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Safety Performance Evaluation of Continuous Flow Intersections in the Era of Connected Vehicles: A Microsimulation Modelling Approach

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ABSTRACT

This study employed Federal Highway Administration's Surrogate Safety Assessment Model (SSAM) to investigate the safety of implementing Connected Vehicles (CVs) at the Continuous Flow Intersection (CFI), by reproducing a real-world corridor, that has multiple successive implementations of CFIs, in VISSIM. Econolite's ASC/3 Software-in-the-Loop signal controllers and Python-programmed Vehicle to Infrastructure (V2I) communications were embedded in VISSIM. Additionally, the effect of CV-Market Penetration Rate (CV-MPR) on safety is taken into consideration. The study shows that CV deployments at partial and full CFIs leads to notable reductions in crash likelihoods and severities. The total number of conflicts, rear-end and lane change conflicts dropped by 23.8%, 23.6% and 24.4%, respectively at full CFIs and 100% MPR, whereas those were reduced by 6.4%, 4.8% and 17.9%, respectively at partial CFIs and 100% MPR. It was also found that at least a 50% MPR of CVs is required for safety improvements to be influential.

1. Introduction

Traffic crashes lead to more than 1.35 million deaths and 50 million injuries each year, globally (World Health Organization, 2018). Road traffic crashes are categorized by the World Health Organization as the eighth leading cause of death worldwide, specifically the death of children and young adults (World Health Organization, 2018). Highway geometric design is one of the key contributing factors to fatal and serious injury crashes. Therefore, roadway re-design projects including creative design of unconventional intersections must be considered to mitigate crashes (World Road Association, 2015). Unconventional geometric designs are those that aim to reduce the number of conflict points and separate the remaining ones. This leads to decreasing crash severities and frequencies. This is mainly done by favoring the arterials' heavy through movements and re-routing the left turn movements. As a consequence, the number of signal phases is reduced leading to delay reductions and improved progression along arterials (Reid, 2004). Recent studies have shown that unconventional geometric designs are capable of improving the overall operational and safety performances substantially (Alzoubaidi, Molan, et al., 2021; Moon et al., 2011; Zlatkovic, 2019). The continuous flow intersection (CFI) is an unconventional intersection design in which left turns are displaced from the intersection approaches using an added upstream crossover. The CFI can either be full, in which left turns are displaced on all approaches, or otherwise partial where left turns are displaced in some of the approaches. A partial CFI has 30 conflict points by design, whereas a full CFI has 28, and the conventional intersection has 32. A reduced number of conflict points is anticipated to contribute to fewer crashes (Hughes et al., 2010).

With the emergence of connected vehicle (CV) technologies, vehicles would communicate wirelessly by means of two approaches (a) vehicle-to-vehicle (V2V) and (b) vehicle-to-infrastructure (V2I) communications in real time. Through this communication, sharing Signal Phasing and Timing (SPaT), for instance, as well as vehicles' statuses including position, speed, among others, is enabled (U.S. Department of Transportation, 2015, 2016) According to (Alzoubaidi, 2017; Alzoubaidi, Al-Balbissi, et al., 2021; Hadi et al., 2021; Rahman et al., 2019; Shams & Zlatkovic, 2019; Tibljaš et al., 2018) the introduction of CVs has improved safety, reduced delays and travel times considerably.

Former studies assessing the safety of CFIs have mainly investigated CFIs while traversed by conventional vehicles (Abdelrahman et al., 2020; Abramson et al., 1995; Hughes et al., 2010; Park & Rakha, 2010; Zlatkovic, 2019). Additionally, various studies have examined the safety impact of the implementing CVs at conventional intersections (Arvin et al., 2021; Rahman et al., 2019; Tibljaš et al., 2018). However, the coupled implementation of CVs and unconventional intersections has not been studied in depth yet. Specifically, the safety of the coupled implementation of CV technologies and CFIs has never been assessed previously, to the best of the authors' knowledge. Hence, the novelty of this research lies within targeting this knowledge gap. This study is an effort to complement our previous work on assessing the operational performance of the coupled implementation of CV technologies and CFIs (Alzoubaidi & Zlatkovic, 2022c). In particular, the goal of this study is to assess the safety of the CFI under varying market penetration rates (MPRs) of CVs. The results of this study shall provide a great insight to practitioners and researchers on the safety performance of CFIs in terms of the surrogate measures of safety (SMoS) in the era of CVs. To address the goal of this study, a simulation modeling network consisting of full and partial CFIs, based on a real-world corridor along Bangerter Highway in Salt Lake County, UT, was built using the VISSIM microsimulation software. The study used CV communication protocols that exchange both vehicles' and signal controllers' latitude/longitude (lat/long) coordinates via V2I communication protocols. Through these protocols, vehicles would be detected, and the CV behavior would be simulated. The V2I communication protocols were programmed in Python and embedded in VISSIM. This research also used the Federal Highway Administration's (FHWA's) Surrogate Safety Assessment Model (SSAM) to process VISSIM's outputs and produce SMoS results. The MPRs in the field will increase gradually as the CV technology is implemented, until achieving 100% throughout the upcoming years. Therefore, it would be sensible to examine the safety performance considering various MPRs of CVs.

