



Evaluating the Effectiveness of a Connected Vehicle Environment on an Arterial Road Using the Trajectory Data

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ABSTRACT

The transportation system is a complex interaction between the infrastructure, vehicles, and users. Over time, many innovations have come through in the field of transportation. The connected vehicle technology is one such innovation with potential to improve mobility, reduce congestion, and enhance safety of the transportation system. However, the successful deployment of connected vehicle technology depends on improved system-level performance and user experiences. In order to understand and assess the real-world behavior of this technology, the United States Department of Transportation (USDOT) has built several testbeds across the United States. The focus of this research is to evaluate the effectiveness of a connected vehicle environment using the trajectory data of test vehicles collected from the Arizona testbed, United States, an arterial corridor with a series of signalized intersections. Vehicle to infrastructure communication using the dedicated short range communication (DSRC) technology was tested along this corridor. The test vehicle trajectories were captured after processing data points obtained from a Global Positioning System (GPS) device. The trends in built trajectories in the connected vehicle environment and base condition were compared by time of the day. The results show a statistically significant increase in the average speed of the test vehicles along the arterial corridor in the connected environment compared to the base condition.

Keywords: Vehicle to infrastructure communication, Connected vehicle testbed, Vehicle trajectory.

INTRODUCTION

The connected vehicle technology could help solve many existing transportation problems such as congestion, ineffective utilization of road capacity, and safety. The connected vehicles can communicate with each other as well as with the infrastructure using advanced information and communication technology. They can contribute by enhancing complex decision-making processes such as prioritization and maintaining a minimum safe distance between two vehicles. The successful deployment of connected vehicle technology mainly depends on improved system-level performance and user experiences. In order to understand and assess the real-world behavior of this technology, the United States Department of Transportation (USDOT) has built several testbeds across the United States. The focus of this research is to evaluate the effectiveness of a connected vehicle environment on an arterial corridor using trajectory data of test vehicles collected from a testbed in Arizona, United States.

Over the past decade, several researchers have explored the connected vehicle technology from different disciplinary perspectives, e.g., transportation engineering, electrical engineering, computer science, and mechanical engineering. Trajectory data of vehicles are typically captured using Global Positioning System (GPS)-enabled devices, cell phones, radio frequency identification (RFID) tags, and Bluetooth devices.

The vehicle trajectory data was successfully used in car-following model calibration [1], signal optimization [2], and the calibration of the network-wide fundamental diagram [3]. Guo et al. [4] proposed a graph-based approach for vehicle trajectory analysis. They collected and analyzed the truck trajectories using the regional-level dataset of Athens, Greece. Liu et al. [5] studied the one-year GPS trajectories of over 5,000 taxis in China. They proposed a weighting-based map matching algorithm and a trajectory interpolation-information (WI-matching) algorithm to improve the accuracy of GPS trajectories. Jin et al. [6] addressed the error accumulation issue in calibrating the car-following models using the vehicle trajectory dataset collected in Los Angeles, California, United States. Five car-following models were checked using the proposed error dynamic model. They concluded that the weighted location mean absolute error (MAE) and the location MAE with crash rate penalty can achieve the best overall error accumulation performance for the five car-following models.

Feng et al. [7] modeled signalized intersections using VIS-SIM traffic simulation software. They developed a two-phase algorithm and tested the real-time adaptive signal control in a connected environment. Their results indicate a 16.33% reduction in delay at 100% connected vehicle penetration. Kim et al. [3] proposed a framework to characterize the spatial and temporal

travel patterns in a traffic network using vehicle trajectories. The trajectories data from New York City, New York, United States, was used to demonstrate the network-level traffic flow patterns and travel time reliability. Goli et al. [8] addressed the vehicle trajectory prediction for collision avoidance using the Gaussian Process Regression method. The results showed improved prediction accuracy when compared from the connected vehicle trajectory dataset collected in Los Angeles, California, United States.

Overall, vehicle trajectory data applications such as studying the headway distribution, car-following model, acceleration-deceleration behavior, safe gap, etc. were documented in the literature [1, 6, 8, 9]. Most of the past studies on evaluating the effectiveness of a connected environment used a simulation-based approach assuming a fully connected and automated environment. However, the penetration rate of connected vehicles is minimal at this time and is expected to grow over a period of time. It is likely that what is observed in the real-world could differ from what is predicted using a simulation-based approach due to differences in the penetration rate. Furthermore, studies focusing on evaluating using real-world data in a connected vehicle environment and comparing with the base condition are very limited. While the effectiveness of any transportation system could vary by the time of the day, the procedures adopted to process the data (for example, vehicle trajectories) could have a bearing on the results. This research contributes by focusing on the aforementioned areas and gaps.

