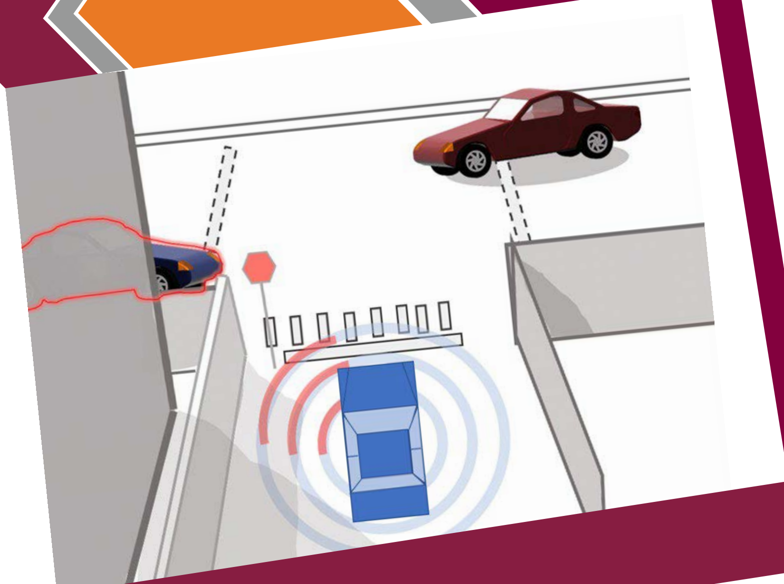
Impacts of Connected Vehicle Technology on Automated Vehicle Safety

May 2022 | Final Report



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16. Abstract
Connected vehicle technologies have a promising role in advancing vehicle safety, but just how much of an impact can connected vehicles have on driver safety? This study uses crash and near-crash events from the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP2 NDS) to reconstruct crash events so that the benefit of line-of-sight (LOS) systems and connected vehicle technologies (CVT) can be compared. The benefits of CVT over LOS systems includes additional reaction time before a predicted crash, as well as a lower deceleration value needed to prevent a crash. These values were then used to predict the probability of severe injury for any crashes that could occur. This work acts as a baseline effort to determine the potential safety benefits of CVT-enabled systems over line-of-sight technologies alone.

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Abstract

Connected vehicle technologies have a promising role in advancing vehicle safety, but just how much of an impact can connected vehicles have on driver safety? This study uses crash and near-crash events from the Second Strategic Highway Research Program Naturalistic Driving Study (SHRP2 NDS) to reconstruct crash events so that the benefit of line-of-sight (LOS) systems and connected vehicle technologies (CVT) can be compared. The benefits of CVT over LOS systems includes additional reaction time before a predicted crash, as well as a lower deceleration value needed to prevent a crash. These values were then used to predict the probability of severe injury for any crashes that could occur. This work acts as a baseline effort to determine the potential safety benefits of CVT-enabled systems over line-of-sight technologies alone.

Acknowledgements

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Introduction

Data shared over connected vehicle technologies may provide a variety of performance benefits to transportation. Over the past several years, the pace of new cellular connections within vehicles has surpassed that of handheld devices providing travelers with vehicle-based applications focused on convenience (e.g., streaming media, traffic updates), diagnostics, and safety (e.g., automatic calling of emergency services). These products are focused on applications which require relatively low bandwidth and can tolerate timing variability and higher latency. However, with the advent of more advanced interoperable networks, such as 5G LTE, DSRC, and cellular V2X (c-V2X), the sphere of possible applications expands to cover low latency high-reliability applications – enabling rapid exchange of information between various road users in near, real-time. This new level of collaborative communication could directly improve safety as events unfold. Although previous work has characterized some of the potential advantages of connectivity on human operated vehicles, the impacts of connectivity on automated driving systems (ADS) is not well established.

As automated and connected vehicles become more of a reality on the road, the safety of these vehicles must be rigorously tested. There are many studies that evaluate the potential safety benefits of such vehicles, as well as other factors that can contribute to mobility, efficiency, and safety (i.e., reduced delay times, ride smoothness, crash avoidance). We reviewed studies that focused on investigations, tests, and simulations for connected/autonomous vehicles interacting in intersections. We also found benefits in addition to safety afforded by connected vehicle technology within traffic intersections, as well as recommendations by the National Highway Traffic Safety Administration (NHTSA).

Method

The primary steps used in the research were:

- Identify relevant events from naturalistic driving data
- Extract position and kinematic data from identified events
- Reconstruct events
- Develop kinematic model of event for simulation
- Perform risk analysis to compare potential safety benefits

The following section describes the above steps in more detail.

Dataset

The Second Strategic Highway Research Program Naturalistic Driving Study (SHRP2 NDS) is the largest naturalistic driving study that has been undertaken to date. The SHRP2 database consists of over 5.5 million trips driven by 3,542 drivers across 6 collections sites (see Figure 1) in the continental United States[1].

Figure 1. Map showing SHRP2 data collection sites.

VTTI developed a data acquisition system (DAS) to support the research questions and objectives of the SHRP2 NDS program, which included compiling a data set that could be used to support future data mining activities such as this one. The DAS facilitated the collection of the following data of interest to this study:

- Video data of the forward view
- Host vehicle (HV) speed data
- HV yaw rate data
- Global Positioning System (GPS) data

While the SHRP2 data contains significantly more data including data from the vehicle network, forward radar, 6-axis inertial data, and additional video channels, the above channels provided a minimum set that was sufficient to perform the research. This set also eliminates the use of personally identifiable information and presents a method that other researchers could use to perform similar analysis from data that is easily collected.

Event Identification

Events were identified in the NDD where connected vehicle technology (CVT) could provide a potential benefit compared to line-of-sight (LOS) systems. For example, events where an object obstructed the view of a LOS system. In this case, the conflict object, or principal other vehicle (POV), was out of sight for most of the time leading up to the event. In this condition, a CVT

[1] Further background information regarding the SRHP2 NDS program including the study design and data collected can be found at https://insight.shrp2nds.us/documents/shrp2_background.pdf.

system would activate prior to when an LOS would. Figure 2 illustrates an example of such an event.

