SAFETY ASSESSMENT OF COOPERATIVE VEHICLE INFRASTRUCTURE SYSTEM-BASED URBAN TRAFFIC CONTROL

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ABSTRACT

Cooperative vehicle infrastructure system (CVIS) or connected vehicles, formerly known as IntelliDrive, has emerged and is expected to provide unprecedented improvements in mobility and safety. A recent study developed a CVIS-based urban traffic control system that does not require a stop-and-go style traffic signal. A simulation-based study on the CVIS-based control found significant improvements in mobility, energy (i.e., reductions in fuel consumption), and greenhouse gas emissions. However, safety was not considered in that study.

This paper investigated safety aspects of the CVIS-based urban traffic control system by applying surrogate safety assessment model (SSAM). The purpose of this study was to assess whether safety has been impacted and, if so, how much safety has been compromised due to reduced time headways between vehicles and higher acceleration/deceleration rates under the CVIS-based urban traffic control system.

A simulation-based case study was performed on a hypothetical arterial consisted of four intersections with four traffic congestion cases covering high to low volume conditions. As a

result, the CVIS control, when compared to the coordinated actuated control, reduced the averages of time to collision (TTC) and post encroachment time (PET) by 0.69 and 1.94 seconds, respectively. Note that shorter TTC and PET indicate more dangerous situation. However, it was discovered that the number of rear-end conflict events decreased by 58% under the CVIS-based control, indicating more safer driving conditions would be achieved with the CVIS-based control system.

Keywords: Cooperative Vehicle Infrastructure System (CVIS), Connected Vehicle, Safety Surrogate Assessment Model (SSAM), Safety, Simulation

INTRODUCTION

Transportation safety is a major concern in the United States that impacts the economy, personal well being, and overall quality of life. Approximately 40,000 people die each year in the United States due to automobile accidents (NHTSA, 2010). Transportation engineers spend a great deal of time and energy trying to find solutions to safety issues.

Connected Vehicle (CV) research is a USDOT program that aims at improving transportation safety, mobility, and environmental impacts (Connected Vehicle Research, 2011). The intension of CV applications is that they will improve transportation safety. In the past, taking some tasks away from the driver was not necessarily perceived as a measure that would foster safety. A cooperative vehicle-infrastructure system (CVIS) based on the CV environment for managing intersection controls, namely CVIS control for short, in which assumed automation of vehicular accelerations/decelerations (i.e., taking some driving tasks away), has shown significant mobility and environmental impacts improvements over the coordinated actuated signal control (Lee, 2010; Malakorn, 2010). Thus, there is a need to investigate safety impacts due to a CVIS control system.

The purpose of this study was to assess whether safety has been impacted and, if so, how much safety has been compromised due to reduced time headways between vehicles and higher acceleration/deceleration rates under the CVIS control system.

The remainder of this paper is organized into four sections. The literature review section summarizes the previous research on the CVIS control algorithm (i.e., the CV-based urban traffic control system) and the state-of-the-art safety surrogate assessment model. The methodology section provides little more details about the CVIS control algorithm and addresses the workflow of how to assess the safety impacts of the CVIS control. The case study section presents the design of simulation experiments and the simulation results of the mobility and safety impacts of the CVIS and the actuated controls. Finally, conclusions and recommendations regarding the safety assessments of the CVIS control are provided at the concluding remarks section.

LITERATURE REVIEW

Lee (2010) proposed a CVIS control algorithm and assessed its potential benefits. The core of the algorithm examined the predictive trajectories of vehicles that would be at risk for coming into conflict with one another at an intersection area. When multiple vehicles on conflicting approaches are projected to cross the intersection area at the same time, with a safe gap constraint between two consecutive vehicles the algorithm optimizes their trajectories in search of optimal speeds and accelerations that will prevent the occurrence of trajectory overlaps. Comprehensive microscopic traffic simulation-based experiments covering various traffic congestion conditions were performed on a hypothetical isolated intersection. Statistically significant benefits were observed: for mobility 99% and 33% of improvements on stop delays and travel time, respectively, were estimated and about 34% of both CO_2 emission reductions and fuel savings were also reported.