In order to deploy connected and automated vehicle technology efficiently in a real-world environment, the United States Department of Transportation has constructed several connected vehicle testbeds in Arizona, California, Florida, Michigan, New York, Tennessee and Virginia. The trajectory data of test vehicles from the Arizona testbed connected environment to improve progression over an arterial corridor passing through a series of signalized intersections was considered for evaluation and analysis in this research.

METHODOLOGY

The methodology adopted includes gathering testbed details, data processing, and comparison of test vehicle trajectories in a connected vehicle environment with the base condition. Each step is discussed next in detail.

2.1 Testbed Details

The testbed located in Anthem, Maricopa County, Arizona, United States was selected for this research. The testbed consists of six signalized intersections along N Daisy Mountain Dr, an arterial road (Figure 1). It starts prior to N Gavilan Peak Pkwy in the west and extends past W Anthem Way in the east. While these two intersections are ~1.9 mi apart, the overall study corridor is ~2.5 mi long. It is a six-lane divided road (three lanes in each direction) with a posted speed limit of 40 mph. An interstate highway (I-17) is closely located (within 0.5 mi) to N Daisy Mountain Dr & N Gavilan Peak Pkwy intersection. The

annual daily traffic volume is 10,142 in the eastbound (EB) direction and 11,411 in the westbound (WB) direction on N Daisy Mountain Dr [10, 11].

2.2 Data Processing and Analysis

The data was gathered from the United States Department of Transportation's (USDOT) Intelligent Transportation Systems (ITS) Joint Program Office (JPO) opensource website. The data gathered was collected on March 3rd and March 4th of 2015. Test vehicles capable of communicating with roadside infrastructure were used to collect the data.

Selected drivers were asked to drive the test vehicles as per a scheduled departure plan (say, at 2-min intervals to minimize being in close proximity) and maintain the traffic stream conditions. However, the purpose of the study and information about the connected vehicle technology was not disclosed to the drivers to obtain naturalistic driving data [10, 11].

Dedicated Short Range Communication (DSRC) technology (5.9 GHz) was used for communication between the test vehicles and the road-side infrastructure. A Multi-Modal Intelligent Traffic Signal System (MMITSS) prototype in the connected environment was tested along the testbed [10, 11]. The connected environment technology enabled two-way wireless communication between the test vehicles with an on-board equipment (OBE) and the road-side infrastructure (signalized intersections) with DSRC equipment (typically installed on one of the traffic signal heads). The signalized intersections equipped with the DSRC equipment along the testbed recognized the approaching DSRC equipped test vehicles. The algorithms in the MMITSS prototype optimized the phase sequence and signal timings and made the decision to serve the test vehicles (give priority, green signal). Other than the two-way wireless communication between the test vehicles and the road-side infrastructure for prioritization in the case of the connected environment, no notable changes in signal timing and phasing details are known between the two data collection dates that would influence the research results.

The trajectory data was collected using GPS-enabled devices in the connected environment on March 3, 2015, while the base condition data was collected on March 4, 2015. Both the connected environment and base condition tests were conducted on weekdays (Tuesday and Wednesday) to minimize the variations due to traffic condition [12]. The variation due to driver behavior, age, and gender was minimized by having the same selected pool of drivers drive several trips in both the connected environment and the base condition.

The gathered GPS-enabled data was processed using R and ESRI's ArcGIS Pro software, unlike using a MATLAB code by defining the coordinates of the study corridor boundary sections [11]. It is envisioned that using geospatial software like ArcGIS Pro provides flexibility to visualize the datapoints and exclude outliers that could influence the analytical results. This approach might be more beneficial when the study corridor is not a straight section and comprises horizontal curves.

