2014 IEEE Intelligent Vehicles Symposium (IV)
June 8-11, 2014. Dearborn, Michigan, USA

A Simulation-based Benefit Analysis of Deploying Connected Vehicles Using Dedicated Short Range Communication*

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Abstract - **In this research we utilize PARAMICS traffic micro-simulation software to study the impact of deploying Connected Vehicles (CV) in Deerfoot trail, Calgary, Alberta. We have implemented a V2V (Vehicle-to-Vehicle) Assisted V2I (Vehicle-to-Infrastructure) system for PARAMICS. It uses Dedicated Short Range Communication (DSRC) protocol to acquire traffic data, calculate and compare important traffic safety and mobility parameters and their impacts on CV by testing five scenarios differentiated by the percentage of 0% to 40% market penetration of CVs. Despite of previous studies which focused on upstream traffic, in this study we demonstrate effect of considering DSRC, re-routing guidance and advisory speed for upstream and downstream traffic. The study demonstrated that the CV technology can enhance traffic safety and mobility in freeways, if the percentage of CVs is significant (e.g. 30-40%) and the CV technology is accompanied by advisory speed reflected on Variable Message Signs (VMS) on both upstream and downstream of the incident location using DSRC range. In other words, equipping freeways with VMS, to use V2I communication, complements the CV technology, improves CV efficiency and leads to higher safety and mobility enhancement in freeways.**

I. INTRODUCTION

Connected Vehicles (CV) is a suite of technologies and applications that use varieties of wireless and/or cellular communications and sensor devices to provide seamless connectivity between the vehicles and/or the infrastructure. The main objective of CV systems is to improve safety, mobility and sustainability. Vehicular communication systems are emerging type of communication networks in which vehicles and roadside units/equipment are the communicating points; supplying information, such as traffic events, safety messages and general traffic information. Vehicular communication systems are mainly incorporated into the Intelligent Transport Systems (ITS) for safety improvement and traffic congestion mitigation.

ITS's communication system is categorized as V2V (Vehicle to Vehicle), V2I (Vehicle to Infrastructure) and V2D (Vehicle to Device). In V2I, vehicles exchange information with roadside beacons, which are fixed. These beacons act as an interface between the vehicle network and external networks. V2I function varies from safety information, weather forecast, and traffic conditions transmission to vehicles, or opportunistic vehicular data collection.

V2V is a main component of vehicular communication systems and allows detailed information to be exchanged among the individual vehicles especially when it comes to a limited geographical area. It was suggested that V2V system could be comparable to costly traffic infrastructure development projects [1]. The main idea behind V2V is to use advanced information and communication technologies to prevent road collisions and alert motorists. Moreover, V2V systems may lead to decreasing travel time and crash risk in traffic networks in case of a reasonable penetration rate, i.e., percentage of equipped vehicles [2]

Dedicated Short Range Communication (DSRC) is short to medium range (5.9 GHz) one- or two-way wireless communication channels, protocol and standard, developed mainly for automotive industry. DSRC's communications service enables reliable, high speed vehicle-based information exchange. DSRC is meant to be a complement to cellular communications by providing very high data transfer rates in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important. DSRC is the only short-range wireless alternative that provides communication with low latency, high reliability, fast network acquisition, designated license bandwidth, security and privacy [3].

The main objective of this paper is to assess the potential of DSRC enabled V2V and V2I in traffic safety and mobility enhancement using a micro-simulation environment. In this study several plug-in software modules have been developed for the PARAMICS micro-simulator. APIs (Applications Programming Interfaces) were developed to assess the performance of V2V and V2I in enhancing the safety of the road using proven safety indices.

The structure of this paper is as follows. In Section II we review a number of works focusing on V2V and V2I in micro-simulation environment. Furthermore, we provide a brief summary of the related technologies used in this work. In Section III we present the study area and the designated scenario for this study. In Section IV we walk through the steps of experimentation and simulation and in Section V we evaluate the results. Finally, in Section VI we provide conclusions and discuss future works.

