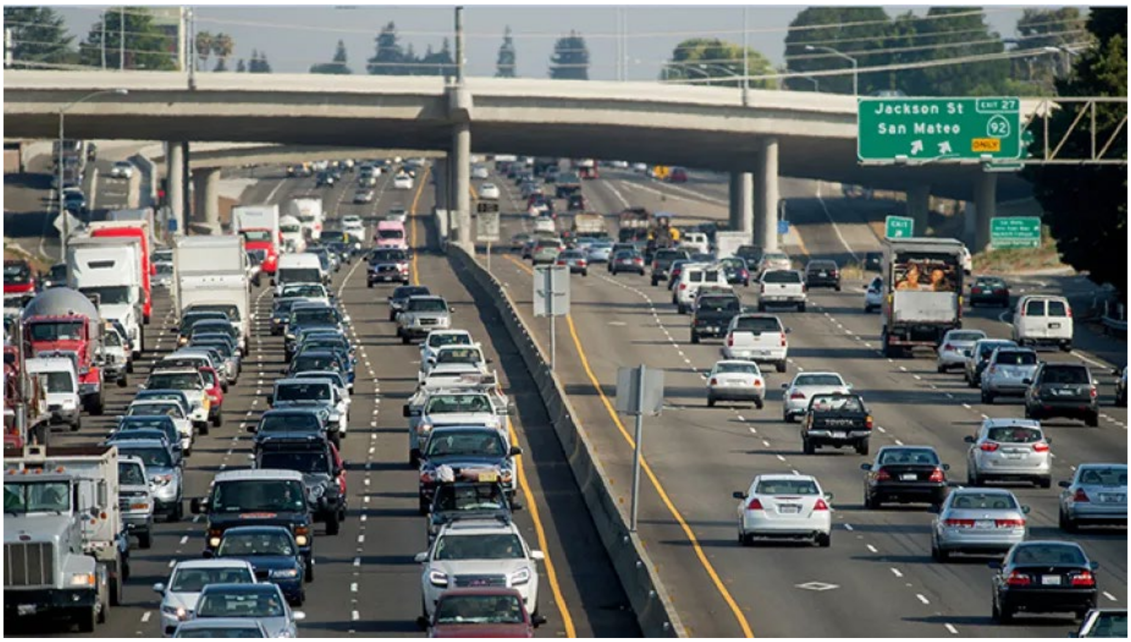
Exploring the Use of Probe Vehicle Telematics Data for Freeway Detector Speed Accuracy Check

By Jianyuan Xu, Ph.D., EIT[1], Aobo Wang[2], Ph.D., Zong Tian[2], Ph.D., P.E., and Zhongren Wang[1], Ph.D., P.E., T.E.
[1] Caltrans
[2] University of Nevada, Reno



Freeway detector data quality establishes a foundation of accurate and reliable freeway operational performance monitoring. In practice, the quality of detector data is monitored by internal diagnostic algorithms in central management system. However, the ground-truth value of freeway data remains to be verified. The emergence of crowdsourced probe vehicle telematics data (PVTD) has great potential to address this challenge through large-scale and high-resolution vehicle trajectory waypoints. Therefore, this research aims to explore the use of PVTD to verify the accuracy of lane-by-lane speeds measured by freeway detectors. A calculation framework for trajectory-based speeds from PVTD is proposed and applied to six detector stations on different freeways in California. It is concluded that PVTD can be utilized as a useful data source to verify the accuracy of freeway detector speeds on lanes with no trucks and provide insight into identifying speed mismatch patterns. PVTD is found to be less representative on lanes with trucks. The lane-by-lane speed difference between trajectory-based speeds and detector speeds tends to increase as the lane-by-lane truck proportion increases. The lessons learned from this research aim to assist transportation agencies in using PVTD to effectively manage and maintain freeway detectors for more accurate and reliable freeway operational performance monitoring, evaluation, and enhancement.