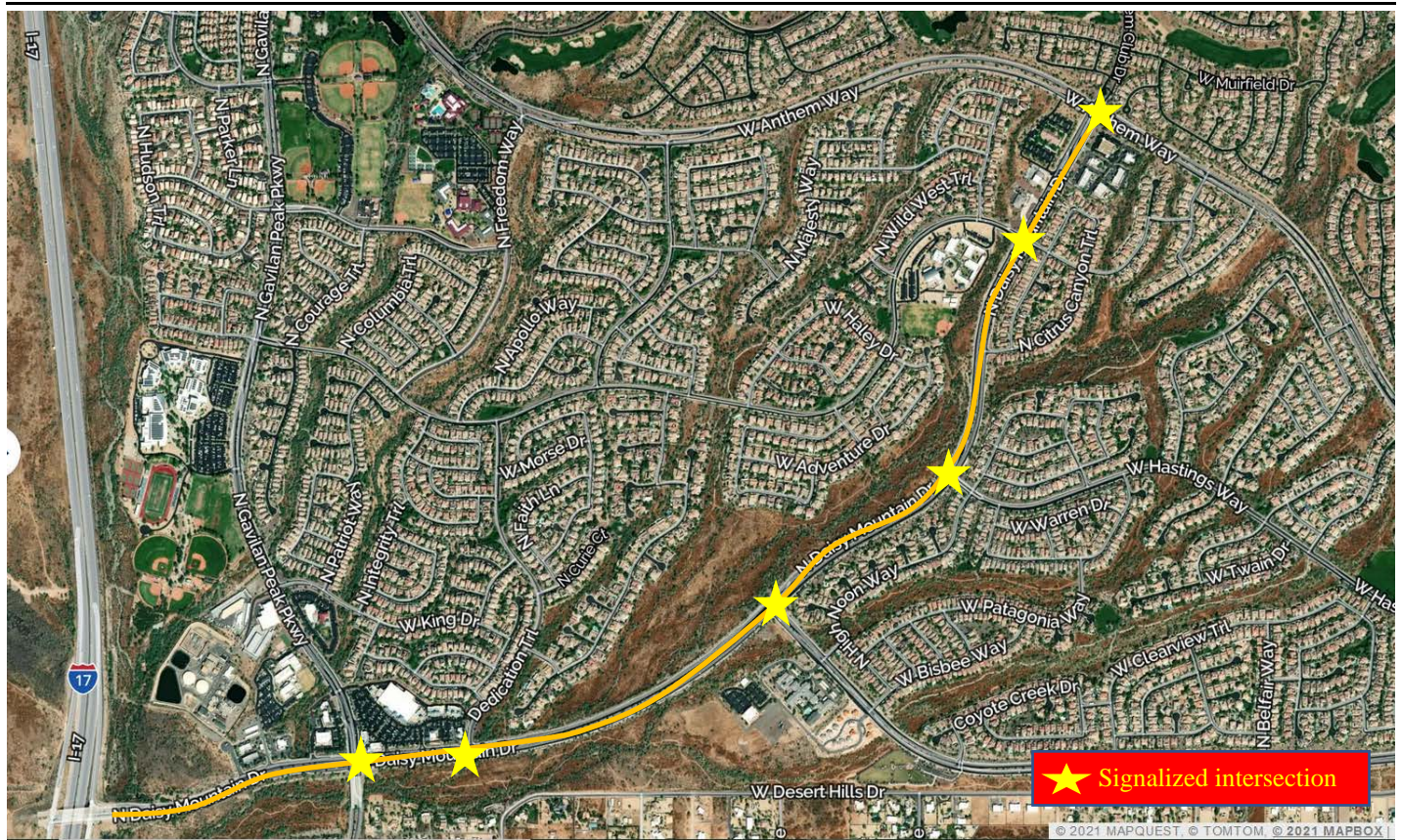


Figure 1. Study corridor

The raw dataset included some outliers (datapoints) located outside the testbed. These data points represent the incoming and outgoing of test vehicles from the nearby parking lot/rest areas and increase the data processing and analysis complexity. The plotted trajectory data points were, therefore, examined and such outliers were manually excluded from the raw dataset.

Data for eight to ten trips were gathered and processed for each test vehicle. The data from three test vehicles comprising of 113 trips were analyzed in this research. The raw dataset included timestamp, latitude, longitude, speed, altitude, heading, and GPS source information. The moving direction of vehicles (EB/WB), and start and end time of each trip was noted after manually verifying the data. The data points with turning movements from EB/WB, and vice versa were excluded in this research.