This paper is organized as follows. A literature review is presented in the next section. A subsequent section is then dedicated to methodology of the study. The analyses results and discussion are provided in a following section. Lastly, we conclude the study.

2. Literature Review

2.1. Safety Assessment of Continuous Flow Intersections

Despite its wide implementation in the United States, the safety of the CFI has not been thoroughly analyzed. Former CFI studies were focused mainly on the examination of its operational performance. Many studies (Alshayeb et al., 2021; Alzoubaidi, 2022; Alzoubaidi & Zlatkovic, 2022b, 2022c; Autey et al., 2013; Esawey & Sayed, 2007; Goldblatt et al., 1994; Hughes et al., 2010; Jagannathan & Bared, 2004; M. Kim et al., 2007; T. Kim et al., 2007; Reid & Hummer, 2001; Shayeb et al., 2021; Zlatkovic, 2019) employed traffic simulation tools to study various performance measures of the CFI, other unconventional intersection configurations and conventional intersections. The results of these studies showed that the CFI could increase capacity, reduce delays and travel times considerably. The results also showed that the operational performance of the CFI markedly outperforms that of the conventional intersection and other unconventional intersections, particularly the upstream signalized crossover intersection (Autey et al., 2013; Esawey & Sayed, 2007; Goldblatt et al., 1994; Hughes et al., 2010; Jagannathan & Bared, 2004; M. Kim et al., 2007; T. Kim et al., 2007; Reid & Hummer, 2001; Zlatkovic, 2019). Only one study (Alzoubaidi & Zlatkovic, 2022c) has studied the operational performance of the combined implementation of CFIs and CVs. Results of the study show that the deployment of CV technology at CFIs improved the overall operational performance substantially, in that, travel times, delays and queue lengths were reduced by 65.3%, 29.2% and 57.8%, respectively, at the 100% MPR. According to (Alzoubaidi & Zlatkovic, 2022c) higher MPRs would lead to greater operational benefits.

The major drawback of unconventional intersection designs is that they confuse unfamiliar drivers. Park & Rakha (2010) utilized VISSIM to examine the changes in driver behavior. The results of their study showed an increase in the number of hazardous maneuvers, which was attributed to the unfamiliarity of drivers with the CFI configuration. However, a 50% decrease in the number of unsafe maneuvers was observed after a year of implementing the CFI. Therefore, the authors concluded that driver confusion was a temporary effect and was resolved once drivers became accustomed to CFIs. Another study that also examined the drivers' discomfort with the CFI reported similar findings (Abramson et al., 1995). Abdelrahman et al. (2020) performed a before-after analysis to evaluate the safety performance of the CFI. While the authors reported that the CFI has is promising in terms of reducing non-motorized crashes, they found that the CFI could increase crash frequencies when compared to the conventional intersection.

Contrarily, the Louisiana Department of Transportation and Development carried out a simple before-after crash analysis to assess the safety of the CFI. The results indicated a reduction of 27% in the total number of crashes and a 17% reduction in serious injury crashes (LADOTD, 2007). Qu et al. (2020) implemented collision diagram-based to investigate the safety of CFIs. The results of their study suggested that the CFI did not increase the overall frequency of crashes. Contrarily, the CFI reduced the number of left-turn and right-turn crashes considerably. Another study employed the empirical Bayes method to develop crash modification factors (CMFs) for the CFI (Zlatkovic & Kergaye, 2018). The analysis resulted in a CMF of 0.877 for the total number of crashes, which approximately translates to 12% total crash reduction.