From initial data mining, out of the 5.5 million trips in the SHRP2 data, 594 were selected. The candidacy of each event was then rated by its relevancy to the project and its ability to be reconstructed. Those that were not good candidates were excluded due to insufficient video, unpredictable agent intentions, host driver error, or other issues. This second round of screening yielded 18 crash and 162 near crash events to carry forward in the analysis.

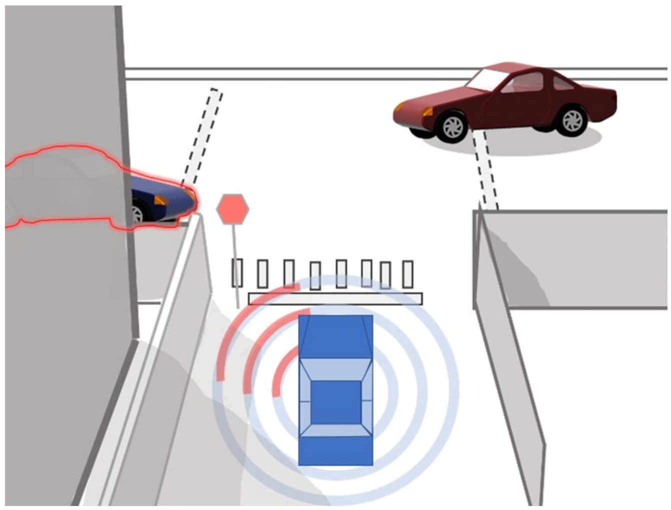

Figure 2. Wall on the left blocks the HV's view of the POV. Since the vehicles are equipped with CVT, then the HV is able to identify a potential conflict.

Data Enclave Extraction

VTTI's data enclave contains all recorded and analyzed information from the SHRP2 naturalistic driving study, including video feed and GPS traces of the HV. The GPS data were used to superimpose the position of the HV over the corresponding Google map image[2]. The GPS coordinates were then converted into pixel locations on the image. This eliminated personally identifiable information and allowed the vehicle path to be corrected relative to the world coordinate system. Kinematic data recorded during each event was extracted to allow reconstruction of the motion of the HV. Additionally, the front-facing video was exported to use in the identification of the relative location of objects of interest. The researchers used these four pieces of data to reconstruct each event and determine the system activation times for LOS and CVT, the deceleration level needed to prevent a crash, and the estimated crash severity if the crash was unavoidable.

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[2] Google Maps. (2019, December 6). "Figure 3. Step 1 GUI; Figure 4. (a) Correct Calculated Trajectory (b) Incorrect Calculated Trajectory; Figure 5. Step2 GUI. Retrieved from Google Maps.

Event reconstruction

Step 1: Identifying Impact Proximity Frame and HV Locations

As noted previously, the first step in recreating the event was to superimpose the HV trajectory over the Google map image. Although the GPS location was recorded with the DAS during the event, the error associated with standard GPS data is greater than what was necessary for this research. Thus, points were marked individually on the map of the HV location, and the kinematic information from the host vehicle was used to generate a corrected trajectory.

The GUI shown in Figure 3 was developed to facilitate the following two tasks.

1. The first identified the impact proximity frame from the event video. This is the approximate frame in which the HV and POV come in contact (or near contact).
2. Next, the two frames within the video were identified that corresponded to two locations of the HV on the map. The frames were chosen based on our ability to accurately place the concurrent HV position and heading with respect to other elements on the map (i.e., lane markings, buildings, trees, etc.)

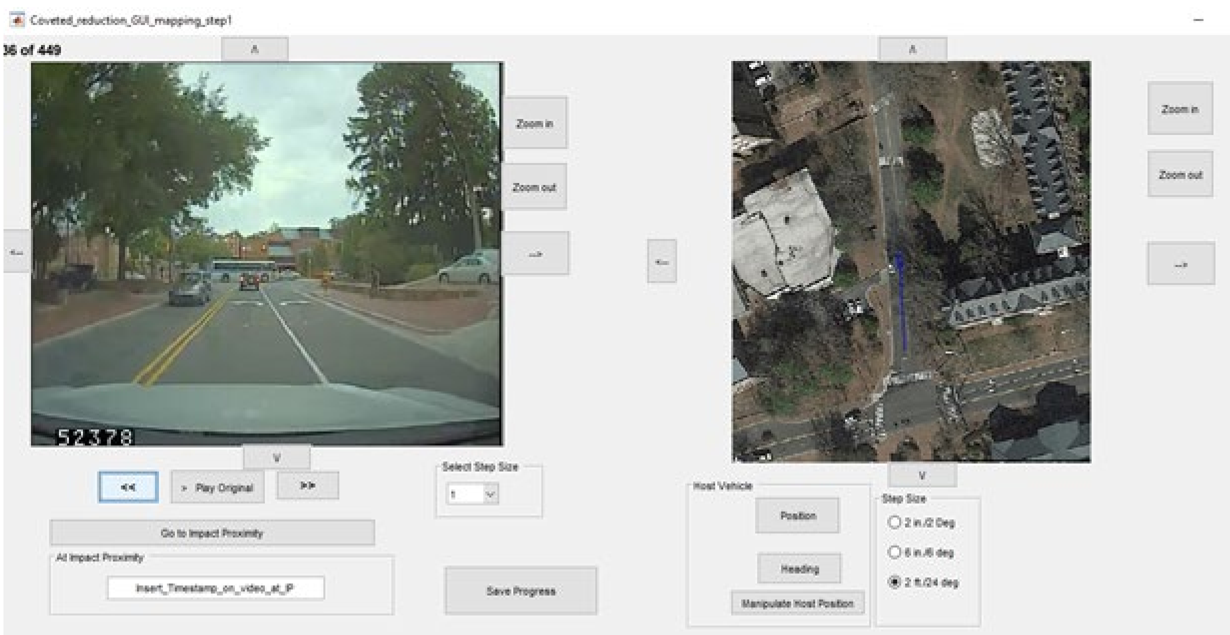

Figure 3. GUI developed for identifying impact proximity frame and HV locations.