The performance was evaluated using distance-time plots, average trip travel time, and the average speed. The distance-time plots were used to assess progression along the study corridor, number of times each test vehicle stopped along the corridor, and delay during such stops. For distance-time plots (example, Figure 2), the distance between consecutive points were computed using speed and time data. The travel time data for the three test vehicles was averaged to compute the average trip travel time and the average speed.

RESULTS

Figure 2 (a-d) shows the trajectories of a selected test vehicle in the base condition and in the connected environment for EB and WB directions (starting trip at 16:40 in the EB direction and at 16:45 in the WB direction). Each trajectory represents a single trip in EB or WB direction. The trajectories slope is steeper and relatively stable (consistent) in the connected vehicle environment than in the base condition. The spacing between the trajectories is also lower in the connected vehicle environment than in the base condition. The test vehicle was able to complete eight trips in ~30% lesser time in the connected vehicle environment than in the base condition.

In addition to variations in the trajectories, differences in travel times and the number of stops per vehicle were observed in the connected environment compared to the base condition. In addition to an increase in delay, the number of stops were two to three times more for the test vehicles in the base condition than in the connected environment. For example, trip travel time in the connected environment was 32 sec to 257 sec less in the EB direction and 93 sec to 255 sec less in the WB direction for a test vehicle when compared to the base condition (Table 1). Hence, it can be inferred that the test vehicle travels faster and with a relatively fewer number of stops, resulting in a reduction in delay, along the considered arterial corridor in a connected

environment. Differences were observed when trajectories are compared by the direction of travel.

The distance-time plots and trajectories were also used to assess the performance at signalized intersections (for example, Figure 3). It can be observed from Figure 3 that the number of stops per test vehicle at the selected intersection was higher in the base condition than in the connected environment. Three out of five times during the 20-min observation period, a test vehicle had to stop and wait for two signal cycles to cross the signalized intersection in the base condition. On the other hand, a test vehicle received priority and did not have to stop five out of nine times in the connected environment. As was observed previously, the delay and number of stops differed by the direction of travel.

Analysis was also conducted to compare the connected environment and the base condition by the time of the day (evening peak and evening off-peak). Table 2 shows the speed variation of test vehicles in the base condition and in the connected environment at selected times of the day, by the direction of travel. The average speed of the three test vehicles at selected times of the day is presented in Figure 4. The increase in the average speed was observed to be varying between 7.62% and 20.95% in the EB direction, and between 6.03% and 28.27% in the WB direction at selected times of the day (Figure 4). Considering the entire time period, the results show a 17.36% (base condition - 25.76 mph; connected environment - 30.24 mph) increase in the average speed in the EB direction and a 12.06% (base condition - 27.24 mph; connected environment - 30.53 mph) increase in the average speed in the WB direction along the arterial corridor.