2.2. Safety of Unconventional Intersections with Conventional Vehicles

T. Kim et al. (2007) assessed the safety performance of the superstreet intersection, an unconventional intersection design, using SSAM. Findings of the study indicated that the superstreet design with one U-turn lane offers enhanced safety when compared to the conventional designs. Alzoubaidi & Zlatkovic (2022) were the first to investigate the safety of the continuous green T-partial cloverleaf A (CGT-parclo A) and compare it to the conventional partial cloverleaf (parclo) A, parclo progressA, parclo B and folded interchanges. The results show that the CGT-parclo A is the best form of parclo A interchanges, with the potential to reduce the likelihood of crashes as well as their frequencies and severities. Moon et al. (2011) studied the potential of implementing the superstreet design on an arterial in South Korea. The authors evaluated the safety of the superstreet intersection using SSAM. It was found that the superstreet design has fewer conflicts than the current conventional design of the corridor. Particularly, the superstreet has shown a notable decrease in rear-end conflicts. Mohamed et al. (2020) employed SSAM to perform a comparative safety evaluation of the mega elliptical roundabout interchange against other interchange configurations. They concluded that the mega elliptical roundabout interchange displayed the second lowest total number of vehicle-vehicle simulated conflicts in their analysis.

2.3 Safety of Conventional Intersections with Connected Vehicle Technologies

According to the National Highway Traffic Safety Administration (NHTSA), approximately 94% of traffic crashes are attributed to human error, and it is expected that connected and autonomous vehicle (CAV) technology is going to provide the means to avoid human errors and potentially prevent these crashes (NHTSA, 2018). Alzoubaidi et al. (2022) studied the effect of the combined implementation of signal coordination and CVs using VISSIM and SSAM. Results of their study showed that coordinated signals had lower likelihoods of collisions as well as fewer number of conflicts compared to uncoordinated signals. Hadi et al. (2021) assessed the safety benefits of a red-light violation warning algorithm through VISSIM and SSAM. The findings of the study suggested that CV technology could enhance safety at signalized intersections by approximately 51% at a 100% MPR. (Rahman et al., 2019) performed a simulation-based safety evaluation of CVs at conventional intersections using VISSIM and SSAM. The study revealed that a minimum of 40% MPR is required to observe influential safety benefits of CVs. Arvin et al. (2021) established a simulation framework to model and examine the interactions of AVs, CAVs and conventional vehicles at a conventional intersection. The research team used two SMoS, namely the variations in travel speeds and the number of longitudinal conflicts. The findings of the study indicated that the number of conflicts increased at low MPRs of the AVs equipped with adaptive cruise control (ACC) technology. However, the number of conflicts did not increase when AVs were incorporated with the cooperative ACC (CACC), which is a V2V communication system that aids AVs in adjusting their speed behavior in accordance with the preceding vehicle. In addition, Arvin et al. (2021) maintained that an increase in speed variability was observed in scenarios of AVs with ACC systems at MPRs of 0% to 40%. As for the AVs with CACC systems, the study findings showed a notable drop in speed variability, and the reduction was perceived to be exceedingly higher than that of the vehicles equipped with ACC systems. As such, the authors concluded that by incorporating communication systems into AVs, substantial reductions in the number of conflicts and speed variabilities could be achieved.

2.4 Safety of Unconventional Intersections with Connected Vehicle Technologies

Virdi et al. (2019) assessed the safety benefits of CAVs at DDIs, CDIs, conventional signalized intersections, priority-controlled intersections and roundabouts via VISSIM and SSAM. The results showed that the number of conflicts would decrease with the increase of CAVs’ MPR at roundabouts and priority-controlled intersections. However, an increase in the number of conflicts was noted at DDIs and conventional signalized intersections with the increase of the CAVs’ MPR. This increase peaked thrice at the 30%, 40% and 60% MPRs of CAVs at the DDI. It also spiked at the 20% and 50% for the conventional signalized intersections. Alzoubaidi (2022) studied the operational performance of CFIs in a CV environment. The authors reported statistically significant reductions in travel times, delays and queue lengths at all MPRs. The authors particularly concluded that travel times, delays and queue lengths were reduced by as high as 65.3%, 29.2%, and 57.8% as a result of CV deployment at CFIs.

Alzoubaidi (2022) studied the mobility impact of implementing CVs at the CDI, DDI, and the Single Point Diamond Interchange (SPDI). The study revealed that the interchange design has a greater impact on traffic operations than does the CV MPR. Specifically, a 100% CV MPR leads to 6.4% reductions in delays compared to a 0% CV MPR, without taking the effect of interchange design into consideration. Contrarily, the CDI increases delays as high as 24.0% as opposed to the SPDI, without considering the effect of CVs. In a similar manner, the DDI reduces delays by up to 60.6% compared to the SPDI, without considering the effect of CVs, according to Alzoubaidi (2022).