II. BACKGROUND

A. Connected vehicle simulation

There are a few works focusing on modeling CV applications and assess their benefits in a micro-simulation environment. Micro-simulation offers a low cost and necessary step to test, design and conduct sensitivity analysis for CV before moving to real implementation. Traffic simulation tools have been widely used to observe the effects of various ITS on traffic stream [4]. Simulation tools enable transport planners to evaluate multiple tactics without actual testing them in a real traffic network. Moreover, using simulation does not affect public driving and consequently traffic safety.

Numbers of researchers investigated on providing comparative and functional evaluations on various traffic

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simulators [5-9]. From all of the studied microscopic simulators, the models AIMSUN [10], PARAMICS [11], and VISSIM [12] are found to be suitable for congested arterials and freeways, and integrated networks of freeways and surface streets. Also, these models are potentially useful for ITS applications. While these packages have many similarities, each has its own specific characteristics that make it more or less suitable for certain modelling purposes.

In this research, PARAMICS was selected for its proven reliability for urban freeways and its use in previous works examining variable speed limits and real-time crash risk [13-15].

PARAMICS [11] is a suite of software models for microscopic stochastic traffic simulation which allows a unified approach to traffic modeling encompassing the whole spectrum of network sizes starting from single junctions up to national networks. It is very comprehensive and has the potential for application to a wide set of freeway, arterial, and network situations. It models the emerging ITS infrastructures. PARAMICS is beneficial over other types of micro-simulation packages as it lets users to test their own traffic control scenarios. In order to implement CV system within PARAMICS, a special purposed software component was developed in C++ through the use of API in PARAMICS [2].

In an earlier research project [2] we developed a model for traffic monitoring application of CV in a micro-simulation environment using API to simulate the traffic information dissemination by individual CV to roadside units. We also examined the impact of considering advisory speed and re-routing guidance. Although the study found the improvement in travel time and crash likelihood in Deerfoot trail, we did not develop the DSRC range as a factor for distributing messages in V2I module and we only focused on upstream traffic. This study is an extension of our previous work to make it more effective by using DSRC range and advisory speed on both downstream and upstream traffic.

In [16] authors evaluated various route guidance strategies within CV using VISSIM micro-simulation model. In their study, the authors conducted a sensitivity analysis to examine the impact of various factors such as market penetration of CV, congestion levels of a road network, updating intervals of route guidance information and drivers' compliance rates. The results of the study showed that CV-based route guidance reduced travel time over the no guidance case. Re-routing means that vehicles which are more familiar with the road conditions, after noticing that there is an accident ahead of them, will choose the alternative routes to reach their destination. They avoid encountering the present accident and creating further possible accidents. This will lead to decreasing the amount of travel times and crash probability.

B. Safety index calculation

In [2] we used crash likelihood calculation model presented [14] as the safety measure to predict crash probability. The drawback of this work is that this model was designed specifically for a section of interstate 4 in Orlando, FL. Therefore in this study we decided to utilize the Overall Risk Change Index (ORCI) as the primary measures of safety for the rear-end and lane-change crash risks between any particular test case and the base case. The ORCI is calculated in the following manner: First, the crash risk is calculated for each 5-minute period at every location. Second, the crash risk at each location is averaged over the entire simulation length. Next, a plot of the average crash risk value vs. location is created for the base case and the test case. The area between the two crash risks curve represents the ORCI [17]. This measure is shown in (1).

$$ORCI = \sum_I \left[\sum_{t=1}^{T}((Risk\_profile)_{tI} / T)\right]_{Base} - \sum_I \left[\sum_{t=1}^{T}((Risk\_profile)_{tI} / T)\right]_{Test} \quad (1)$$

Where: $(Risk\_profile)_{tI}$ is the average rear-ends crash risk at time t and station I; T is the number of time periods in the simulation run.

C. Travel time measurement

The other benchmark that is considered in this study is the point-to-point (P2P) travel time along freeways. This value is calculated by the PARAMICS software and is equal to the summation of the individual vehicle travel times along the studied corridor for the length of the simulation period [11]. The travel time index is considered as a relevant proxy for mobility improvement of a freeway.