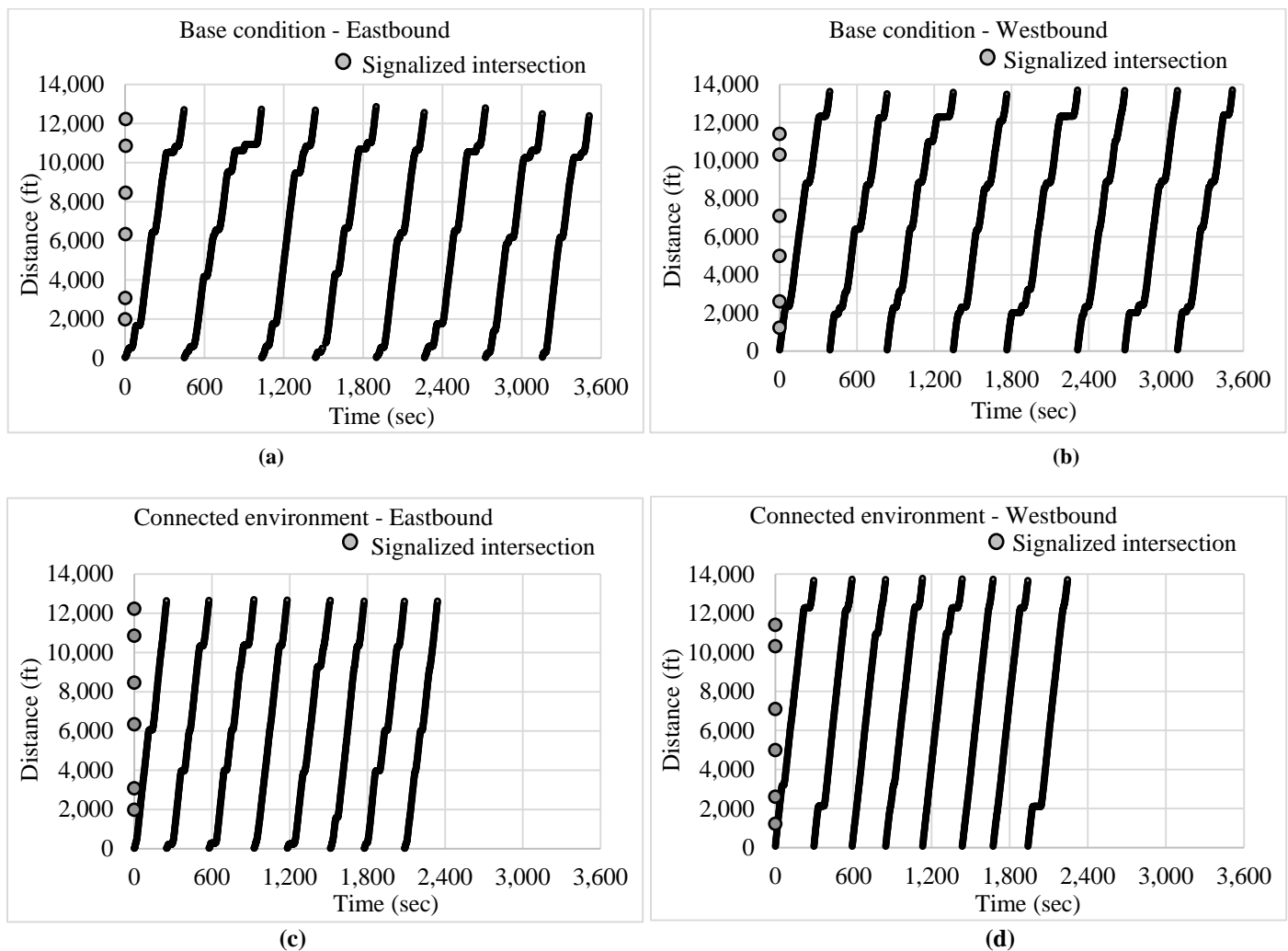


Figure 2. Distance-time plots for a test vehicle in the base condition and the connected environment along the study corridor

Table 1. Travel time and delay for the test vehicle shown in Figure 2

	Direction	Trip 1	Trip 2	Trip 3	Trip 4	Trip 5	Trip 6	Trip 7	Trip 8	Average
Travel time (sec) - base condition	EB	447	585	408	459	365	461	431	354	439
	WB	390	445	514	415	549	367	409	427	440
Travel time (sec) - connected environment	EB	250	328	348	256	333	262	311	254	293
	WB	297	293	259	283	304	238	267	304	281
Difference in travel time (sec)	EB	-197	-257	-60	-203	-32	-199	-120	-100	-146
	WB	-93	-152	-255	-132	-245	-129	-142	-123	-159
% difference	EB	-44	-44	-15	-44	-9	-43	-28	-28	-32
	WB	-24	-34	-50	-32	-45	-35	-35	-29	-35

Note: Difference in travel time (an indicator of delay) is travel time in the connected environment minus travel time in the base condition. % difference is the difference in travel time divided by travel time in the base condition multiplied by 100.