Introduction

Efficient freeway system management is closely associated with accurate and reliable freeway operational performance monitoring. Traditionally, transportation agencies rely on the existing freeway detector networks to monitor freeway operational performance by collecting freeway data from a variety of in-pavement and roadside detectors installed at fixed locations, such as inductive loops, radars, magnetometers, etc. Due to the limited spatial coverage and the challenging maintenance process of detectors, transportation agencies are seeking alternative data sources to support and facilitate freeway operational performance monitoring.

The emergence of crowdsourced data, such as probe vehicle data (PVD) and probe vehicle telematics data (PVTD), opens a new path to facilitate freeway operational performance evaluation[1-16]. Compared with traditional detector data, PVD can provide wide spatial and temporal data coverage and generate segment travel times and travel speeds from all probe vehicles on the predefined roadway segments for freeway operational performance evaluation[8]. As advanced technology evolves, PVTD emerges as a next-generation data source consisting of millions of high-resolution vehicle trajectory waypoints which record detailed spatial, temporal, and operational information on individual vehicles. Compared with PVD, PVTD offers more flexibility of in-depth freeway operation analysis in addition to segment-level analysis, such as detailed lane-by-lane operation analysis, different types of freeway segment operation analysis defined in the Highway Capacity Manual (HCM)[17], etc.

Although the effectiveness and reliability of PVTD in freeway operation analysis were preliminarily investigated by a few studies[2,3,4], the full potential of PVTD still remains to be explored. In practice, the quality of detector data is monitored by internal diagnostic algorithms in central management system[19]. However, the ground-truth value of freeway data remains to be verified. PVTD has great potential to this challenge based on the nature of direct speed measurement from vehicle telematics and high-resolution vehicle trajectory waypoints. To bridge the gap, this research aims to explore the use of PVTD to verify the accuracy of speeds measured by freeway detectors. A calculation framework for trajectory-based speeds from PVTD is proposed and applied to six detector stations on different freeways in California. The findings from this research aim to assist practitioners in better understanding the use of PVTD as an alternative tool to support freeway operation analysis and performance monitoring.

The entire paper is organized into six sections. After the introduction, PVTD is provided in the second section. Then the calculation framework for trajectory-based speeds from PVTD is presented in the third section followed by the case study in the fourth section. Discussions and conclusions are presented in the fifth and sixth sections.

Probe Vehicle Telematics Data

PVTD is an emerging data source generated from connected vehicles which are equipped with internet connectivity and onboard sensors. It consists of a tremendous number of high-resolution vehicle trajectory waypoints which record detailed spatial, temporal, and operational information of individual vehicles, including latitude, longitude, speed, heading, date, time, engine status, etc[2]. Each vehicle's trip is associated with a unique 'journeyID', which can be used to track the detailed trip information of this vehicle through continuous trajectory waypoints with the same 'journeyID'. The high-resolution spatial nature of PVTD with the precision of less than 10 feet allows for tracking detailed vehicle operations on freeways, such as driving lanes, lane changing behavior, etc. Figure 1 demonstrates an example of part of the continuous trajectory waypoints of an individual vehicle on freeway segments.

As shown in Figure 1, each trajectory waypoint (highlighted in yellow dots) includes latitude, longitude, speed, heading (the angle moving clockwise from the north direction to the vehicle's driving direction), date, and time for the vehicle. In this example, the starting trajectory waypoint on the top indicated that the vehicle was traveling southbound (SB) with the speed of 73.37 mph on the innermost lane at 17:13:07 on March 5th, 2023. Each trajectory waypoint was captured every 1 second. Figure 1 clearly demonstrates the capability of PVTD for detailed lane-level operation analysis, which paves the way for lane-by-lane speed comparisons between PVTD and freeway detectors. To better understand the difference between PVTD and freeway detector data, a qualitative comparison between PVTD and freeway detector data in terms of data source, data component, data coverage, and data penetration rate is shown in Table 1.