Step 1.5: Calculating HV Trajectory

Next, the trajectory of the vehicle frames was calculated using the recorded vehicle kinematic data and the positions and headings identified at the initial and final frames in step 1. This was done by taking the vehicle's starting position and heading, then applying the recorded yaw rate and speed to determine the position and heading at the next time step. This process was repeated for each frame to get the HV trajectory throughout the event.

The trajectory was then superimposed on the corresponding map as shown in Figure 4. We then reviewed each frame to evaluate the quality of the trajectory. If the trajectory calculation produced an unrealistic trajectory, (Figure 4b), the researcher adjusted two of the algorithm parameters, the trace factor and theta shifter, to generate more accurate positions and headings for the HV in step 1. The trace factor helps establish the distance between the first and second marking of the HV, while the theta shifter helps establish the correct heading and position of both markings.

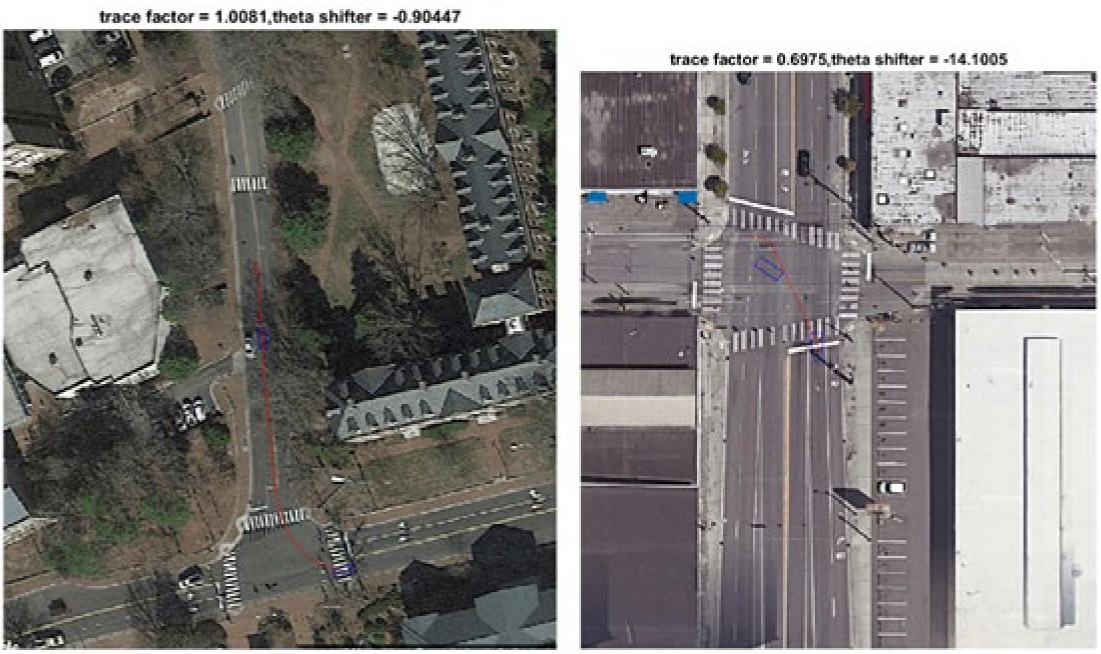

Figure 4. Review step showing an example of (a) correctly calculated trajectory and (b) an incorrectly calculated trajectory.

Step 2: Determining Locations of Objects of Interest

For step 2, the analysis tool was used to create a file that contained the positions of the HV, the view obstructing objects, and the POV (Figure 5). The left side of the GUI shows the front camera from the HV. The right side of the GUI shows the position of the HV (blue) at that timestamp.

First, we used the impact proximity frame (the video frame in which the impact occurs) and identified the POV. We then went back four frames at a time until we reached the frame in which the POV was no longer visible. Each object that may be obstructing the view of the HV driver was marked in this frame. We then went forward four frames at a time and marked the locations of each of the identified view obstructing object and the POV.

This process went quickly when the position and heading of the HV were accurate (as determined by the previous two steps) and there was one POV and one stationary, view-obstructing object. If either of these conditions were not true, the process took much longer. When the HV position accuracy was insufficient, the previous steps were repeated to improve the accuracy of the reconstruction.

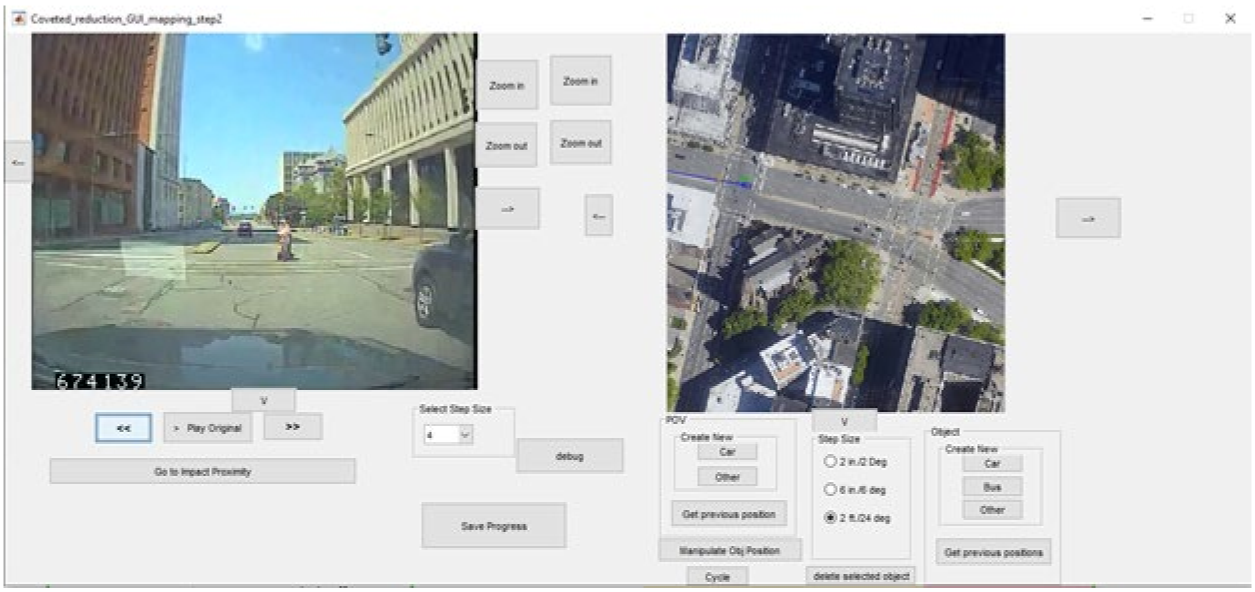

Figure 5. GUI used for determining locations of objects of interest within scene.