Malakorn (2010) extended the CVIS control algorithm to an arterial, and examined its potential benefits of mobility and sustainability. As a result, the improvements to environmental impact were about 63% and 60% for carbon dioxide emissions and fuel consumption, respectively (Malakorn, 2010). The mobility benefits were greater due to increased capacity at the corridor. For example, total delay time was improved by 86% to 100% for the volume cases evaluated (Malakorn, 2010).

It is generally understood that the transportation safety is challenging to evaluate, especially where no post crash data are available. The most straightforward way to evaluate safety would be through archived crash data. However obtaining such archived data would require tremendous efforts or practically impossible under the CVIS control. To overcome such a challenge, Gettman and Head (2003) proposed a simulation-based safety surrogate assessment model (SSAM). The performance of the SSAM program was well validated through simulation-based case studies covering various intersection geometries, traffic conditions, operational strategies, and demonstrated remarkable performances (Gettman et al., 2008).

METHODOLOGY

In order to assess the safety impacts of the CVIS control system, this paper incorporated two software programs: i) a CVIS simulation test-bed utilizing VISSIM, a commercial microscopic traffic simulator (PTV, 2011) and ii) the SSAM software for evaluating the safety impacts of the CVIS controls. In this section, both CVIS control algorithm and SSAM are briefly presented.

CVIS Control Algorithm

Assuming two vehicles approaching from conflicting streets to an intersection, Figure 1 illustrates the vehicles' anticipated trajectories that would likely result in a crash in the intersection area. The length of the trajectory overlap, denoted as l, is given by Equations 1 and 2. With vehicles' driving information such as locations, speeds, and acceleration/deceleration rates obtaining through connected vehicles environment, the CVIS control system projects

individual vehicles traveling trajectories and identifies whether potential crashes would occur at the intersection or not by examining the overlaps of trajectories. In case trajectory overlaps are detected as shown in Figure 1, the CVIS control system seeks optimal trajectories to avoid the crash.

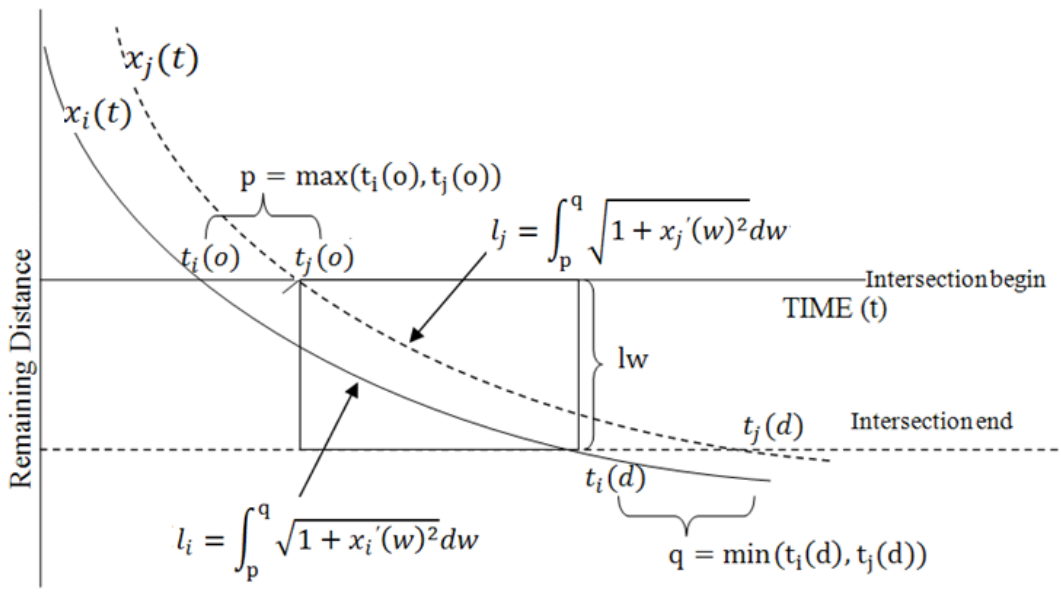

Figure 2 Illustration of Vehicle Trajectory Overlap at an intersection (Lee, 2010)

if $a_n \neq 0$,

$$l = \int_p^q \sqrt{1 + x'(w)^2 dw} \quad (1)$$

otherwise,

$$l = \sqrt{(q-p)^2 + (lw - x(p))^2} \quad (2)$$

where:

l : Length of trajectory overlap

$x_n(t)$: Predicted remaining distance to the intersection stop bar of vehicle n at time t $(= x_n(0) - 0.5a_n t^2 - v_n t)$