As shown in the literature review, previous studies were chiefly focused on the safety performance of CV technologies at conventional intersections. This prompts the need to examine the safety of CVs at unconventional intersections in general and this study addresses this knowledge gap. In addition, no previous studies have investigated the safety benefits of the joint deployment of CVs and CFIs. Hence, this study is intended to address this area by assessing the safety of CFIs in the presence of CVs.

3. Research Methodology

3.1. Simulation Testcase and Data Collection

A section of Bangerter Highway (SR-154), a major urban arterial in Salt Lake County, Utah, was chosen for this study. Since it has several successive implementations of partial and full CFIs with high traffic demands, this corridor was considered suitable for the study. The testcase section is nearly 6.6 miles in length and consists of six signalized intersections: four partial CFIs, one full CFI and one single point diamond interchange (SPDI) as shown in Figure 1. Additionally, all intersections in the vicinity of the test section, that are expected to affect the arrival pattern or lane choice, were included in the simulation network. Consequently, the total number of simulated signalized intersections is 21. As mentioned previously, the CFI can either be full, in which left turns are displaced on all approaches, or otherwise partial. In a CFI, left turning vehicles are displaced to the far-left side of the intersection using an upstream crossover as show in Figure 1.

The traffic data necessary for building the simulation modeling network were acquired from the Utah Department of Transportation's (UDOT's) Automated Traffic Signal Performance Measures (ATSPMs), UDOT's Traffic Operations Center, as well as INRIX data. The collected data include traffic signal timing data, traffic volumes for the base year of 2019, the annual traffic growth rate, traffic composition, and sectional travel times. According to the data, the peak hour is from 4:30 to 5:30 P.M.

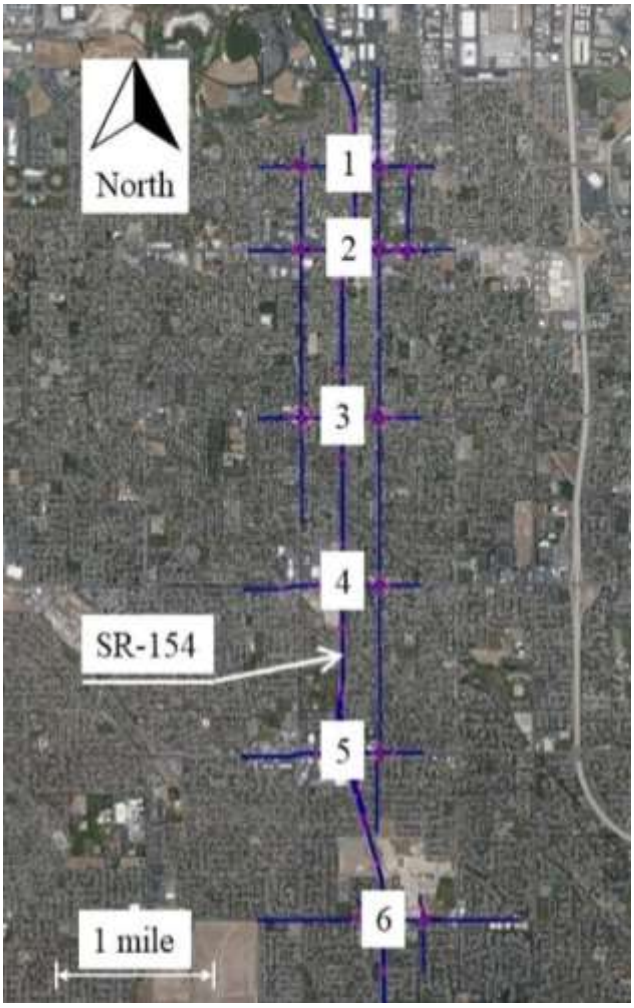


Figure 1. Testcase network of Bangerter Highway, Utah.
1 – 3100 S (Partial CFI); 2 – 3500 S (Partial CFI);
3 – 4100 S (Full CFI); 4 – 4700 S (Partial CFI);
5 – 5400 S (SPDI); 6 – 6200 S (Partial CFI)
Source: (GoogleEarth).