Figure 1 Part of the Continuous Trajectory Waypoints of an Individual Vehicle on Freeway Segments

Table 1 Qualitative Comparison between Probe Vehicle Telematics Data and Freeway Detector Data

		Probe Vehicle Telematics Data	**Freeway Detector Data**
Data Source		Vehicle telematics	Freeway detectors
Data Component		Vehicle trajectory waypoints	Flow, occupancy, and speed
Data Coverage	**Spatial**	Statewide	Installation locations
	Temporal	24 hours for everyday	24 hours for everyday with no detector malfunction
Data Penetration Rate		3%-10% with passenger cars only	100% with no detector malfunction

Calculation Framework For Trajectory-Based Speeds From Probe Vehicle Telematics Data

PVTD has emerged as a promising data source to generate prolific and large-scale vehicle trajectory data. Therefore, this section presents a calculation framework for trajectory-based speeds from PVTD which consists of three steps described in the following subsections.

Step 1: Extract Trajectory Waypoints on the Analyzed Basic Freeway Segment

The raw PVTD usually consists of millions of vehicle trajectory waypoints spreading in the entire state. Therefore, the initial step is to extract all trajectory waypoints on the analyzed basic freeway segment in the selected analysis periods based on the predefined spatial range, which establishes a foundation for lane-by-lane speed calculations.

Step 2: Extract Lane-by-lane Trajectory Waypoints

After Step 1, the next step is to extract lane-by-lane trajectory waypoints on the segment, which paves the way for calculating average lane-by-lane speeds. A polygon can be defined and drawn following the lane path to extract trajectory waypoints on each lane. Figure 2 illustrates an example of extracted SB lane-by-lane vehicle trajectory waypoints in an hour on the part of a basic segment with a total of four lanes.

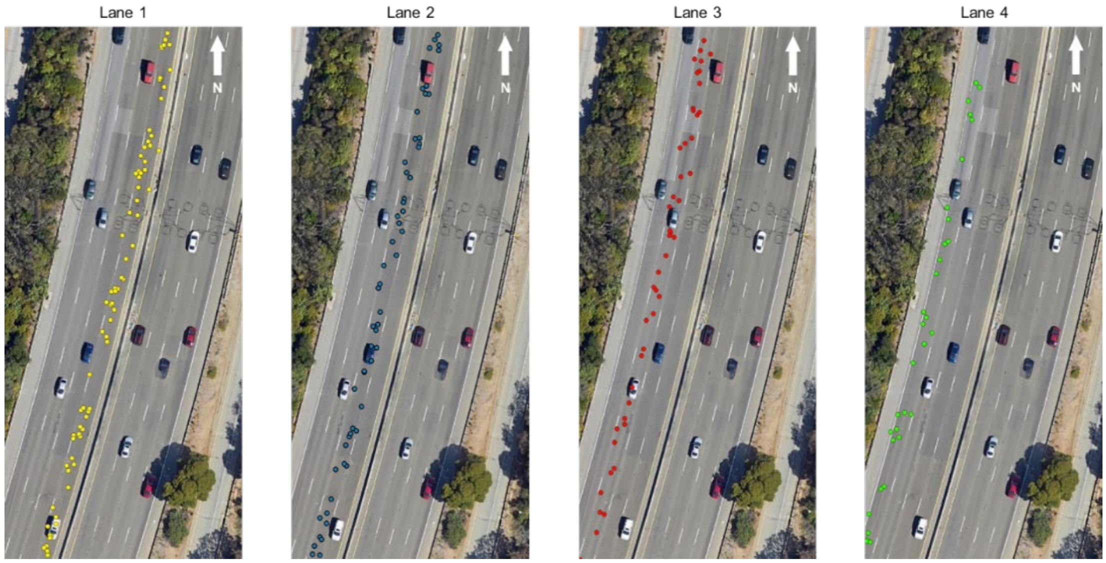


Figure 2 Lane-by-lane Vehicle Trajectory Waypoints on the Part of a Basic Freeway Segment

As shown in Figure 2, trajectory waypoints on each lane are extracted separately, and trajectory waypoints on the same lane are shown in the same color and aggregated with different data resolution rates (every 1s, 3s, and 9s) from captured vehicles. It should be noted that very few trajectory waypoints were observed to distribute over lane markings because the spatial precision of trajectory waypoints is not 100% accurate and within 10 ft.