$x_n(0)$: Current (t=0) remaining distance to the intersection stop bar of vehicle n at time t

p: Arrival time at the beginning of intersection

q: Arrival time at the end of intersection

lw: Intersection length in meters

a_n : Acceleration or Deceleration rate of vehicle n

v_n : Current speed of vehicle n

t : time

To seek the optimal trajectories, the CVIS control utilizes non-linear constraint optimization techniques, which are designed to solve an optimization problem given the Equations 3 through 6. With optimal acceleration/deceleration rate for each vehicle approaching to the intersection, the overlapping trajectory for each vehicle is adjusted to safely cross the intersection without stops or the need for a traffic signal. In case no feasible solutions are found, however, the CVIS control system runs in a recovery mode, a traffic signal-based special period designed to be quickly returned to normal optimization-based control mode (Lee, 2010). It is noted that the recovery mode is not discussed in this paper.

$$Min\,TL = \sum_{i=1}^{P}\sum_{k=1}^{L_i}\sum_{m=1}^{N_{ik}}\sum_{j=1}^{P}\sum_{l=1}^{L_j}\sum_{n=1}^{N_{jl}}\int_p^q \sqrt{1+x'_{ikm}(w)^2\,dw} \tag{3}$$

such that,

$$a_{ikm} \geq \max\left(a_{\min}, \frac{-v_{ikm}^2}{2x_{ikm}(0)}, \frac{u_{\min}^2 - v_{ikm}^2}{2\left(x_{ikm}(0)-x_{ikm}(t)\right)}\right) \quad \forall i,k,m \tag{4}$$

$$a_{ikm} \leq \min\left(a_{\max}, \frac{u_{\max}^2 - v_{ikm}^2}{2\left(x_{ikm}(0)-x_{ikm}(t)\right)}\right) \quad \forall i,k,m \tag{5}$$

$$S\left(0.5(a_{i,k,m}-a_{i+1,k,m}\right)R^2 - (a_{i,k,m}h - v_{i,k,m} + v_{i+1,k,m})R + S > 0 \;\; \forall i,k \;\; and \;\; m = 1,2,...N_{i,k}-1 \tag{6}$$

Where:
P : Total phase numbers
i, j : Phase number indices (1 if phases are conflicted, 0 otherwise)
k, l: Lane identifier
m, n: Vehicle identifier
L_i, L_j: Total number of lanes of phase i,j, respectively
N_{ik}, N_{jl}: Total number vehicles on lane k and l of phase i and j respectively.
p: Arrival time at the beginning of intersection ($=\max\left(t_{i,k,m}(o), t_{j,l,n}(o)\right)$)
q: Arrival time at the end of intersection ($=\min\left(t_{i,k,m}(d), t_{j,l,n}(d)\right)$)
$t_{i,k,m}(o)$, $t_{j,l,n}(o)$: Arrival times at the beginning of the intersection of vehicle m(n) on lane k(l) in phase i(j)
$t_{i,k,m}(d)$, $tl_{j,l,n}(d)$: Arrival times at the end of the intersection of vehicle m(n) on lane k(l) in phase i(j)

$$S = 0.5a_{i,k,m}h^2 - v_{i,k,m}h - x_{i,k,m}(0) + x_{i+1,k,m}(0)$$

$$R = a_{i+1,k,m}^{-1}\left(-v_{i+1,k,m} + \sqrt{v_{i+1,k,m}^2 + 2a_{i,k,m}x_{i+1,k,m}(0)}\right)$$

Safety Surrogate Assessment Model (SSAM)

The SSAM program identifies conflicts by analyzing each vehicle's interaction found in the trajectory records from the microscopic traffic simulation software. Given the trajectory record of each individual vehicle obtained from microscopic traffic simulation models, the SSAM program evaluates i) surrogate measures such as time to collision (TTC), post encroachment time

(PET), maximum speeds, and maximum decelerations to determine crash events, and ii) conflict angles to determine crash types such as rear-end, lane changing, and crossing crashes, as depicted in Figure 2.

