TRAFFIC OPERATION AND SAFETY ANALYSIS ON AN ARTERIAL HIGHWAY: IMPLICATIONS FOR CONNECTED VEHICLE TECHNOLOGIES

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Abstract - This paper presents the results of operational and safety analysis of test bed corridor in which connected vehicle (CV) technologies are being implemented to allow for vehicle to infrastructure (V2I) and infrastructure to vehicle (I2V) connectivity. The study corridor is approximately 7.7 miles in length and is located in the City of Tallahassee, United States. The study corridor has a total of 22 signalized intersections that currently have roadside units (RSUs) installed for the purposes of broadcasting signal phase and timing (SPaT) and geometric description (MAP) information. The quantitative analysis of travel in the study corridor using traditional measures such as speed, travel time, level of service, and delay was conducted to establish benchmark prior to full implementation of CV applications. Qualitatively, the potential for crash reduction was examined by analyzing crash topology in the study corridor and estimating crash reduction that will occur once CV applications are fully deployed. The paper will discuss various basic safety messages that, once broadcasted, will enable drivers to increase their situational awareness, to determine immediate threats, alert travelers, and allow evasive action to be taken by drivers, pedestrians, or bicyclists. The basic safety messages can also be used by signal controllers to monitor traffic and optimize signal timing through the online implementation of Advanced Traffic Signal Performance Measures (ATSPM) system.

Keywords - Connected vehicles, automated vehicles, traffic operations, and highway safety.

I. INTRODUCTION

Roadway crashes claim more than 30,000 lives each year in the U.S., and they continue adversely affecting people's well-being. More specifically, in 2016, there were 37,461 people killed in crashes on U.S. roadways, which is a significant increase from 35,485 in 2015 [1]. Despite substantial efforts towards implementing preventive solutions for crashes, they still remain a serious problem[2]. The National Highway Traffic Safety Administration (NHTSA) has been continuously working on the crash data to determine the significant factors that contribute to the crashes. Their initial results indicate that 94% of the crashes in the U.S. are due to either human error or bad/wrong decisions, which may happen due to driving under influence[3]. This is especially a critical concern in the State of Florida since Florida is among the highest ranked states in the United States with regards to crashes. This problem becomes even more complex in Florida when the gradually increasing older adult population is considered.

One such solution for this problem is the development and utilization of Connected Vehicle (CV) technologies. Morespecifically, statistics show that over 80% of avoidable collisions could be prevented with the inclusion of connected vehicle technology[4]. Therefore, CVs have the potential to play an important role in the upcoming decades not only by reducing emissions and congestions but also by improving traffic safety [5]. Especially given the high risk of death and injuries posed by roadway crashes, CVs have emerged as key technologies in order to reduce the human error associated with these crashes. As such, elderly people can possibly benefit the most from such new technologies.

In this study, a traffic operations- and safety-focused analysis has been presented with a focus on 2017 crash data for a specific study corridor, which is located on the US 90 in Tallahassee, the capital of Florida. For this purpose, traditional measures of traffic operations have been used in analyzing operational characteristics. Furthermore, the safety characteristics of the study corridor have been assessed qualitatively by analyzing crash types that have the potential of being mitigated by connected vehicle applications over a long run.

II. DATA SET

The corridor evaluated in this study is approximately 7.7 miles, and it has a total of 22 intersectionsthat currently have roadside units (RSUs) installed for the purposes of broadcasting signal phase and timing (SPaT) and geometric description (MAP) information in the near term. In addition, the signal controllers at these intersections have Automated Traffic Signal Performance Measure (ATSPM) system that provides high-resolution data. The posted speed limit in the study corridor is mainly 35 miles per hour (mph) in some sections closer to downtown but the speed limit increasesto 45 mph in most sections in the outskirts of the city.

The analysis of mobility characteristics was conducted using two data sources: BlueTOAD and Waze crowdsourced data. A total of 9 Bluetooth MAC readershave been installed in the study corridor (Fig.1), composing 16 segments that can be evaluated. The longest and the shortest segments in the study corridor are 3.3 miles and 0.5-mile long, respectively.