Step 3: Calculate Average Lane-by-lane Speed

Based on the extracted lane-by-lane trajectory waypoints from the previous step, the average lane-by-lane speed can be calculated using **Equation 1**:

$$S_i = \frac{\sum_{t=1}^{n_i} S_{it}}{n_i} \qquad (1)$$

where
S_i = Average speed for lane i on the analyzed basic freeway segment (mph),
S_{it} = Speed for the trajectory waypoint with index t on lane i (mph), and
n_i = The number of trajectory waypoints on lane i.

In **Equation 1**, the average lane-by-lane speed is obtained as the arithmetic mean of speed values for all trajectory waypoints on the same lane. In reality, although vehicles may change lanes on the segment, all of their trajectory waypoints are classified into one of the lanes for average lane-by-lane speed calculation.

Case Study

To investigate the speed relationship between PVTD and freeway detector data, a case study was carried out to compare trajectory-based speeds with detector speeds by selecting six detector stations with different types of detectors on different freeways in California.

Study Sites

Table 2 presents detailed information on the selected six detector stations in terms of freeway, direction, population, etc. The relative detector location on the segment in the last row refers to the ratio of the distance between the starting point of the segment and the detector location to the segment length. For instance, 14% indicates that detectors are placed 0.08 miles from the beginning point of the segment for Auburn Oaks, which accounts for 14% of the segment length (0.59 miles).

TABLE 2 Detailed Information on the Selected Detector Stations

Name	Auburn Oaks	Sierra Point Pkwy	Yale Ave	Temecula	Alvarado-Niles Rd	Coyote Creek
Freeway	I-80	US 101	I-5	I-15	I-880	US 101
Direction	SB	SB	SB	NB	NB	NB
Population	Urban	Urban	Urban	Rural	Urban	Urban
Terrain	Flat	Flat	Flat	Rolling	Flat	Flat
Speed Limit (mph)	70	70	70	70	70	70
Number of Lanes	5	4	6	4	4	4
AADT (veh)	89465	94570	125545	68595	91853	69318
Managed Lane Existence	Yes	No	Yes	No	Yes	No
Detector Type	Radar	Dual Loops	Dual Loops	Magnetometer	Dual Loops	Dual Loops
Truck Proportion (%)	0.2	2.6	4.0	1.2	3.8	4.7
Segment Length (mile)	0.59	0.89	0.81	1.29	0.57	0.94
Relative Detector Location on the Segment (%)	14	69	26	49	59	57

Note: AADT = annual average daily traffic; NB = northbound; SB = southbound

Data Description

PVTD used in this research was provided by Wejo Data Services, Inc and covered two weeks from March 5th to March 20th in 2023. The vehicle trajectory data was only captured from passenger cars with three resolution rates: 1s, 3s and 9s. As for freeway detector data, hourly lane-by-lane and segment speeds as well as volumes with 100% observed in the same analysis period were exported from six detector stations in the PeMS. By counting the number of different 'JourneyID' from PVTD, Table 3 summarizes vehicle trajectory data penetration rates at the selected six detector stations.

TABLE 3 Vehicle Trajectory Data Penetration Rates of the Selected Basic Freeway Segments

Name	Auburn Oaks	Sierra Point Pkwy	Yale Ave	Temecula	Alvarado-Niles Rd	Coyote Creek
Segment Penetration Rate at the Detector Location (%)	2.7	2.2	2.1	3.4	1.9	3.0

In Table 3, the segment penetration rate at the detector location was obtained by dividing the total number of vehicles at the detector location from PVTD by the total volumes from detectors in the analysis period. Following

Step 2 in the calculation framework, a smaller polygon can be drawn based on the detector location to extract trajectory waypoints on each lane and sum the number of vehicles. Because trajectory waypoints may not be captured exactly in the detector location with low resolution rates, such as 3s and 9s, a total of 350-ft detection zone extending 175 ft both from upstream and downstream to the detector location was used for data processing to increase the number of captured vehicle trajectory waypoints to reduce bias in trajectory-based speed calculations. A vehicle's speed can be assumed to be constant during such a short distance.