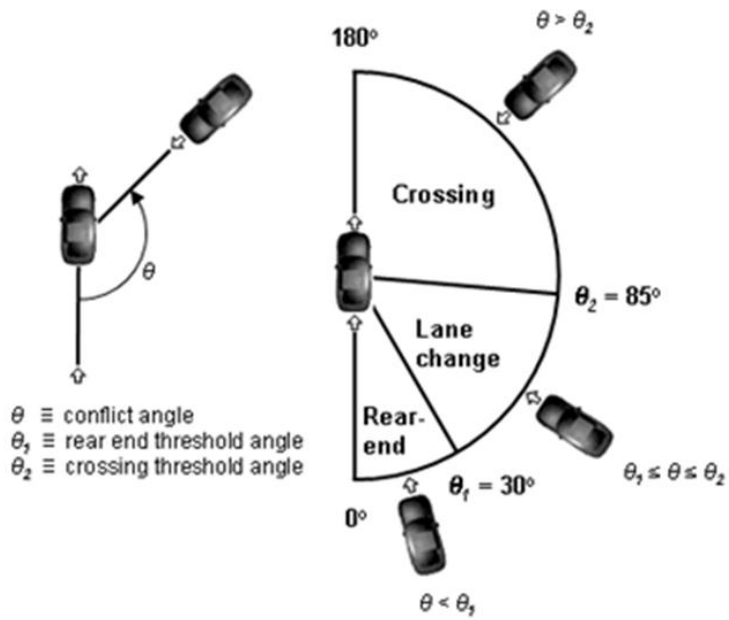

Figure 2 Crash type identification in the SSAM program (Gettman et al., 2008)

As illustrated in the conceptual workflow in Figure 3, SSAM is a post processing-based safety surrogate measure estimator. For example, once the simulations of the CVIS control completed, the resulting trajectory data of each individual vehicle run through the SSAM software to determine what safety issues may exist. If both the TTC and the PET of a pair of vehicles in the trajectory data are found to be within their threshold values and their conflict angle is less than 30-degree, the SSAM program identifies it as a rear-end crash event. Note that the crash event does not indicate an actual crash but the likelihood of potential crashes. Thus, the use of proper TTC and PET threshold values are crucial as different thresholds would result in different crash estimations. This paper employed 1.5 seconds and 5 seconds of TTC and PET threshold values, respectively, based on the previous research (Sayed et al., 1994; Hyden, 1987).

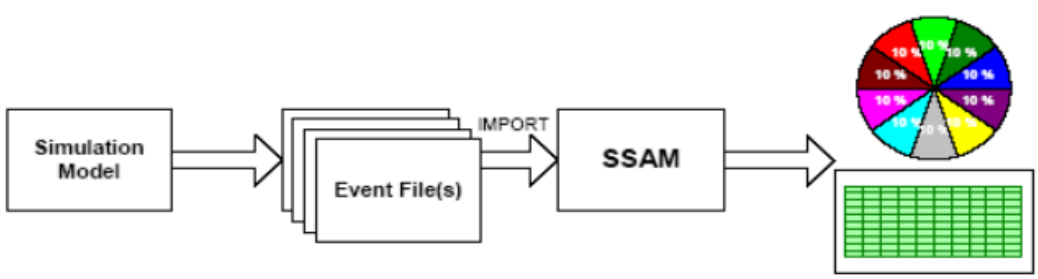

Figure 3 Conceptual Workflow (Gettman et al., 2008)

CASE STUDY

Experiments set-up

A hypothetical arterial network consisted of four single-lane intersections was created by using the VISSIM program. The test network has a 2.7-kilometer long major street expanding eastbound and westbound. Each intersection along the corridor is spaced at about 400 meters with each other. Figure 4 shows the test network modeled in the VISSIM program.