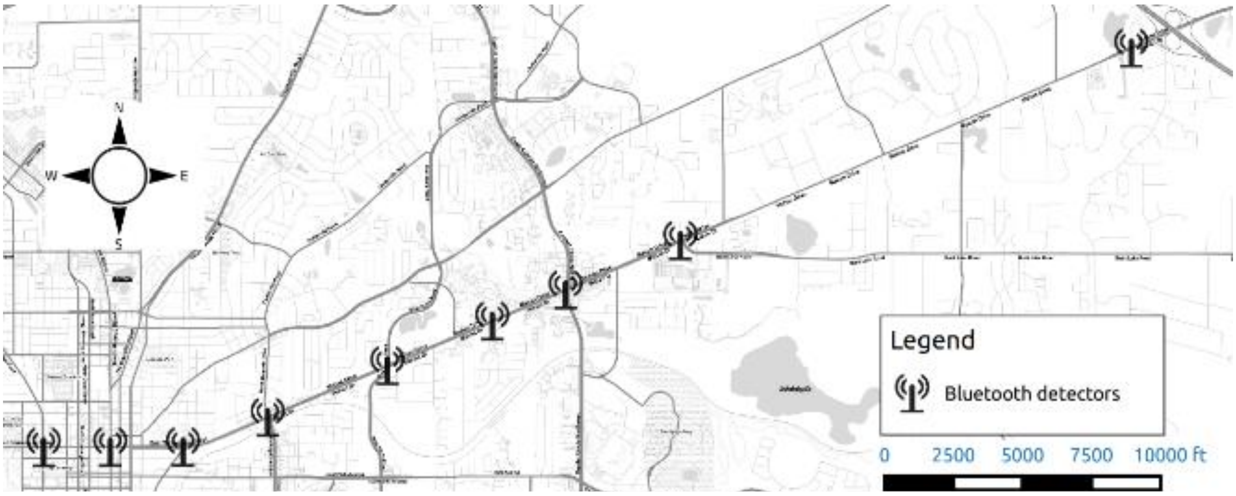


Fig. 1.Location of Bluetooth detectors on the study corridor

Waze "crowdsourced" traffic data, downloaded using the Application Program Interface (API), was also explored in the analysis. An algorithm outlined in Procedure 1 (P1) below was implemented to capture the real-time segment travel times in the study corridor. The downloaded data were aggregated at a 5-min resolution following the segmentation used in BlueTOAD data for comparison purposes. The selected period for the analysis was evening peak period between4 P.M. and6 P.M. eastbound traffic. As part of preprocessing, weekends, Mondays, and Fridays were omitted from the dataset because they were not representatives of commuter peak traffic conditions. The traffic data from March 7, 2018 to March 23, 2018 excluding holidays were used.

P1: Waze data collection algorithm

function WAZEDATACOLL (*dayweek, timeday, timeinterval, ODpair, WazeAPI*)

Input: *dayweek* – day of the week*; timeday* – time of the day*; timeinterval* – time interval of data collection (15 min)*; ODpair* – origin and destination coordinates pair*; WazeAPI* – Waze web address (URL)

Output: *starttime* – current time; *traveldistance* – segment distance (mile); *traveltime* – travel time (min); *INDO – segment id; WazeData.csv – output file*

```
Run on dayweek at timeday every timeinterval
starttime ← current time
For each ODpair and INDO do
    route ← requests (WazeAPI)
    traveldistance ← extract distance from route
    traveltime ← extract travel time from route
WRITE starttime, traveldistance, traveltime, INDO to Wazedata.csv
end for
return Wazedata.csv
```

For the safety analysis,2017 crash datawere acquired from the Signal Four Analytics website maintained by the University of Florida. Section and intersection crashes occurring in the corridor were downloaded. For the crashes that occurred at intersections, ArcGIS software was used to retrieve all the crashes that occurred within 250 ft. from the center of the intersection. This procedure was conducted to ensure crashes that occurred on the intersecting segments are captured.