D. ANOVA test

Analysis of variance (ANOVA) is used to determine whether there are any significant differences between the means of three or more independent groups. ANOVA generalizes t-test to the groups and is useful when testing three or more variables for statistical significance [18]. In this study, we have used ANOVA test to determine the level of confidence.

III. STUDY AREA AND DESIGNATED SCENARIO

In our previous works CV has been simulated by two APIs added to PARAMICS micro-simulator. The original API was developed for V2V to allow vehicles communicate with each other. In order to implement the communication between vehicles and infrastructures (V2I), second API has been developed. Consequently, with the integration of the two APIS, a V2V capable vehicle can also communicates with the Road Side Units (RSUs) [2].

Fig. 1 depicts a typical scenario for a traffic accident. Once the incident happens, the involved cars will promptly send message to other CVs to inform them about the incident and provide the advisory speed and re-routing recommendations. Concurrently, a message is sent to the nearest RSU in DSRC range to inform non-CVs about the incident and to reflect an advisory speed on the corresponding VMS beacons. The RSU, in turn, sends the aforementioned message to the control center. The control center is assumed to be the decision maker and planner. It sends an advisory speed to each VMS beacon falling in the DSRC range along the freeway. The message "Incident ahead" is common for all the VMS beacons falling in the DSRC range; whilst, the advisory speed varies according to the VMS beacon's distance from the incident. Checking the DSRC range and creating advisory speed for downstream of

