CV related research about heavy vehicles, which was conducted by National Highway Traffic Safety Administration (NHTSA), including Forward Collision Warning (FCW), Lane Change Warning & Blind Spot Warning (LCW + BSW), and Intersection Movement Assist (IMA).

However, there are three major limitations existing in above-mentioned literature: (1) not all of the CV&DA technologies that have been tested were included; (2) the estimations of the CV&DA's effectiveness were only based on one or two studies, in which limited experiment conditions or evaluation methodologies were considered. Thus, those estimations of the CV&DA effectiveness may not be transferable to other situations; (3) few research has evaluated the performance of the CV&DA technologies under specific conditions, e.g., extreme weather conditions.

This research aims to summarize most of the previous CV&DA research, involving all of the major CV&DA technologies which have been tested in the last ten years. The research tries to provide a more general estimation of CV&DA effectiveness by comparing the estimated effectiveness between different studies. Although those CV&DA technologies were tested under different conditions or used different methodologies, it is still possible to reach some conclusions that are consistent between various studies. This comparison work between studies is crucial to provide a better estimation of the safety effectiveness of the CV&DA technologies, which could be used for policy making or resource allocation in the future. In addition, this study also provided some insights into the CV&DA effectiveness under extreme weather conditions, specifically the effectiveness of FCW under fog conditions.

In this study, the crash avoidance effectiveness is defined as the measurement for the safety effectiveness of CV&DA technologies The safety effectiveness of CV&DA technologies can be divided into two categories: crash-avoidance -based effectiveness (NHTSA, 1996; Koziol et al., 1999; Najm and Wiacek, 1999; Sugimoto and Sauer, 2005; Najm et al., 2006; Battelle, 2007; Dang, 2007; Wilson et al., 2007; Gordon et al., 2010; Nodine et al., 2011a,b; Perez et al., 2011; Van Auken et al., 2011; Harding et al., 2014; Yanagisawa et al., 2014; Chang, 2016; NHTSA, 2016), and vehicle-performance-improvement-based effectiveness. For crash-avoidance-based effectiveness, measurements of severe conflicts and near-crash events are widely employed to analyze the crash reduction effectiveness of the CV&DA technologies, since the occurrence of a crash is rare in the real world. For vehicle-performance-improvement-based effectiveness, it involves metrics of speed (Marsden et al., 2001; Dowling et al., 2015), headways (Ma et al., 2004), rejected gaps (Rakauskas et al., 2009), time-to-collision (Aliubavicius et al., 2016), conflict rates (Deng and Ma, 2015), etc. The vehicle-performance-improvement-based effectiveness is also called surrogate safety