III. TRAFFIC OPERATIONAL ANALYSIS

Two performance measures that were used to evaluate the operational characteristics of all segments in the study corridorare travel time reliability (TTR) andaverage delay per trip (DPT).These performance measures were calculated using the procedures recommended in the Highway Capacity Manual (HCM-6) [6]. Among the TTR metrics,theplanning time index (PTI) was selected to represent the TTRin a segment.The PTIcompares the 95^{th} percentile travel time to the travel time at the base free-flow speed. This metricreflects the time that a traveler should plan on spending to ensure that the on-time arrival is within the 95% probability (Equation 1).

$$\text{PTI} = \frac{\text{95th travel time}}{\text{TT}_f} \quad (1)$$

$$d_{trip} = \text{TT}_f \times (\text{TTI}_{mean} - 1) \quad (2)$$

$$\text{TTI}_{mean} = \frac{\text{Average of travel times}}{\text{TT}_f} \quad (3)$$

where,

$TT_f$is the travel time at base free-flow speed

TTI_{mean} is the mean based travel time index

d_{trip} is the average delay per trip.

To account for measurement and stochastic noises (uncertainties), the performance measures above were estimated using the Markov Chain Monte Carlo (MCMC) simulation. Fig. 2 shows the hierarchical diagram and the prior distribution of the model that was implemented in the analysis. In particular, the non-informative priors were selected.

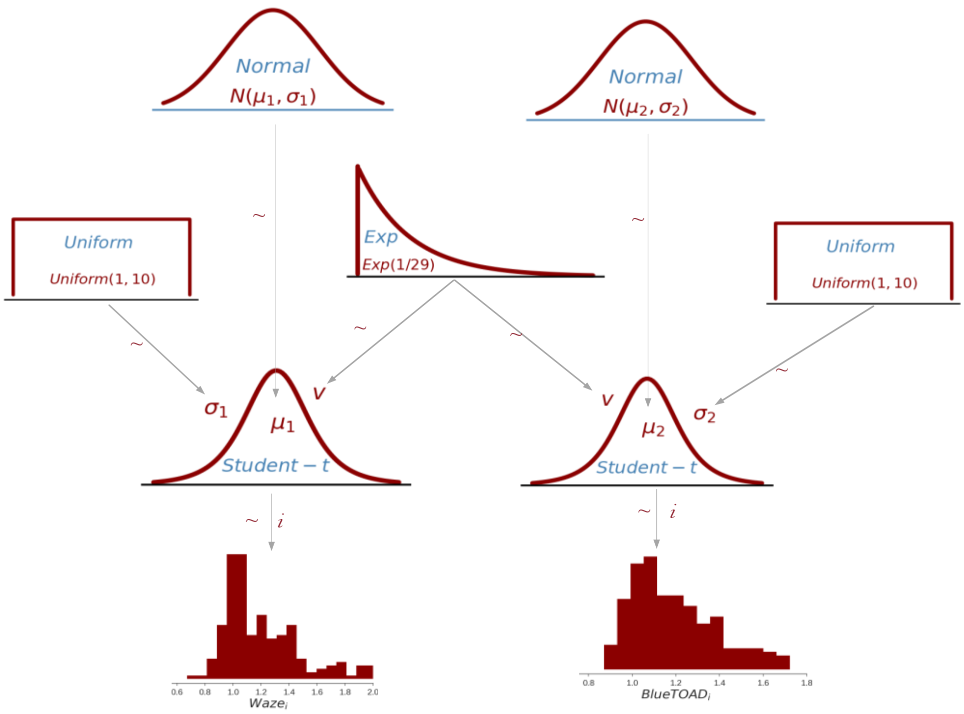


Fig. 2.Hierarchical diagram of the developed model

As indicated in Fig. 2, the student-t distribution was selected to describe the data distribution for the reason of accommodating for the outliers. Mean parameters of the student-t distributions followed the normal distributions with the mean and the standard deviation of data. Since travel times are always positive, the student-t distributions were truncated at zero avoiding sampling negative travel times in the simulation. Moreover, uniform prior distributions of one lower and ten of upper boundaries were used for the standard deviation of the student-t distributions. For the degree of freedom prior, the exponential distribution, exp(1/29), was implemented in the analysis [7]. The model in Fig. 2was also used for comparison purposes between the TTR and the average DPT of the Blue TOAD and Waze dataset.

IV. RESULTS AND DISCUSSIONS

This section first presents the discussion of traffic operation characteristics:TTR and average DPT. Afterward, traffic safety and the envisioned benefits of applying connected vehicle technologies to reduce the crashes are discussed. This safety benefit is especially critical for vulnerable populations such as older adults.