3.2. Microsimulation Scenario Development and Modeling Methodology

The acquired data were used to develop the network's microsimulation models and investigate their safety performances for the traffic conditions of 2019, as well as those of the future year, 2029. This study also evaluated the safety impact of varying MPRs at CFIs. To address this part of the objective, five scenarios were developed for each modeling year where the scenarios differed in the CV MPR as follows: 0% MPR, 25% MPR, 50% MPR, 75% MPR and 100% MPR. Traffic signal timings for the CFIs in future models of the year, 2029, were optimized using previously developed Excel-based deterministic applications (Zlatkovic, 2019), whereas the signal timings for the nearby intersections were optimized using Synchro 10. VISSIM microsimulation software version 11 was used for developing the simulation network. To ensure that the created models would imitate real-world signal operations of the CFIs, Econolite's external ASC/3

Software-in-the-Loop (SIL) signal controller was embedded in the simulations. The ASC/3 SIL controllers were previously used in several studies (Alzoubaidi, 2022; Alzoubaidi et al., 2022; Alzoubaidi & Zlatkovic, 2022a; Hadi et al., 2021). Additionally, with the use of Bing's high-quality maps, the simulation network was developed, therefore ensuring accuracy in the representation of roadway and intersection geometries. Furthermore, VISSIM's user-defined attributes were coded to convert VISSIM coordinates into global coordinates. The V2I communication protocols were coded in Python and integrated in simulations. These protocols were developed to allow for exchange of the lat/long coordinates between the vehicles and the signal controllers. This practice is implementable in field deployments as lat/long coordinates are included in the real-world basic safety message set of the dedicated short-range communication (DSRC). In each time step, the distance between the vehicles and the controllers is calculated using these algorithms which utilize the following Haversine formulae (Upadhyay, 2020):

$$d = R \times c \tag{1}$$

Where R represents the Earth's radius of 20,902,231 ft (~3,960 mi), and c is computed using the following equation.

$$c = 2 \times \operatorname{atan2}\left(\sqrt{a}\sqrt{1-a}\right) \tag{2}$$

The atan2 function yields the angle between the line projected by the input coordinates and the positive side of the abscissa. The outputted angle ranges between -π and π radians (Palm, 2005). The parameter, a, is computed using the Haversine formula expressed as follows (Upadhyay, 2020):

$$a = \sin^2\left(\frac{\Delta lat}{2}\right) + \cos(lat_{veh}) \times \cos(lat_{int}) \times \sin^2\left(\frac{\Delta long}{2}\right) \tag{3}$$

The terms, lat_{int} and lat_{veh}, are the latitudinal coordinate of the intersection's center the latitudinal coordinate of the vehicle, respectively. The term Δlat represents the difference between the latitudinal coordinates ($lat_{veh} - lat_{int}$). Similarly, $\Delta long$ represents the difference between the longitudinal coordinate of the vehicle, $long_{veh}$, and the longitudinal coordinate of the intersection's center, $long_{int}$, expressed as $long_{veh} - long_{int}$.

To enable VISSIM to calculate the distance between each vehicle and each intersection in each simulation time step using the previous Haversine's formulae, V2I communication algorithms were coded in Python. These V2I algorithms were developed particularly to exchange lat/long coordinates of both vehicles and centers of the intersections. This practice is replicating real-world deployments of V2I technologies since lat/long coordinates are included in the real-world DSRC basic safety message (BSM) set. The Python code also included algorithms to use the lat/long coordinates as inputs to the Haversine's formula to provide distance results and driving behavior decisions. The developed V2I communication algorithms were then embedded in simulations through VISSIM's COM interface. The latter ensures constant communication between vehicles and intersection in each simulation time step.

In VISSIM, an urban driving behavior was established to simulate drivers' behavior in urban traffic. Therefore, in the developed models for this study, conventional vehicles behave according to VISSIM's default urban driving behavior. CV driving behavior is enabled and simulated in this study through the developed V2I Python communication algorithms. As mentioned previously, the latter was coded to imitate real-world BSM transfer, which provides CV drivers with awareness of their nearby events and allows them to change their driving behavior accordingly. The V2I communication range was set to a radius of 1,000 ft, measured from each intersection's center, as this is consistent with the communication range of the DSRC technology (Harding et al., 2014). In the simulation, once the vehicles equipped with the DSRC on-board units (OBU) enter the detection range of 1,000 ft, V2I communication starts and CVs in simulation will start applying the actual behavior of CV drivers but in a simulation environment. A wide body of the literature (Alzoubaidi et al., 2022; Rahman et al., 2019; Rahman & Abdel-Aty, 2018; Sinha et al., 2020; Stanek et al., 2018; Yang et al., 2020) made CV behavior possible in VISSIM through adjustments to VISSIM's driving behaviors, with (Rahman et al., 2019) focusing primarily on the urban driving behavior of VISSIM to create a calibrated CV-modified urban driving behavior. (Rahman et al., 2019) performed a sensitivity analysis on VISSIM's driver behavior parameters based on a set of their allowable minimums and maximums in the simulation model. For each of the parameters, a range of values between the minimum and maximum (including the default value) were selected to run the VISSIM model and the corresponding values of the objective function MANE were calculated. Therefore, following the guidelines for the CV-modified urban driving behavior by (Rahman et al., 2019) and (Alzoubaidi et al., 2022; Rahman and Abdel-Aty, 2018; Sinha et al., 2020; Stanek et al., 2018; Yang et al., 2020) ensured that the parameters we followed are consistent with the current state-of-the-art. As such, in this study, CVs within a detection range of 1,000 ft behave in accordance with the CV-modified urban driving behavior parameters shown in Table 1. The trajectory output files from VISSIM's were then processed in FHWA SSAM to produce results of SMoS.