Physics-based model for event simulation

With the events reconstructed, we could manipulate different parameters to simulate three detection conditions for each event. The first scenario was the base condition which used the data in the original event reconstruction. The second condition applied LOS technology to the HV for detecting the POV. For simplicity in calculation, for a LOS, it was assumed that the HV detected the POV when an uninterrupted line could be drawn between the centroid of each vehicle (Figure 6). The third condition assumed the HV and POV were equipped with V2V technology allowing the HV to know the location, speed, acceleration, and trajectory of the POV at all times during the event.

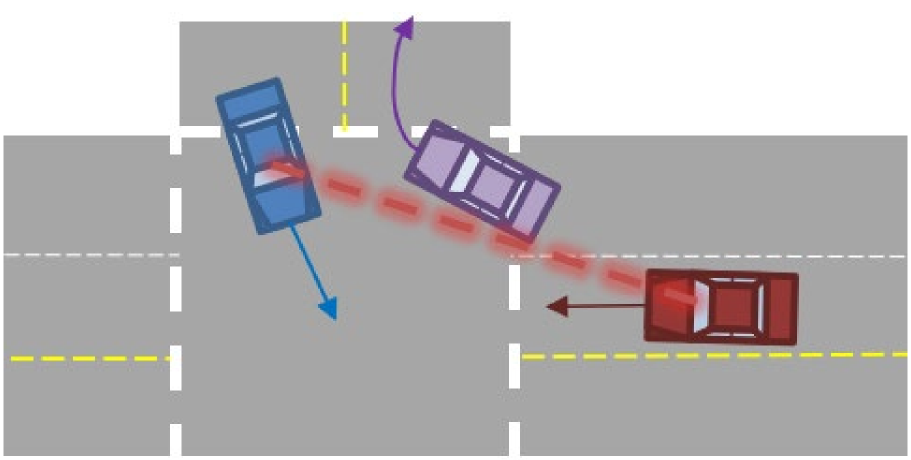

Figure 6. The centroid of the POV (blue) is within the line of sight of the HV (red), which determines LOS system activation.

Using the data from the previous two steps, the team identified the frames in which a potential conflict was identified, and the required deceleration of the HV needed to prevent a crash.

To calculate these, the team used the relative speeds and locations of the POV and view-obstructing objects. This was done by interpolating the positions of the POV and objects (determined in step two) throughout the event. Then in each frame, the current speed and heading of the HV and POV were used to determine the expected trajectory of each vehicle. A conflict was defined as the vehicle centroids being within 4 meters of each other at some point within their predicted trajectories. This was iterated over each frame of the event so that there was an updated predicted trajectory for each frame.

The output from the previous step provided a vector that contained each frame at which a conflict was identified. The first frame in which a potential conflict was determined corresponded to when the CVT system would activate. The analysis then continued frame-by-frame until the HV had a clear line of sight with the POV (as shown in Figure 6). This provided the time at which the LOS system would activate. Using these two vectors, we can determine the time to collision (TTC) for each system. Similarly, the minimum deceleration required to prevent the crash can be estimated based on the relative distance and speed of the HV and POV. The minimum required deceleration assumes the HV only brakes without any other evasive maneuver e.g., the HV does not swerve. Additionally, a further simplifying assumption was made that the POV does not take evasive action. This allowed us to calculate a single metric, the minimum required deceleration, to use for comparison. A less conservative approach would be to apply some degree of evasive action by the POV or include lateral evasive control. These additions would improve the fidelity of the model in predicting a crash, but not the ability of the method to determine the threat detection time for each system.

Risk Analysis

In 2018, 48.1% of crashes in the US that resulted in injury occurred at intersections (National Highway Traffic Safety Administration, 2018). To evaluate the potential safety impact that connected vehicle technologies could provide, the potential severity of crashes was estimated between vehicles equipped with CVT and LOS systems. A commonly used surrogate measure used to predict crash severity is the delta-v value. This describes the change in velocity of the vehicle throughout a crash event. We used an injury risk model (Bareiss & Gabler, 2020) to predict the probability of a severe injury given the delta-v value of the HV involved in a crash. To simplify the calculation of the risk, the delta-v value was based on the pre-collision velocity of the HV. For our analysis, we defined the pre-collision velocity to be when the centroid of HV was within 2 meters of the centroid of the POV.

Results

The initial data mining extracted 594 safety critical events (SECs) for subsequent review from the 5.5 million SHRP2 trips. The candidacy of each event was then rated by its relevancy to the project and its ability to be reconstructed. Those that were not good candidates included events with insufficient video, unpredictable agent intentions, and host driver error.

Figure 7 shows the distribution for the screening of the initial 594 events based on the following categories.