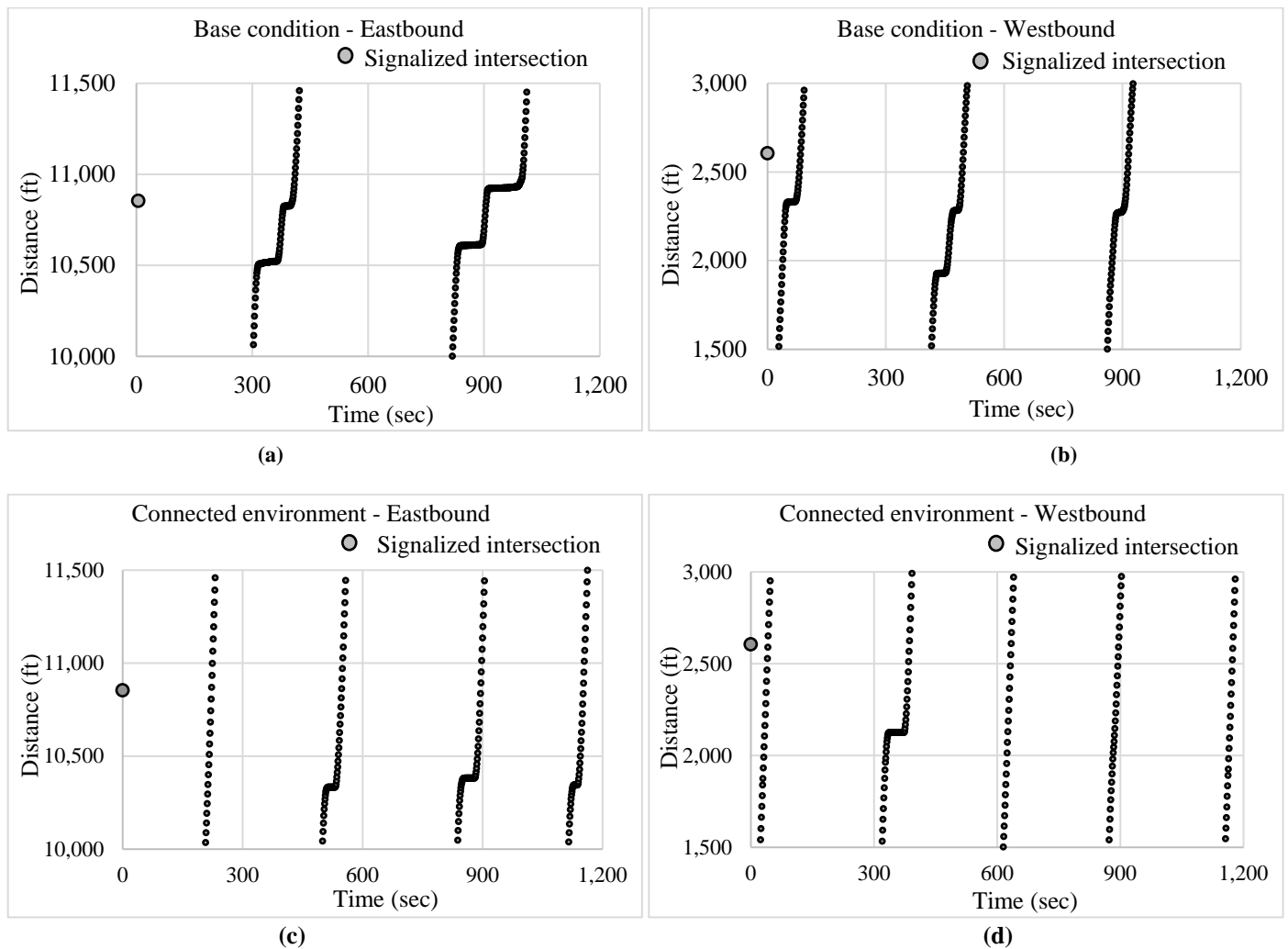


Figure 3. Distance-time plots for a test vehicle in the base condition and the connected environment at a signalized intersection

Table 2. Summary of speed (mph) - base condition and the connected environment

Vehicle	Direction	Time of the day 16:30-17:30		Time of the day 17:30-18:30		Time of the day 18:30-19:30	
		Base condition	Connected env.	Base condition	Connected env.	Base condition	Connected env.
Vehicle 1	EB	28.86	30.69	29.36	36.11	29.65	26.94
Vehicle 2	EB	18.49	28.63	20.72	30.84	21.18	30.67
Vehicle 3	EB	26.79	30.36	30.41	29.03	28.94	28.24
Vehicle 1	WB	26.89	33.46	28.98	34.73	27.89	31.80
Vehicle 2	WB	20.85	33.29	21.58	34.49	24.19	32.79
Vehicle 3	WB	36.08	27.20	25.51	28.35	33.76	26.42
Average	EB	24.71	29.89	26.83	31.99	26.59	28.61
	WB	27.94	31.32	25.36	32.53	28.61	30.34