Table 1. VISSIM's urban driving behaviour parameter.

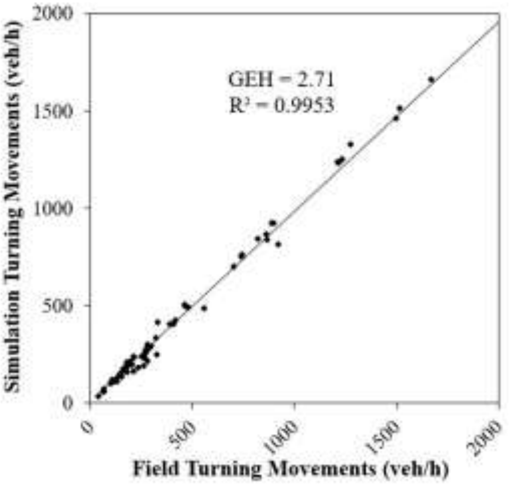
Driving behaviour parameter	Default Value	CV Modified Value
Average standstill distance	2.00 m	1.50 m
Additive part of safety distance	2.00	1.25
Multiplicative part of safety distance	3.00	2.25
Lane-change minimum clearance (front/rear)	1.31 ft	1.25 ft
Lane-change safety distance reduction factor	0.60	0.45
Minimum deceleration for cooperative braking	-9.84 ft/s^2	-13.12 ft/s^2

3.3. Calibration and Validation

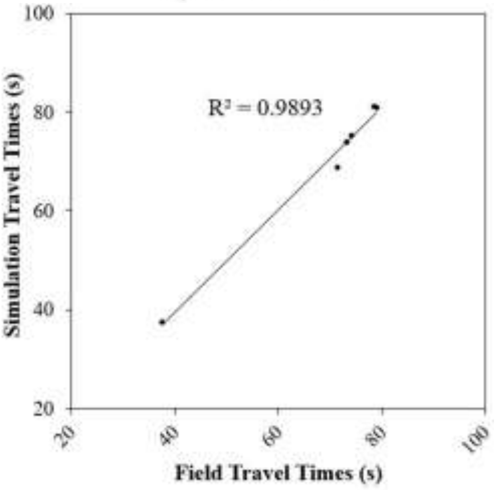
Using the 2019 field traffic conditions, VISSIM models were calibrated and validated following the standards of the current practices and recommended methodology for calibration and validation of various agencies across the nation (Florida Department of Transportation, 2014; Oregon Department of Transportation, 2011; Utah Department of Transportation, 2018; Washington State Department of Transportation, 2014) .

The findings of calibration and validation are depicted in Figure 2. For model calibration, the field intersection movement counts were plotted against the traffic counts generated by the simulation models. The Geoffrey E. Heavers (GEH) statistic was employed in addition to the linear regression, to compare the actual field traffic volumes with the simulation-generated traffic volumes. Based on the current standards for calibration a GEH value of less than 5 ensures that the model is well calibrated (Florida Department of Transportation, 2014; Oregon Department of Transportation, 2011; Utah Department of Transportation, 2018; Washington State Department of Transportation, 2014).

Therefore, a GEH value of 2.71 and R^2 value of close to 1.0, shown in Figure 2, indicate a strong correlation between the simulation-generated and field-collected datasets. For model validation, sectional field travel times obtained from INRIX were compared to those from the simulation. The R^2 value of 0.99 shows a good comparison between the field and simulation sectional travel times. Both calibration and validation results show a good fidelity of the developed base simulation model.



a) Calibration



b) Validation

Figure 2. VISSIM model calibration and validation scatterplots.