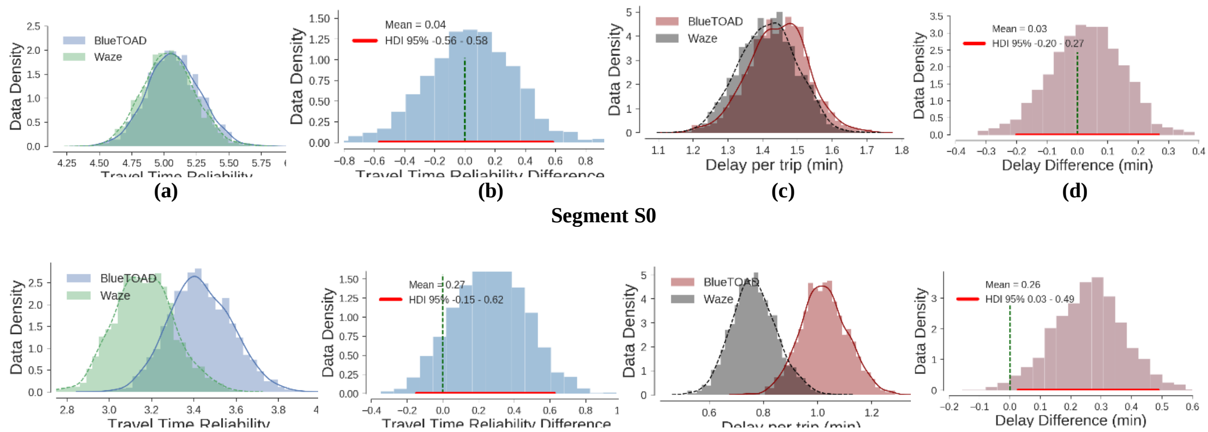
A. Delay and Travel Time Reliability

The results of TTR analysis, measuredusing the PTI, indicates that segment S5 is the most congested segment followed by segmentS0 (Table I). These findings are consistent with our prior knowledge because segment S5 and S0 intersect major arterial roads that have high traffic volumes – CapitalCircle and Monroe St, respectively.The posterior summaries (i.e., mean and the standard deviation) estimated using BlueTOAD data indicates that the TTR of segment S5 is 7.66 +/- 0.51 while Waze data is 6.42 +/- 0.36 (Table I). On the other hand, segment S7 was estimated with the least TTRin the study corridor. This could be attributed to the fact that the segment is located in the outskirts of the city. Furthermore, evaluating the estimated average DPT measure, findings are similar to those revealed by the TTR measure.

To compare the two data sources statistically, the Bayesian hypothesis test was conducted. The null hypothesis was formulated that the mean travel times of the two data sources are the same and the alternative hypothesis was the mean travel times are credibly different at 95 percent high density interval (HDI). As seen in Fig. 3a and 3c, the estimated TTR and the average DPT posterior distributions for segment S0 between the two datasets nearly overlap to each other. A closer examination of these figures shows that the BlueTOAD TTR is marginally larger than the Waze TTR. To confirm these, Fig. 3b and 3d show the TTR difference posterior distributions between Waze and BlueTOAD. The horizontal line at zero data density in this figure shows the 95 percent HDI and the vertical dashed line shows the decision rule for the null hypothesis. If the vertical dashed line is outside the HDI, it means that zero is not one of the most credible value, thus, reject the null hypothesis in favor of the alternative hypothesisat 95 percent HDI [7]. From the analysis, there is no credible difference between Waze and BlueTOAD mean travel time (mean difference = 0.04) at 95 percent HDI for both TTR and DPT. In contrast, the average DPT for segment S3 in Fig. 3h reveals that there is a credible mean difference between the two average DPT values at 95 percent HDI. This figure shows that difference zero is not one of the credible value in the posterior distribution. Similar analyses were conducted to other segments and the results of hypothesis test are presented in Table I. Generally, this table indicates that majority of the evaluated segment using the Waze and BlueTOAD data sources produce the same mean travel time, which results inthe interpretation presented here.