- **None –** Unable to reconstruct or no relevance to scope of work
- **Mild –** Potential difficulties with reconstruction, may require too many assumptions, or event lacks sufficient severity
- **Strong –** High likelihood of successful reconstruction and event is relevant to scope of work

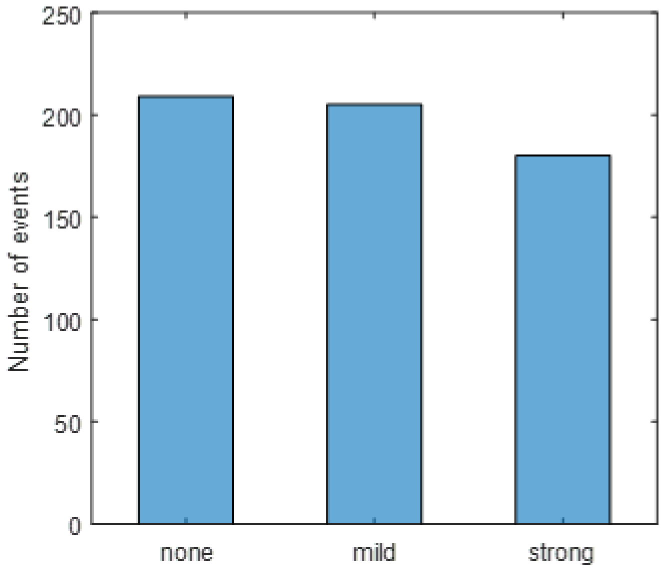

Figure 7. Event candidacy results

This initial screening yielded 18 crash and 162 near crash SECs that had strong candidacy scores.

Table 1 provides a summary of the obstruction type for the events with strong candidacy.

Table 1. Events With Strong Candidacy by Obstruction Type

Leading Cause of Conflict	Near Crashes	Crashes
Obstructed view	157	17
Agent difficult to see (frequently small)	3	1
Unpredictable agent intention	2	0

After analyzing the 162 near crash and 18 crash events that fit our criteria, we were able to calculate the minimum required deceleration for 68 of these events. The rest were not included due to incorrect satellite images (e.g., major construction since the date of the event), incorrect GPS data points in SHRP2, or missing kinematic data.

For the final 68 events, the team calculated:

1. the minimum required deceleration to avoid a collision
2. the activation time difference between the systems
3. the probability that at least moderate injuries would result from this crash event

Figure 8 shows the results for the deceleration levels calculated for the events. Here we see that the required deceleration to prevent a potential crash was, on average, 2.95 m/s^2 higher for the LOS system than for the CVT system. In general, a deceleration value of less than 1g is not unreasonable for most modern vehicles (Bareiss & Gabler, 2020). Applying this threshold, 91.2% of the CVT events and 75.0% of the LOS events analyzed required an acceleration of less than -9.8 m/s^2 (i.e., a deceleration of more than 1g).

This analysis implies that three quarters of accidents (assuming braking only) could be avoided using LOS features whereas nine out of ten could be eliminated if the vehicles had CVT. However, the actual accident rates from the NDS, which involved vehicles that did not have CVT or LOS systems, were lower. As shown in Table 1, only 10.4% of the SECs selected were crash scenarios and, of the 68 SECs simulated, only 4.4% resulted in a collision. The discrepancy is due to the simplifying assumptions regarding the actions taken by the drivers to avoid an accident. In the actual event, one or both actors performed evasive maneuvers that included more than simply longitudinal control i.e., braking. While the simulated event shows a higher required deceleration than what was observed in the NDS data, the results still provide useful insight when comparing the different sensing technologies.

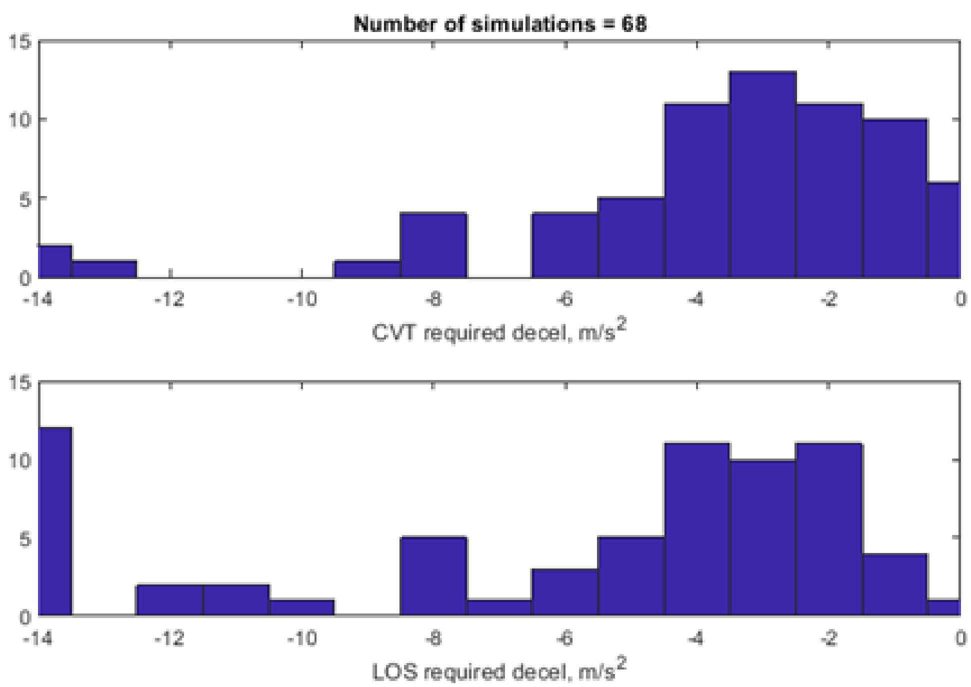

Figure 8. Minimum required acceleration to avoid collision for CVT and LOS systems

The results were also stratified based on the standard accident configuration of the HV in relation to the POV (see Appendix: Event Configuration). The average difference in deceleration between a CVT system and an LOS system is shown in Figure 9 for each of the 12 configurations.