4. Results and Discussion

The SMoS employed for this study are the time-to-collision (TTC), difference in speeds (DeltaS), crossing conflicts (CC), rear-end conflicts (REC), lane change conflicts (LCC) and the total number of conflicts (TNC). As per (Gettman et al., 2008) TTC is a metric of the chance of a collision, while DeltaS provides an insight into severity of a collision. For each modeled scenario, the results of these measures were obtained and averaged from ten randomly seeded simulation runs, which is consistent with the current practice of many agencies across the nation (Florida Department of Transportation, 2014; Oregon Department of Transportation, 2011; Utah Department of Transportation, 2018; Washington State Department of Transportation, 2014). To assess the statistical significance of the results, two-tailed t-tests were performed to compare the different MPRs with the baseline (0% MPR) at the 95% confidence level. Tables 2 and 3 show the SMoS for years 2019 and 2029, respectively.

Table 2. 2019 Modelling Year SSAM Results.

	Full CFI SMoS					
	TTC (s)	**DeltaS (m/s) [a]**	**CC**	**REC**	**LCC**	**TNC**
0% MPR	1.05	0.61	3.00	6299	634	6935
25% MPR	1.06	0.62	3.00	6130	645	6778
p-value	0.18*	0.49*	1.00*	0.02	0.49*	0.04
50% MPR	1.08	0.62	4.00	5911	634	6549
p-value	0.01	0.62*	0.29*	<0.01	0.99*	<0.01
75% MPR	1.10	0.63	2.00	5673	667	6342
p-value	<0.01	0.13*	0.23*	<0.01	0.26*	<0.01
100% MPR	1.10	0.64	3.00	5462	689	6154
p-value	<0.01	0.10*	1.00*	<0.01	0.06*	<0.01
	Partial CFI SMoS					
	TTC (s)	**DeltaS (m/s) [a]**	**CC**	**REC**	**LCC**	**TNC**
0% MPR	1.01	0.73	4.00	6625	675	7304
25% MPR	1.02	0.75	7.00	6577	673	7256
p-value	0.46*	0.30*	0.28*	0.75*	0.90*	0.77*
50% MPR	1.03	0.77	7.00	6634	698	7339
p-value	0.04	0.13*	0.07*	0.94*	0.33*	0.76*
75% MPR	1.04	0.78	6.00	6775	734	7515
p-value	0.03	0.13*	0.30*	0.52*	0.27*	0.46*
100% MPR	1.04	0.80	6.00	6485	668	7160
p-value	0.03	0.14*	0.19*	0.41*	0.77*	0.45*

**: The mean difference is statistically insignificant at the 95% confidence level.*
[a]: (m/s) = meter/second

According to the results, CVs improved the safety performance of both full and partial CFIs by reducing the likelihood of collisions. This is especially observed in the TTC values that increased with the rise in the CV MPRs. The latter is true since, according to the FHWA SSAM report developed by Gettman et al. (2008), TTC is a time measurement which is estimated in SSAM based on vehicle trajectories outputted from VISSIM and the larger the estimated values of this time measurement correspond to a lower likelihood of collisions. While a 25% MPR of CVs reduces the likelihood of collisions by increasing TTC, it was observed that at least a 50% MPR of CVs is needed so that the safety improvements are pronounced.

Table 3. 2029 Modelling Year SSAM Results.

	Full CFI SMoS					
	TTC (s)	**DeltaS (m/s) [a]**	**CC**	**REC**	**LCC**	**TNC**
0% MPR	1.02	0.79	15.00	8249	1137	9401
25% MPR	1.02	0.83	7.00	7137	1008	8152
p-value	0.33*	0.06*	0.03	0.01	0.03	0.01
50% MPR	1.04	0.78	2.00	6272	812	7085
p-value	0.04	0.51*	<0.01	<0.01	<0.01	<0.01
75% MPR	1.04	0.75	2.00	6408	805	7215
p-value	0.04	0.04	<0.01	<0.01	<0.01	<0.01
100% MPR	1.05	0.74	4.00	6301	860	7164
p-value	<0.01	0.03	<0.01	<0.01	<0.01	<0.01
	Partial CFI SMoS					
	TTC (s)	**DeltaS (m/s) [a]**	**CC**	**REC**	**LCC**	**TNC**
0% MPR	0.89	0.95	14.00	9271	1194	10479
25% MPR	0.89	0.95	11.00	9166	1124	10300
p-value	0.66*	0.99*	0.24*	0.36*	0.20*	0.28*
50% MPR	0.90	0.91	11.00	9350	1117	10478
p-value	0.49*	0.21*	0.12*	0.65*	0.06*	0.99*
75% MPR	0.92	0.87	8.00	8961	1021	9990
p-value	0.04	0.04	0.04	0.17*	0.01	0.08*
100% MPR	0.93	0.85	7.00	8822	980	9809
p-value	0.02	<0.01	0.02	0.07*	<0.01	0.02

**: The mean difference is statistically insignificant at the 95% confidence level.*
[a]: (m/s) = meter/second

In terms of the severity of crashes, it is observed that the increase in CV MPR would not affect the DeltaS (difference in speeds) values significantly for the 2019 modeling year. However, a significant reduction in the DeltaS is observed for the 2029 models as the CV MPR increases indicating a decrease in the severities of the crashes conditional on their occurrences.