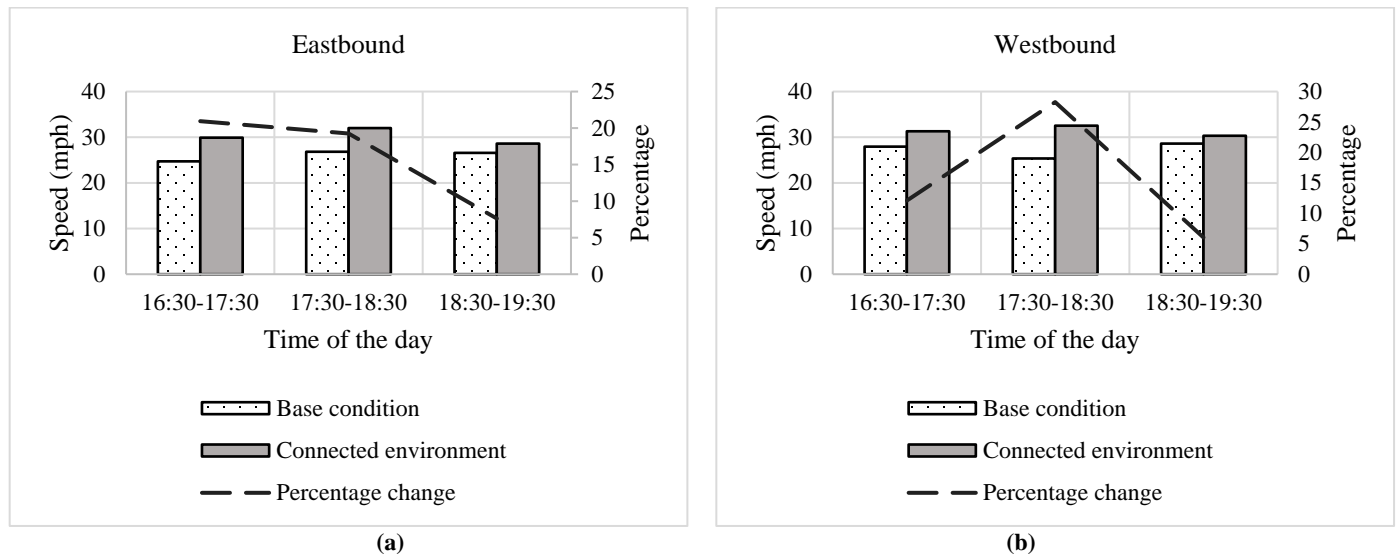


Figure 4. Average speed and percentage change in the speed - base condition compared to the connected environment

A one-tailed t-test was conducted to examine the statistical significance of an increase in the average speed in the connected environment. The null hypothesis is defined as the average speed in the base condition is greater than or equal to the average speed in the connected environment while the alternate hypothesis is defined as the average speed in the base condition is less than the average speed in the connected environment. The computed hourly average speeds in the base condition and the connected environment (irrespective of the direction of travel or time of the day) are 26.7 mph and 30.8 mph, respectively. The computed p-value is 0.007 (t-statistic = -2.73), indicating a significant increase in the average speed in the connected environment compared to the base condition. A similar analysis of speeds comparing trips that were departing within ± 2 -min also indicate a significant increase in the speed in the connected environment compared to the base condition.

CONCLUSION

In this research, the effectiveness of the connected vehicle environment was evaluated using real-world test vehicle data gathered from a connected vehicle testbed, MMITSS, located in

Arizona, United States. DSRC technology (5.9 GHz) was used to communicate between roadside equipment and the test vehicles. The data stored in the server was used to optimize the signal phase/time.

The vehicle trajectories in the connected environment and base condition were plotted and analyzed. Lower variation in travel speeds and relatively fewer number of stops were observed in the connected environment compared to the base condition. The results show a 12% to 18% increase in the average speed of the test vehicles along the considered arterial corridor with six signalized intersections in the connected environment compared to the base condition. The increase in speeds or decrease in travel time from the trajectory data differed by the direction of travel and time of the day.

The underlying factors that influence the effectiveness of a connected vehicle environment should be further explored in the future. Further, the effectiveness by vehicle type and priority scenario like emergency vehicle, transit vehicle, or truck compared to a passenger car by time of the day and different traffic conditions should be explored using larger datasets in the future.

Also, the influence of the connected and automated environment on the operational performance at each individual intersection, along the corridor, and on the cross-streets merits an investigation. The data from other testbeds and technologies should also be compared to check how the effectiveness varies with the facility type, built environment, and technology.

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