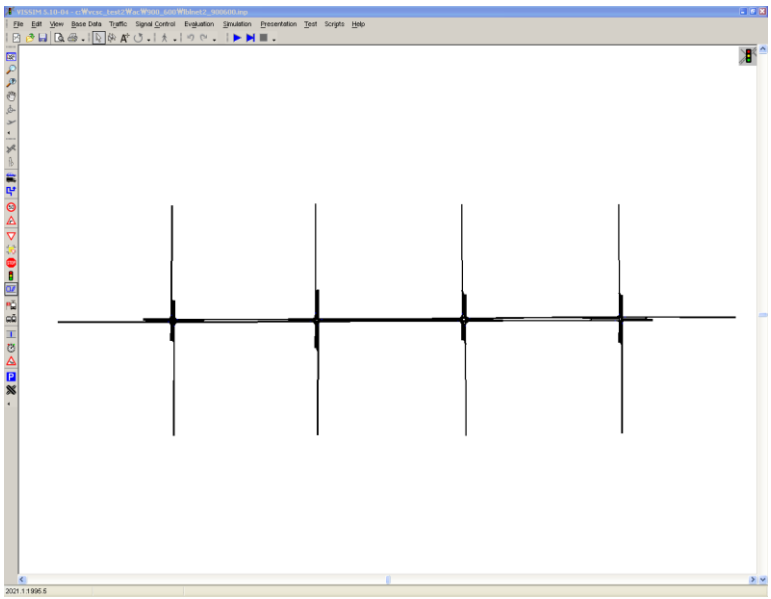

Figure 4 A hypothetical test network in VISSIM

To examine the safety impacts under varying traffic congestion conditions, four different volume cases were developed and tested. Table 1 shows specific details about each volume case. Five repetitions of each volume case were simulated. Each repetition was 35 simulation-minutes long, including a 5-minute warming-up period. To compare the performance of the CVIS control, the coordinated actuated control system was used for each volume scenario with the same number of replications and simulation period. The timing plans for the coordinated actuated intersection controls were developed by the Synchro program, in which was used as a base case for comparison purpose (Husch and Albeck, 2004). Note that the volume to capacity ratio (v/c) for each volume scenario presented in Table 1 was estimated with the optimal timing plans obtained from the Synchro program, assuming the corridor is operated by a coordinated actuated control.

Table 1 Volume Conditions tested

Scenario	Major Approach Volume, vph	Minor Approach Volume, vph	v/c Ratio
1	900	500	0.97
2	800	500	0.92
3	600	500	0.88
4	400	400	0.71

In assessing safety performances, this paper employed i) a time to collision (TTC) and ii) a post encroachment time (PET) as safety surrogate measures. TTC is a measure of seconds that vehicles would have to continue behaving as they are to collide with one another. PET is the time required for the lead vehicle to leave a position and the following vehicle to occupy that position. Obviously, shorter PETs are more dangerous. Recall that the maximum threshold value of TTC for identifying a crash was set at 1.5 seconds and a PET of 5 seconds was used as a maximum threshold value in this paper.

It was assumed that all vehicles in the simulations of CVIS control can communicate with one another and with the infrastructure through the connected vehicle environment. In addition, all vehicles were assumed to be equipped with the necessary cooperative cruise control device to allow the vehicle to manipulate its own speed, acceleration, and deceleration.

Results

Table 2 summarizes the mobility benefits of the CVIS control algorithm applied to the hypothetical arterial network. Compared to the actuated control (AC) system, the CVIS control dramatically reduced the total delay times between 92% and 100% depending on volume cases. Note that the total delay times are defined as a sum of the standstill times due to congestion at the intersection. Taking into consideration that the CVIS control algorithm is designed to keep vehicles crossing the intersection without any risks of crashes, such huge savings obtained from the total delays confirms the promising benefits of the CVIS control algorithm.