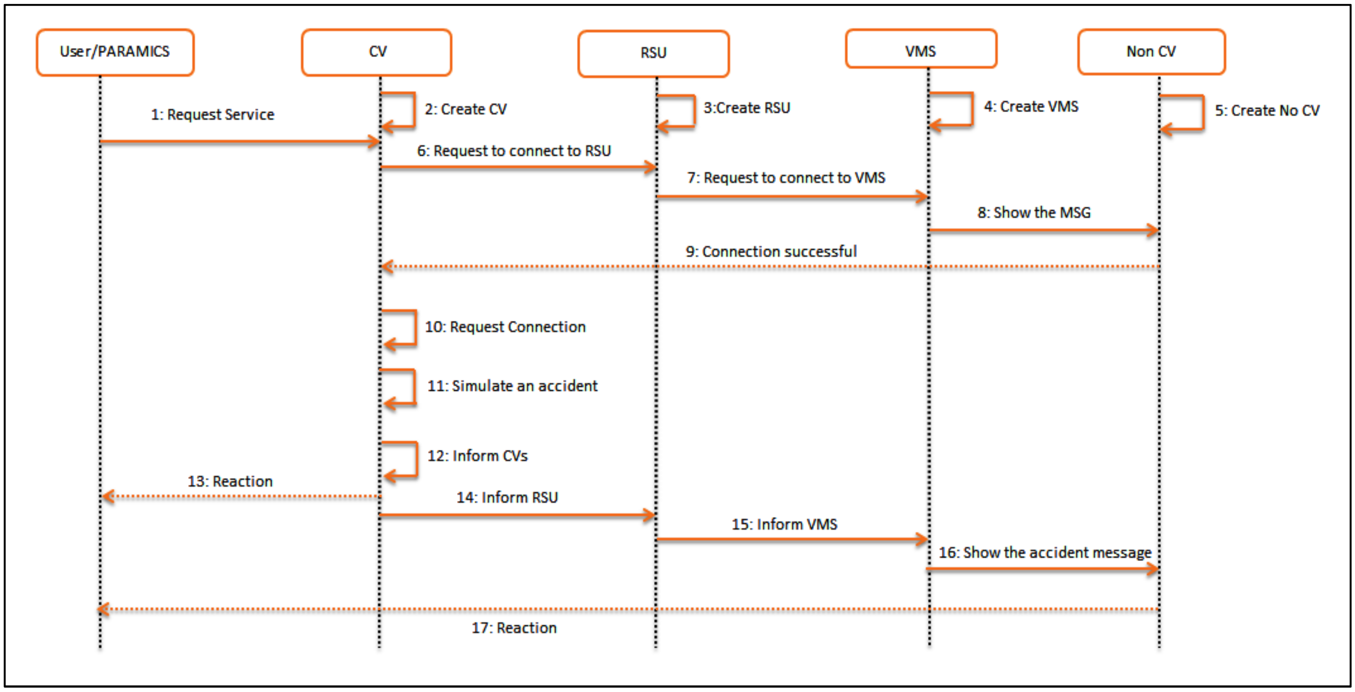

Figure 1: Sequence Diagram for Designated Scenario

traffic were programmed as an extension in the second API. Consequently, non-CVs will be aware of the traffic situation along the freeway very shortly.

Depending on the location, the advisory speeds are diverse:

1. **Upstream of the incident location**: The advisory speed for traffic upstream of the incident ranges from 60 km/h to 100 km/h. Nearby vehicles are advised to reduce their speed to 60 km/h, vehicles 500 meters behind should reduce their speed to 70 km/h, 1,000 meters behind 80 km/h, 1,500 meter behind 90 km/h and 2,000 meter behind 100 km/h [17].
2. **Downstream of the incident location**: The downstream traffic is advised to increase the speed up to 110 Km/h to accelerate traffic flow [17]. The vehicles should clear up the space near the accident to let the vehicles upstream of the accident easily pass the situation. Therefor they should be even advised to increase their speed [19].

IV. METHODOLOGY DETAILS

The analysis was conducted in PARAMICS on a real simulated test network that represented an 8-km southbound section of Highway 2 (called Deerfoot Trail) in Calgary, Alberta, Canada. The study area extended from McKnight Boulevard to Memorial Drive and included four on-ramps/off ramps. The incident location is about 600 meter upstream of the Memorial Drive exit. It should be noted that the link and the lane on which the incident happened remain unchanged to have the same situation for a better comparison of all simulation runs. Furthermore, it was set the vehicle involved in the incident to be a CV. The warning messages would be sent frequently until the accident is completely cleared in the network.

The PARAMICS model was coded and calibrated for the morning rush hour (AM). Updated AM peak origin/destination data were provided by the City of Calgary and calibrated based on recent traffic counts using the PARAMICS Estimator module. PARAMICS' specific parameters, such as minimum gap, mean target headway, mean driver reaction time, traffic assignment feedback period and feedback smoothing factor, were manually calibrated in the simulation model to reflect recent traffic counts obtained from Alberta Transportation. In the understudy network in PARAMICS, 176 loop detectors have been placed [20]. These detectors yield measures of the speed, lane occupancy, and volume on each of the 6 mainline lanes for every 10 minutes intervals. The loop detectors provide reference points for locations along the freeway. The loop detector data from stations 7, 8 and 9 were used in statistical models to create the ORCI and travel time measures that are used in this study. The 70 minutes morning peak period was modeled, however the first 10 minutes were used as a warm-up period and no statistics were collected during this time.

There are 2 types of vehicles in the network: CVs and non-CVs. A CV vehicle in an accident sends warning messages to RSU and the other CVs within the communication range as shown in Fig. 1. A Non-CV vehicle may get the message via VMS. Note that not all the VMSs will show the warning messages, only the ones that fall into DSRC range.

Our experiments showed that if there are more than 40% CV in the network it will have adverse effects on the outputs. Diverting too many cars will cause their route becomes congested, which negatively impacts the travel time at the network level. Regarding this, scenarios with more than 40% of CV have been eliminated for further investigation. In this work, fifteen test scenarios have been examined based on the following configurations:

- CV distribution percentage: Non-CV, 10% CV, 20% CV, 30% CV, 40% CV.
- Demand loading: 60% demand loading; 80% demand loading; 100% demand loading.