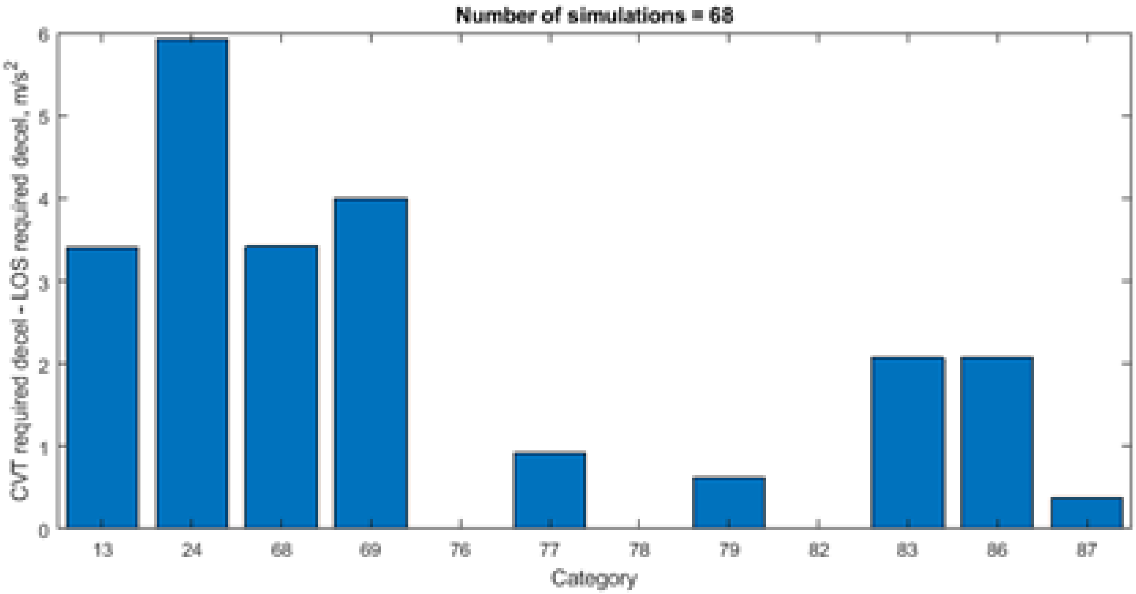

Figure 9. Average difference in deceleration between CVT and LOS systems broken up by configuration

The highest average difference in deceleration happened for configurations 24 and 69 as shown in Figure 10. Configuration 24 occurs when the POV is suddenly revealed to the HV (Figure 10a). Configuration 69 occurs when the POV turns left across the path of the HV (Figure 10b). This means that the CVT system requires a much lower deceleration when straight line braking is used to avoid the accident.

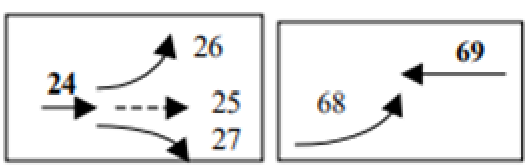

Figure 10. (a) Sudden reveal configuration (b) POV turning into HV path configuration

Comparing the activation time for the CVT and LOS systems provided an indication of the potential safety buffer offered by CVT. Figure 11 shows the additional time it takes a LOS system to activate compared with a CVT system based on the crash configuration. From this figure we see that there was an average time saved of less than one tenth of a second for configuration 68 (i.e., both systems were activated at nearly the same time), but at least 0.25 seconds for the remaining configurations. In fact, the CVT systems allows for more than 0.25 seconds of additional reaction time in more than half (57.4%) of the 68 events analyzed.

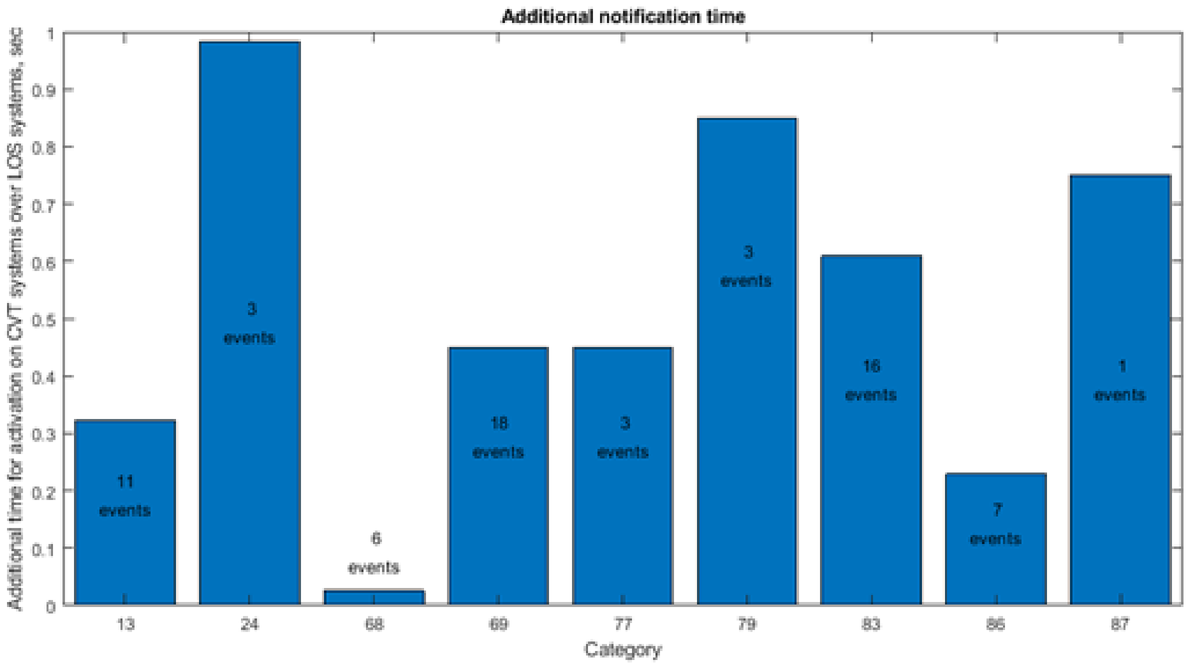

Figure 11. Time saved for connected vehicles: time between activation of a CVT system and a LOS system

Configuration Analysis

Figure 11 shows that configurations 69 and 83 comprised the most common events (at least 15). On average, the CVT system provided an additional 0.45 seconds of notification compared to LOS. Both events occur as the principal other vehicle makes a left turn in front of the HV (Figure 12). From this initial simulation, connected technology could have a significant safety impact on these two scenarios. The benefit would likely be even more pronounced for CVT compared with LOS since both vehicles would have the connected technology and therefore the information regarding the potential threat.