TABLE I. Performance Measures and Hypothesis test

Segment	Distance (miles)	Data source	Travel time reliability		Average delay per trip (min)		Decision
			Mean	Std	Mean	Std	
S0	0.5	BlueTOAD	5.07	0.20	1.44	0.08	Accept H0
		WAZE	5.03	0.20	1.41	0.08	
S1	0.5	BlueTOAD	4.10	0.21	0.80	0.08	AcceptH0
		WAZE	4.11	0.20	0.81	0.07	
S2	0.6	BlueTOAD	3.96	0.18	1.07	0.09	AcceptH0
		WAZE	3.84	0.17	0.98	0.08	
S3	0.9	BlueTOAD	3.43	0.15	1.02	0.09	AcceptH1
		WAZE	3.16	0.14	0.76	0.08	
S4	0.8	BlueTOAD	3.00	0.20	0.44	0.09	AcceptH0
		WAZE	3.30	0.21	0.67	0.10	
S5	0.6	BlueTOAD	7.66	0.51	2.35	0.19	AcceptH0
		WAZE	6.42	0.36	2.08	0.14	
S6	0.8	BlueTOAD	3.36	0.17	0.72	0.08	AcceptH1
		WAZE	3.70	0.17	1.00	0.08	
S7	3.3	BlueTOAD	1.17	0.04	0.98	0.10	AcceptH0
		WAZE	1.63	0.04	0.86	0.10	



(a) (b) (c) (d)

Segment S0

(e) (f) (g) (h)

Segment S3

Fig. 3.Estimated posterior distribution

B. Corridor Crash Topology

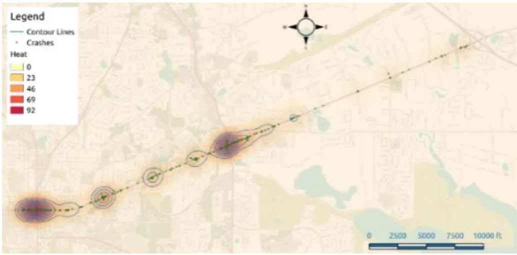
There is abundant literature on the likely safety benefits of the implementation of connected vehicle applications [8, 9, 10, 11, 12]. Once fully implemented, two-way communication through DSRC, as envisioned in the Mahan study corridor, will facilitate the transmission of basic safety messages (BSMs) to in-vehicle systems and mobile systems in the hands of pedestrians, bicyclists, and other non-motorized traffic. When the infrastructure knows the location, heading, speed, and path history of a vehicle, pedestrian, or a bicyclist, it can then broadcast the information to entities (vehicles, peds, cyclists) in the vicinity. The broadcasted data can then be used to increase situational awareness, to determine immediate threats, alert travelers, and allow for evasive action to be taken by drivers or pedestrians. The basic safety messages can also be used by signal controllers to monitor traffic and optimize signal timing through the online implementation of ATSPM.

The level of safety benefits likely to accrue in the Mahan corridor due to the implementation of CV applications and ATSPM was assessed qualitatively by analyzing the crash topology in the corridor and predicting the likelihood of crash reduction by type based on the preponderance of literature review. The review of crash data concentrated only on intersection and segmentcrashes that have the potential of being mitigated by implementation of CV applications and ATSPM.

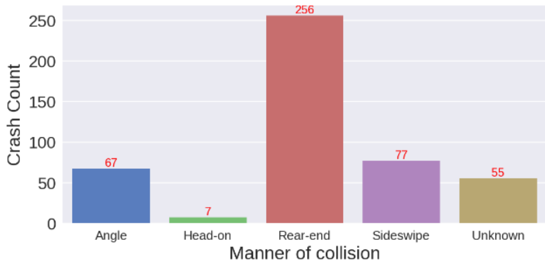
Fig. 4a shows the crash density map across the study corridor. Consistent with the operational analysis discussed earlier, it is clear that major intersections across the corridor that exhibit high traffic volumes and high delays also seem to have a large concentration of crashes. The review of the crash data further shows that 401 (85.1%) crashes were intersection-related while 70 (14.9%) were segment-related. It is worth noting that intersection-related crashes are defined as crashes occurring within the 250 ft. from the center of the intersection in either direction, including intersecting roads, as defined by the Florida Department of Transportation.