Table 2 Mobility improvements

	Case	Total Delay Time (Hour)
1	AC	19.3
	CVIS	1.5
	Improvement (%)	92
	p-value	0.000
2	AC	18.2
	CVIS	0.6
	Improvement (%)	97
	p-value	0.000
3	AC	14.4
	CVIS	0.0
	Improvement (%)	100
	p-value	0.000
4	AC	9.5
	CVIS	0.0
	Improvement (%)	100
	p-value	0.000

While such promising benefits were realized in the mobility, the CVIS control appeared to decrease the intersection safety. As summarized in Table 3, the average TTC of the CVIS control was less than that of actuated control for each volume case. Similarly, the PET values of CVIS

control were all less than the actuated controls. It is noted that smaller TTC and PET indicate larger dangerous situation. However, the number of rear-end crash events for each volume case was significantly reduced as shown in Table 3. It is also noted that the number of rear-end crash events means the likelihood of potential crashes and it increases when both TTC and PET are less than the maximum thresholds, which are 1.5 and 5 seconds, respectively. It is worth noting that approximately 20,000 traffic conflict events account for an actual crash (Gettman et al., 2008). Thus, while the CVIS control incurred more dangerous situations, its frequencies were remarkably reduced, resulting in safer conditions. This is likely because the CVIS control is designed to manipulate the maneuver of each individual vehicle to guarantee its safety condition even when crossing the intersection at high speeds. Note that the crossing events are not considered for the evaluation as they appeared insignificant in terms of the number of observations for both the actuated and the CVIS controls, accounting for approximately 2% of the rear-end crash events.

Table 3 CVIS control safety impacts

Case		Mean TTC (Sec)	Mean PET (Sec)	Number of Rear-End Conflict Events
1	AC	1.23	3.08	796
	CVIS	0.76	1.79	536
	Difference	-0.47 (-38%)	-1.29 (-42%)	-260 (-33%)
	t-value	44.51	41.94	1.88
2	AC	1.24	3.07	679
	CVIS	0.70	1.51	268
	Difference (%)	-0.54 (-44%)	-1.56 (-51%)	-411 (-61%)
	t-value	30.81	36.22	7.36
3	AC	1.26	3.07	492
	CVIS	0.53	0.99	109
	Difference (%)	-0.73 (-58%)	-2.08 (-68%)	-383 (-78%)
	t-value	26.62	34.85	26.26
4	AC	1.28	3.13	287
	CVIS	0.28	0.30	37
	Difference (%)	-1.0 (-78%)	-2.83 (-90%)	-250 (-87%)
	t-value	24.95	56.62	18.50
Overall	AC	1.25	3.09	564
	CVIS	0.57	1.15	238
	Difference (%)	-0.69 (-55%)	-1.94 (-63%)	-326 (-58%)

*Tested at 95% of confidence level

CONCLUDING REMARKS

This paper examined the mobility and safety impacts of the CVIS control system under the Connected Vehicles environment. The CVIS control dramatically improved both the mobility and the environmental performances of the urban corridor: between 92% and 100% of delay time reductions were estimated for the volume cases tested.

Taking into consideration that these improvements were obtained from the adjustments of the driving maneuver of each individual vehicle to ensure high speed crossing at intersection, the

CVIS control would likely to result in more dangerous situations in terms of the safety aspect as indicated by lower TTC and PET values in Table 3. However, the CVIS control reduced the frequency of such dangerous situations, resulting in 33% to 87% of rear-end crash reductions. Such huge safety improvements obviously came from the managed movements of individual vehicles ensuring the safety gap between vehicles provided by the CVIS control.

In this paper, perfect wireless communication conditions for the Connected Vehicles environment were assumed such that there were no communication packet drops and no communication delays, which would not be true in real world. Given that the safety of Connected Vehicles applications would be affected by the quality of wireless communications, the aspect of communication must be incorporated in future research for more realistic safety assessments.

Finally, while the case study was demonstrated on a corridor with a single through lane for each approach, the CVIS control can handle a generic intersection with multi-lanes and left-turn bays as shown in the objective function in Equation (3). Although this paper did not perform additional case studies for multi-lanes and coordinated intersections, the implementations for such case studies would be feasible as future research.

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