It is also observed that the number of conflicts would drop as the MPR of CVs increases. Specifically, for the 2019 full CFI models, the REC and TNC dropped by approximately 13.3% and 11.3%, respectively at the 100% MPR of CVs. On the other hand, for partial CFIs, REC and TNC dropped by approximately 2.0% for the same modeling year. Similar findings were found for the future modeling year of 2029, for instance the CC, REC, LCC and TNC decreased by nearly 73.3%, 23.6%, 24.4% and 23.8%, respectively at full CFIs and 100% MPR. On the contrary, the CC, REC, LCC and TNC dropped by nearly 50.0%, 4.8%, 17.9% and 6.4%, respectively at partial CFIs and 100% MPR.

5. Conclusion and Future Work

The goal of this research was to evaluate the safety of CFIs under various market penetration rates of CVs. This was done by creating a CV communication algorithm that exchanges vehicles' and signal controllers' latitude/longitude (lat/long) coordinates via the V2I communication protocols. In each simulation time step, these V2I protocols use the lat/long coordinates to determine the distance between CVs and signal controllers by employing the Haversine formula. The safety analysis was performed for a simulation network built in VISSIM microsimulation software. Econolite's external ASC/3 Software-in-the -Loop (SIL) signal controllers were leveraged in VISSIM to model the real-world signal operations of the CFIs. Through the COM interface of VISSIM, Python was employed to accurately model the V2I algorithms in the VISSIM simulation network. Afterwards, VISSIM's trajectory output files were processed in FHWA's SSAM. To achieve the goal of this study, four partial CFIs and one full CFI on Utah's Bangerter Highway, a major urban arterial in Salt Lake County, Utah were analyzed. Five scenarios were created for each of the modeling years of 2019 and 2029, where the scenarios varied only in the MPR as follows: 0%, 25%, 50%, 75% and 100%. Two-tailed hypothesis tests were performed for the results where applicable. Various surrogate measures of safety were used to achieve the goal of this research.

This study's results revealed that CVs have enhanced the safety of both full and partial CFIs. An increase in the TTC values was observed at all MPRs indicating a reduced likelihood of crashes. DeltaS was found to decrease for the 2029 models as the MPR increases which is expected to reduce crash severities. Similarly, each of the CC, REC, LCC and TNC dropped as the CV MPR increased. Particularly, TNC dropped by as high as 23.8% at full CFIs and 100% MPR of CVs, whereas that drop was nearly 6.4% for the partial CFIs and 100% MPR of CVs. It was found that at least a 50% MPR of CVs is required so that the safety improvements would be notable. It crucial to realize the importance, practicality, and transferability-to the field of the results this study. It is generally known that the safety performance of already built transportation infrastructure is mostly assessed using police-reported crashes. However, this is not applicable to new facilities and technologies that are yet to be implemented. Therefore, the FHWA developed the SSAM to be used in combination with traffic simulation software as an alternative safety analysis tool capable of using vehicle trajectories to analyze simulated vehicle-to-vehicle conflicts and produce results of SMoS (Gettman et al., 2008). Previous research (Dijkstra et al., 2010; Essa & Sayed, 2015, 2016; Huang et al., 2013; Zheng et al., 2019) has examined the trustworthiness of the simulated traffic conflicts to predict crashes. Most of these studies have shown reasonable to high correlation between field-collected crash data and the results of SMoS produced by the SSAM. These studies have emphasized that the high correlation between field-collected crash data and simulated conflicts is due to the proper calibration and validation of the microsimulation models. It was especially concluded that calibration and validation are vital for microsimulation models to be used for reliable safety evaluations. Therefore, with the R^2 value of close to 1.0 for the calibration and validation results of this study, and the improvements in TTC, DeltaS, CC, REC, LCC and TNC SMoS, actual reductions in crash likelihoods and severities should be achieved in the study area of Bangerter Highway, Utah.

The study is of high value since it is the first to provide an insight to practitioners, researchers and transportation agencies on the safety of CFIs in the era of CVs. Future research should examine the safety performance of CFIs further. For instance, driver simulator studies could be conducted to explore how unfamiliar driver confusion might be diminished with the presence of CVs.

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