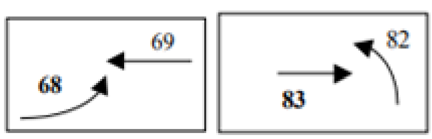

Figure 12. (a) Turn across path: initial opposite directions (b) Turn into opposite directions

Risk Analysis

Each dot in Figure 13 represents one of the events analyzed along with its corresponding delta-v value. The blue dots represent vehicles equipped with CVT systems and the red dots represent vehicles equipped with LOS systems. The delta-v values were used in conjunction with the model proposed by Bareiss and Gabler to predict the probability that the crash would result in a severe injury. The variables used for the risk analysis are shown in Table 2.

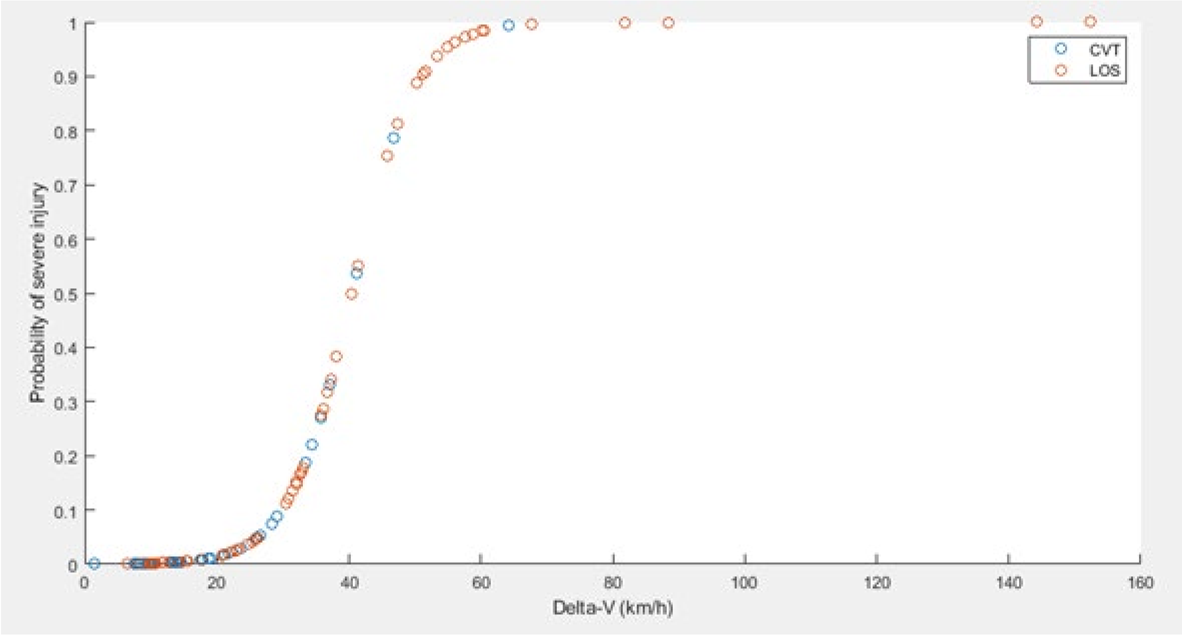

Figure 13. Probability of a severe injury in crashes involving CVT enabled vehicles in blue, and LOS enabled vehicles in red

Using these curves, the red dots (LOS) generally correspond to a higher probability of a severe injury. In fact, there is an average of a 26.0% reduction in likelihood of a crash involving a severe injury in a vehicle with a CVT system versus an LOS system.

Table 2. Risk Analysis Variables

Predictor Variable	Description	Value
Belt Use	Yes (1) or no (0)	1
Age	Occupant ages were divided into two groups: 13-64 (0) and 65 and older (1)	0
Gender	Male (0) or female (1)	0

Statistical Analysis

Figure 11 shows that the average time saved by a CVT system over a LOS system is 0.51 seconds. The faster a vehicle is traveling, the more important this time saved becomes. In the US, there were 34,247 fatal crashes in 2017, and 8,856 of them occurred from excessive speeding (Insurance Information Institute, 2020). The highest classification of crash severity is "most severe", of which there are 106 events within the SHRP2 data. Of these 106 events, 26 (24.5%) correspond to one of the twelve accident configurations from this analysis. It could then be postulated that if 100% of vehicles were equipped with connected vehicle technology, the HV could begin braking over a half second sooner compared to a LOS equipped HV affecting 2,047 fatal crashes in the US in 2017.

Conclusions and Recommendations

The presented results display that in certain crash scenarios, CVT has the potential to provide a significant safety benefit over LOS technology. This benefit includes additional reaction time before a predicted crash (average of 0.51 seconds), as well as a lower deceleration value (average of 3.0 m/s^2) needed to prevent a crash. These values were used to predict that a car equipped with CVT could reduce the probability of a crash involving moderate injuries by 26.0% using established risk-analysis curves. Additionally, crash scenarios that involve the POV turning left in front of the HV were identified as having the greatest safety benefit of implementing CVT systems. This work acts as a baseline effort in determining the potential safety benefits of CVT-enabled systems over LOS technologies alone. Therefore, it would be beneficial to continue analysis efforts in developing additional scenarios and simulate more complex avoidance maneuvers to determine the potential safety benefits of CVT systems compared to LOS systems.

Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the Safe-D website here.

Education and Workforce Development Products

Course Materials

The researchers involved with this project will generate lecture materials and course exercises to be incorporated in Dr. Zac Doerzaph's course on advanced vehicle safety systems. One module of these materials will focus on the various types of simulation software available to researchers. The other modules will focus on data analysis, modeling, and using one of the software packages.

Educational Audience

The primary audience for these materials will be graduate students. Lecture materials will be delivered to graduate students enrolled in Dr. Doerzaph's class course on advanced vehicle safety systems. The module that focuses on the various types of simulation software will also be made available to faculty and researchers in the AV/CV community via webinar. The UTC will assist the team in targeting appropriate channels for the dissemination of the recorded webinar.