The demand loading percentages are correlated to the DSRC range. A higher demand percentage leads to opt for a shorter DSRC range in order to avoid data interference and latency. DSRC range selection is based on choosing one in boundary (1000), one in above, and one in below the boundary. For this case study the following DSRC ranges have been adopted:

- 60% demand loading → 1200m DSRC;
- 80% demand loading → 1000m DSRC;
- 100% demand loading → 800m DSRC.

It is to be noted that the reported run for each of the 15 scenarios correspond to the average of 10 PARAMICS runs with different random seeds. These random numbers are utilized by PARAMICS to calculate different traffic assignment parameters, such as car following, lane changing, route choice and release of demand. Thus, PARAMICS creates a dynamic traffic model for each seed number and varying traffic demand on the freeway section. The same set of random seeds was used for the simulation of the different examined scenarios. In the current model, the control center is implemented as a pop-up window to let the user of the system be the controller. The warning messages include an "Incident ahead" message along an advisory speed. For the simulation purpose, some inputs are provided based on the following preferences: driver behaviour and driver familiarity modules which are defined in PARAMICS. Since the CV has more information about the road conditions, they have the higher amount of driver familiarity input which leads to having more awareness of updated cost to their destination each interval. They will react in lower amount of time to the accident ahead comparing to non-CV and may change their route to reduce their travel time and reduce the number of further accidents.

V. SCENARIO EVALUATION

All fifteen scenarios were assessed based on two factors: mobility and safety. As pointed out earlier, the mobility benchmark is measured based on the average estimated P2P travel time on the studied corridor (Southbound Deerfoot Trail between McKnight Blvd. and Memorial Drive). The safety benchmark is measured based on the consequent ORCI for the rear-end and lane-change crash risks along the freeway.

A. Mobility improvement index

The mobility index is calculated by the PARAMICS Analyzer module and is represented by the origin-destination or P2P travel time between detectors along freeway mainline (Deerfoot Trail) for the length of the simulation period.

Table 1, illustrates the average P2P journey time along the southbound Deerfoot Trail between McKnight Blvd. and Memorial Dr. for six 10-minute intervals from 7 AM to 8 AM on a typical Holiday/Sunday morning when demand doesn't exceed 60%, on a typical Saturday morning when demand doesn't exceed 80% of the freeway's capacity and

TABLE 1: The Average Point to Point Travel Time along the Southbound of Deerfoot Tr. During AM Peak

Traffic flow pattern	**Connected Vehicles percentage**	**Morning Avg. travel time (s)**
60 % Demand loading	Non V2V	404.9
	10% V2V	337.6
	20% V2V	307.2
	30% V2V	289.5
	40% V2V	270.2
80 % Demand loading	Non V2V	582.2
	10% V2V	477.4
	20% V2V	416.4
	30% V2V	371.4
	40% V2V	320.8
100 % Demand loading	Non V2V	881.1
	10% V2V	773.6
	20% V2V	711.9
	30% V2V	658.0
	40% V2V	595.2

on a typical working day's morning when traffic flow is almost equal or even higher than the freeway's capacity (100%). As shown in Table 1, implementing the CV technology reduces the P2P travel time for all six intervals and thus improves mobility in the network.

It also shows implementing 40% CV would lead to the highest mobility improvement, 44% mobility improvement for the case of 80% demand loading and 31% mobility improvement for the case of 100% demand loading, although it is not a very efficient case for 60% demand loading.

Since 150 simulation runs were executed, the ANOVA test was conducted to acquire the level of confidence for the results. It confirmed that there is a significant difference amongst all CV categories for the three scenarios in terms of travel time at the 95% level of confidence (Table 2).

TABLE 2: ANOVA Test for 100% CV

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Non V2V	6	5286.71	881.1183	3581.319
10% V2V	6	4641.8	773.6333	3525.815
20% V2V	6	4271.688	711.9479	3585.488
30% V2V	6	3948.02	658.0033	2505.048
40% V2V	6	3570.94	595.1567	2175.278

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	289506.3	4	72376.58	23.54024	3.62E-08	2.75871
Within Groups	76864.74	25	3074.59			
Total	366371.1	29				

B. Safety index

As shown in Table 3, implementing the CV technology leads to the reduction of the incident probability and accordingly improves the safety index (ORCI). The higher percentage of the CV implemented, the higher safety benefit is achieved. Table 3 also shows that the impact is pretty significant for the case of 40% CVs by achieving 4.43 ORCI.