Further disaggregation of the year 2017 crashes occurring in the corridor by crash type is shown in Fig. 4b. As it was anticipated, the majority of the crashes were the rear end (286), followed by sideswipe (77), angle (67), runoff (9) and the head-on crashes (7). Also, Fig. 4b shows that the manner of collision of approximately 55 crashesthat occurred in the study corridor was unknown.

Table II shows in detail the crash topology and the likely benefits that will result from transmission of BSMs. As presented in this table, a total of 67 angle crashes occurred within the study corridor out of which 23 crashes were attributed to a vehicle running a red light. Based on literature review, the Red Light Violation Warning (RLVW) in the CV system is primarily designed to mitigate this type of crash[13, 14]. The RLVW application uses SPaT information, GPS, and speed of the approaching vehicle to estimate the potential of a vehicle running a red light. Using a DSRC network for communications, a message is sent to a vehicle via V2I to warn a driver about the potential of running a red light, thus it will help the driver to take a preventive action. A nearby vehicle also can be notified the signal light status via V2V communication to prevent it from running a red light. The RLVW is predicted to potentially reduce running red light crashes by 235,000 crashes per year, which they cost approximately $13.1 billion [15].



(a) Crash density



(b) Crash count by Manner of collision

Fig. 4.Crash density and Crash descriptive statisticsalong the study corridor

Furthermore, crash data analysis indicated that 10 angle crashes were associated with the failure of a driver to yield the right of way. The Stop Sign Violation (SSV), Intersection Movement Assist (IMS) and Left Turn Assist (LTA) are CV safety applications that are likely to address this type of crash at intersections in the study corridor. The SSV application explores V2I communication to inform a potential violator approaching an unsignalized intersection to prepare to stop sinceit unsafe entering that intersection due to the presence of a conflicting vehicle. This warning is estimated using an approaching speed of a violator, acceleration/deceleration, trajectory, and distance from the stop sign. The same message is also sent to the conflicting vehicle so that the driver can be aware of the violator in the adjacent approach. The LTA application, on the other hand, warns a driver if there is an approaching vehicle in the opposite direction, thus a driver should not attempt to turn left on the left turn permitted signal due to the high possibility of a crash to occur. The IMS application sends a message about an imminent situation that could lead to a collision if a driver attempts to enter an intersection. These safety applications are anticipated to reduce the number of angle crashes by 36 to 70 percent, which is mainly addressed by the LTA and IMS [8]. It is important noting that nearly half of the angle crashes' (31) contributing behavioral factors are not reported in the database. Also, review of all behavioral factors under angle crashes also revealed that some crashes were reported with more than one contributing factor (i.e., intersecting contributing cause). The complexity of the roadway segments and intersections usually contribute to such crashes collectively. Note that older adults are found to be the most affected segment of the population from such a complexity.

TABLE II. CV Safety Applications and Manner of collision

Crash type	Contributing behavioral causes	Total crashes in the study corridor	Likely CV/ATSPM applications
Angle collision	Red Light Running	23	Red Light Violation
	Failure of a vehicle to yield the right-of-way	10	Warning Stop Sign Gap Assist Stop Sign Violation Warning Left Turn Assist Intersection Movement Assist
	Careless driving	3	
	Driving under influence (DUI)	1	
	Aggressive Driving	9	
Rear-end collision	Careless driving	44	Forward Collision Warning Emergency Electronic Brake Lights Red Light Violation Warning
	Red Light Running	1	
	Failure of a vehicle to yield the right-of-way	1	
	Aggressive Driving	1	
Sideswipe collision	Careless driving	3	Blind Spot Warning Lane Change Warning
	Red Light Running	2	
	Failure of a vehicle to yield the right-of-way	2	
	Aggressive Driving	4	

Analysis of rear-end crashes revealed that approximately44 crashes were associated with careless driving, 1 running on red light, 1 failure of the driver to yield the right of way and 1 aggressive driving. Based on the results of literature review, there are several CV safety applications that are expected to reduce rear-end crashes such asEmergency Electronic Brake Lights (EBL), Forward Collision Warning, (FCW), and RLVW. The EBL application utilizes V2V communication to send a message to a vehicle(s) following behind if there is a hard-braking event in front. This situation helps a driver get additional time to assess the situation developing ahead. The FCW application is designed to alert a driver about an imminent frontal collision. It is projected that about 17 to 70 percent of the rear-end crashes will be reduced if the application is fully operational depending on the vehicle type (i.e., heavy trucks or light vehicles) [8]. It is reported that connected vehicle applications that reduce rear-end crashes are more effective on the heavy trucks than light vehicles.