Student Funding

This research will fully fund one graduate student for a year and partially fund a second graduate student.

Student Enrichment

Both students will be able to apply the following skills and knowledge gained through coursework: advanced vehicle safety systems, vehicle dynamics, signal processing, algorithm development. In addition to expanding upon their technical skills, both students will gain valuable experiences with collaboration, report writing, and presenting.

Technology Transfer Products

Expected Outputs

This project will yield quantitative results that compare the potential benefits of automated vehicle systems with and without connectivity. As a result of the research, methods for evaluation of automated vehicle systems will be made available to the research community.

Expected Publications

This study will strive to produce at least two manuscripts that will be suitable for publishing. The research team will target appropriate journals in an effort to publish research findings. The primary audience for the manuscripts will be members of the AV/CV community. The secondary audience would be members of the NDS community. In addition to publishing in peer-reviewed journals, the researchers would like to present the findings at appropriate conferences.

Expected Consumers of the Outputs

This research will help inform consumers on the potential benefits of integrating connected vehicle technologies into automated vehicle systems. State and federal transportation entities will be able to use the results of this study to make informed decisions regarding policy on connected vehicle systems. Automotive OEMS and automotive technology developers will be able to make more informed decisions regarding the safety of their products. Ericsson is particularly interested in this project because the results may influence Ericsson's business strategy.

Market Assessment

Previous work has characterized some of the potential advantages of connectivity on human operated vehicles, but the impacts of connectivity on automated driving systems (ADS) is not well established. This research will be the first effort to tackle this problem and disseminate the results via publications. If the research yields favorable results for connected vehicle technologies, VTTI would be able to better compete for more funding from other agencies. We anticipate the research will generate algorithms, models, and methods.

Planned Stakeholder Involvement

VTTI has identified an industry partner. Ericsson will review and advise on the project. Ericsson will provide input pertaining to the development of the CVT model. VTTI and Ericsson will work together to disseminate results of the research study.

Data Products

The project will generate annotated data for the analyzed crash and near crash events from naturalistic driving that, in accordance with data usage licenses, will be made available.

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Appendix/Appendices

Appendix: Event Configuration

This list is taken from the General Estimates System (GES) accident type glossary (2012). The following list shows the subset of GES configurations used in this analysis.

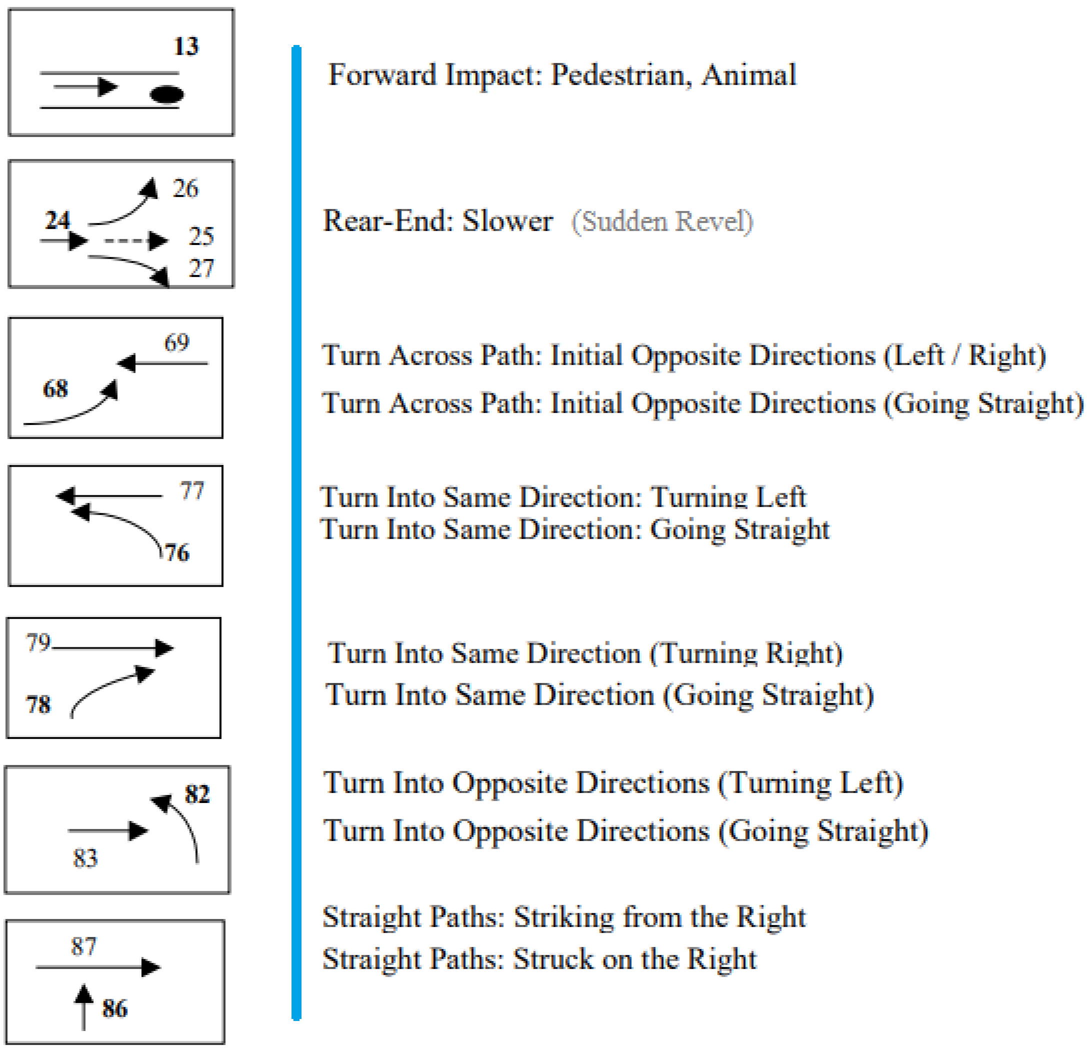

Figure 14. Crash configuration summary chart