Lane-by-lane Speed Comparison at the Detector Location

Because vehicle trajectory data in this research was only collected from passenger cars without trucks, the lane-by-lane speed comparison between trajectory-based speeds at the detector location and detector speeds should be performed for lanes with trucks and no truck separately. It should be noted that both trajectory-based speeds and detector speeds are essentially time mean speeds, which establish a foundation for the same type of speed comparison[13].

Speed Comparison of Lanes with No Trucks

The speed difference between the trajectory-based speed at the detector location and the detector speed was utilized as a measure to investigate the relationship between two speeds. By calculating speed differences on lanes with no trucks for all six spots, two different types of patterns were captured and shown in Figure 3.

In Figure 3, the horizontal axis represents time, and the vertical axis represents speed difference (trajectory-based speed at the detector location – detector speed). The speed difference with 0 (perfect speed match) is marked by the red horizontal line. For each hour, points with the same shape and color were generated for the same spot in the selected analysis period including both weekdays and weekends. For instance, blue circles, orange triangles, and green squares represent speed differences at Auburn Oaks, Sierra Point Pkwy, and Yale Ave, respectively in Figure 3(a). It should be noted that trajectory-based speeds were directly collected from vehicle telematics, which served as ground truth reference to verify the accuracy of detector speeds.

In Figure 3(a), a similar speed difference pattern was observed at Auburn Oaks, Sierra Point Pkwy, and Yale Ave: most points are distributed above and below the red horizontal line ranging from -5 mph to 5 mph except for midnight and late-night periods, such as 0:00-3:00 and 23:00. The correlation coefficient between the two speeds were calculated as 0.89, 0.86, and 0.94 for Auburn Oaks, Sierra Point Pkwy, and Yale Ave, respectively. There were two potential reasons to account for the speed variation between -5 mph to 5mph. Firstly, the trajectory-based speed was captured based on the defined 350 ft-detection zone rather than exactly on the detector location to capture more vehicle trajectory waypoints to reduce bias. Secondly, vehicle trajectory data was only sampled data as shown in Table 3, which echoed the speed bias analysis in a previous study[2]. Due to the fewer number of vehicles captured at midnight and late night compared with other periods of the day, the speed difference variation was found to be greater in those periods. Therefore, the speed difference pattern in Figure 3(a) and calculated correlation coefficients supported accurate detector speed measurements at the above three spots. However, a different pattern was captured at Temecula, Coyote Creek, and Alvarado-Niles Rd shown in Figure 3(b): most points cluster above the red horizontal line ranging over 5 mph and up to 10 mph during most times of the day. In comparison with the speed difference pattern shown in Figure 3(a), detector speeds were constantly lower than trajectory-based speeds, which indicated inaccurate detector speed measurements at those spots. A detailed analysis of speed mismatch patterns at each spot is presented in the discussion section.

Figure 3 Speed Difference between Trajectory-Based Speeds at the Detector Location and Detector Speeds on Lanes with No Trucks: (a) Matched Patterns and (b) Unmatched Patterns

Speed Comparison of Lanes with Trucks

Based on the above speed comparison of lanes with no trucks, it was found that detectors functioned well at Auburn Oaks, Sierra Point Pkwy, and Yale Ave. Therefore, the speed comparison on lanes with trucks was performed at the above three spots as shown in Figure 4.

Compared with Figure 3(a), it can be noticed that more points are distributed over 5 mph especially during midnight and several non-congested periods, such as 0:00-11:00. The truck proportion data in the PeMS indicated a large proportion of trucks in the nighttime. In California, trucks usually followed lower speed limits than passenger cars, which accounted for significantly increased speed differences during midnight. During daytime (6:00-11:00), the increased speed differences between 5 mph and 10 mph can still be captured although the truck proportion decreased in those periods. During PM peak hours (14:00-19:00), the speed difference pattern behaves similarly to Figure 3(a) ranging from -5 mph to 5 mph because both passenger cars and trucks maintained much lower and closer speeds than non-peak hours. The above analysis indicated that the existence of trucks had impacts on the speed difference. A detailed discussion on this is provided in the discussion section.