Only one head-on crash was observed in the study corridor. Reviewing the spatial locations of these crashes, all of them occurred in the undivided section of the corridor - from Meridian St. to Duval St. Out of 7 head-on crashes, only one crash had the contributing behavioral factor (Table II). A literature review of CV applicationsshows that apart from Curve Speed Warning and Safe-Pass Advisory system for a two-lane highway, there is no application that directly addresses head-on collision [13]. This technology is anticipated and needed to be developed in the near future to reduce this type of the

crash. Reviewing the crash database also indicated that contributing behavioral factors for runoff crashes were not available.

There are two major CV applications that can help reducing the number of sideswipe crashes: Blind Spot Warning and Lane Change Warning, which can specifically help at-risk groups of the population such as older adults. The sideswipe crashes are mainly associated with one vehicle drifting or changing lane maneuver. In the study corridor, out of 77 sideswipe crashes, 3 crashes were identified to be associated with careless driving, 2 red light running, 2 failure of a vehicle to yield the right-of-way and 4 aggressive driving. Using DSRC through the V2V communication network, it is anticipated that these applications canreduce this type of crashes by nearly 28 to 70 percent [8].

For non-motorized crashes, analysis of data reveals that only 1 bicycle and 2 pedestrian-vehicle crashes occurred in the corridor in 2017 (ped-bike crashes of about 0.6 percent of all crashes). Although there were no test data to evaluate the effectiveness of the Pedestrian Crash Avoidance/Mitigation (PCAM) System, Yue et al. [8] highlight that this system could potentially reduce pedestrian crashes by 59 to 70 percent. On the other hand, anotherstudy [9]reveals that PCAM can address approximately 10 to 78 percent of vehicle-pedestrian crashes. The PCAM system is the vehicle-based application that warns the driver if they are about to collide with a pedestrian or bicyclist and it is capable of automatically applying vehicle's brakes.

The age of drivers could also be a significant cause of fatal crashes. Braver and Trempel[16] show that the probability of being involved in the fatal crashes increases with age. The analysis of 2017 crash data in the study corridor indicates a total number of 94 crashes involvedelderly drivers (65 years and older). Among these crashes, 58 percent (48) are related to rear-end crashes (Fig. 5b). Especially this type of crashes involving older adults can be potentially reduced by the CV safety applicationsas discussed earlier.

CONCLUSION AND FUTURE WORK

The objectives of this study were to evaluate the pre-ATSPM and connected vehicle operational and safety characteristics of the study corridor, US 90 in Tallahassee, Florida. For the operational analysis, Travel time reliability (TTR) and average delay per trip metrics were used as the performance measures. Moreover, crash data (2017) downloaded from the Signal Four Analytics database were used in the safety analysis. The manner of collision attribute was important in associating crashes with the connected vehicle applications.

As expected, the results of the analysis indicated that segments that intersect with major highways – Monroe St. or Capital Circle – have the worst level of operation than the rest of the segments in the study corridor. For the safety analysis, the findings were somehow similar to those reported in the operational analysis suggesting that many crashes occurred near major intersections (Monroe St. or Capital Circle). Consistent with previous studies, the rear-end crashes were the largest amount of crashes in the study corridor and head-on crashes being the least. Future work will include a more in-depth analysis with a focus on different segments of the population in order to understand which age groups can benefit more from this type of technology.

Similarly, future ATSPM systems will evolve into systems that are integrated with automated/connected (A/C) vehicles systems in a manner that A/C vehicles will act as probes supplying information to ATSPM systems for the purpose of optimizing signal timing. Quantification of operational and safety benefits of such ATSPM and A/C integration for the purpose of before-and-after analysis will pose a challenge. It is thus recommended that these issues should be carefully thought of and researched in the next phase of this project.

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