Comparing the impact of the CV on traffic safety in the aforementioned scenarios, would lead to a further finding. When it comes to a highly penetrated CV technology (40%), they will be more efficient in non-overloaded freeways as the ORCI in Table 3 indicates (4.47 vs. 4.11).

The ANOVA test demonstrates that the difference between the first three CV groups (0% CV, 10% CV, and 20% CV) is significant at the 95% level of confidence, albeit it cannot be concluded that the difference between 10% CV and 20% CV is also significant (Table 4).

VI. CONCLUSION

In this research we used micro-simulation as an effective tool to implement the communication between vehicles and infrastructure. The objective was to explore a low cost modeling approach to provide guidelines for improving safety and mobility on the freeways, specifically by using advisory speed and re-routing guidance in V2V and V2I systems.

The experimentation results showed an overall improved in both mobility and safety. The former benchmark was measured by the aggregate travel time along the freeway, whilst the latter was represented by the ORCI metrics for the rear-end and lane-change crash risks.

The simulation results clearly demonstrated that not only V2V enabled vehicles exhibited significant reductions in their path travel time, but also the non-CV vehicles had pronounced reductions in their path travel time as a result of fewer slow V2V enabled vehicles traveling on their path.

TABLE 3: The Overall Risk Change Index along the southbound of Deerfoot Tr. during AM peak hours

Traffic flow pattern	Connected vehicles percentage	ORCI
60 % Demand loading	Non V2V- 10% V2V	1.32
	Non V2V- 20% V2V	1.71
	Non V2V - 30% V2V	3.41
	Non V2V - 40% V2V	4.47
80 % Demand loading	Non V2V- 10% V2V	1.51
	Non V2V- 20% V2V	1.79
	Non V2V - 30% V2V	3.63
	Non V2V - 40% V2V	4.43
100 % Demand loading	Non V2V- 10% V2V	1.52
	Non V2V- 20% V2V	2.19
	Non V2V - 30% V2V	3.32
	Non V2V - 40% V2V	4.11

TABLE 4: ANOVA Test for 80% CV

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
0% V2V	6	-55.9758	-9.3293	0.426793
10% V2V	6	-65.022	-10.837	0.31915
20% V2V	6	-66.7052	-11.1175	0.637872

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.09926	2	5.549628	12.03115	0.000763	3.68232
Within Groups	6.919074	15	0.461272			
Total	18.01833	17				

Given the fifteen tested scenarios differentiated by the V2V percentage penetration (0%, 10%, 20%, 30%, and 40%), and demand loading (60%, 80%, and 100%) implicitly representing peak and off-peak traffic; the study demonstrated that the CV technology can enhance traffic safety in freeways, if the percentage of CVs is significant (e.g. 30-40%) and the it is accompanied by advisory speed reflected on VMSs on not only upstream but also downstream of the incident location despite of previous works. In other words, equipping freeways with VMS signs complements the CVs technology; significantly improves CVs efficiency and leads to higher safety and mobility enhancement in freeways.

The future work would be enhancing the CV study by providing a simulation environment that combines the capabilities of a traffic network simulator together with wireless communication functionalities in order to optimize the communication (frequency of information update), provide a cost effective alternative through traffic microscopic and wireless communication simulators, and to detect failure or latency of communication thorough testing of V2V and V2I communications systems based on different communication and DSRC ranges.

ACKNOWLEDGMENTS

This work is supported by Alberta Innovates-Technology Futures (AITF) and Natural Sciences and Engineering Research Council of Canada (NSERC). The authors would like to thank Electrical and Computer Engineering department at the University of Calgary, Alberta, Canada, for their logistics and financial support.

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