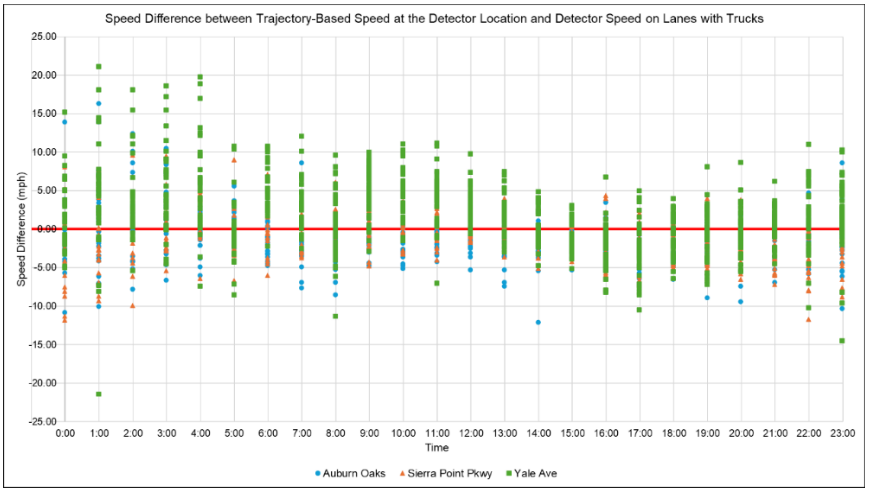


Figure 4 Speed Difference between Trajectory-Based Speeds at the Detector Location and Detector Speeds on Lanes with Trucks

Discussion

Based on the comparison between trajectory-based speeds and detector speeds in the previous section, two subsections are provided in this section to delve into an in-depth discussion of using PVTD to analyze speed mismatch patterns and the relationship between lane-by-lane speed differences and lane-by-lane truck proportions.

Analysis of Speed Mismatch Patterns

Following lane-by-lane speed comparison in the previous section, inaccurate detector speed measurements were found at three spots with different types of detection: Temecula (magnetometer), Coyote Creek (dual loops), and Alvarado-Niles Rd (dual loops). To comprehensively analyze the speed mismatch pattern at each spot, Figure 3(b) was decomposed into three plots in Figure 5 to display speed difference of lanes with no trucks at those spots separately. In each plot, the blue circles and orange triangles represent speed differences on weekdays and weekends, respectively.

In Figure 5(a), it can be noticed that most points are distributed above the red horizontal line (speed difference = 0) except for a group of blue circles from 14:00 to 19:00. Both vehicle trajectory and detector speeds showed that the weekday PM congestion occurred from 14:00 to 19:00 and no congestion occurred on weekends. At this spot, the speed mismatch pattern occurred in uncongested periods while disappeared in congested periods. Some common detection errors of magnetometers include missed calls, false calls, dropped calls, and stuck-on calls (*46-50*). In this case, the reasons may result from inappropriate detector configurations and characteristics of magnetometer for speed measurement. When vehicles passed through magnetometers at high speeds, the magnetic change was not sensitively captured by detectors, which resulted in lower speeds. However, the magnetic change was accurate at low speeds during congestion, which generated speed match patterns in the PM peak. The correlation coefficient between trajectory-based speeds at the detector location and detector speeds was calculated as 0.99 for lanes with no trucks at this spot, which indicated that there was a strong linear relationship between two speeds while an adjustment factor might be considered for magnetometer configuration.

Figure 5(b) shows that most points are constantly over the red horizontal line ranging from 0 mph to 15 mph both on weekdays and weekends at Coyote Creek. The correlation coefficient of 0.7 indicated a weak linear relationship between two speeds, which suggested a potentially inappropriate loop configuration issue at this spot.

In Figure 5(c), the distributions of blue circles (weekday) and orange triangles (weekend) are slightly different from each other at Alvarado-Niles Rd: most triangles cluster above the speed difference of 5 mph while most circles are distributed evenly above and below the red horizontal line. In other words, the speed mismatch pattern mostly occurred on weekends. The potential reasons for this may result from inappropriate loop configurations. By comparing Figure 5(b) and Figure 5(c), although the detection type was the same at both spots, speed mismatch patterns performed differently from each other.

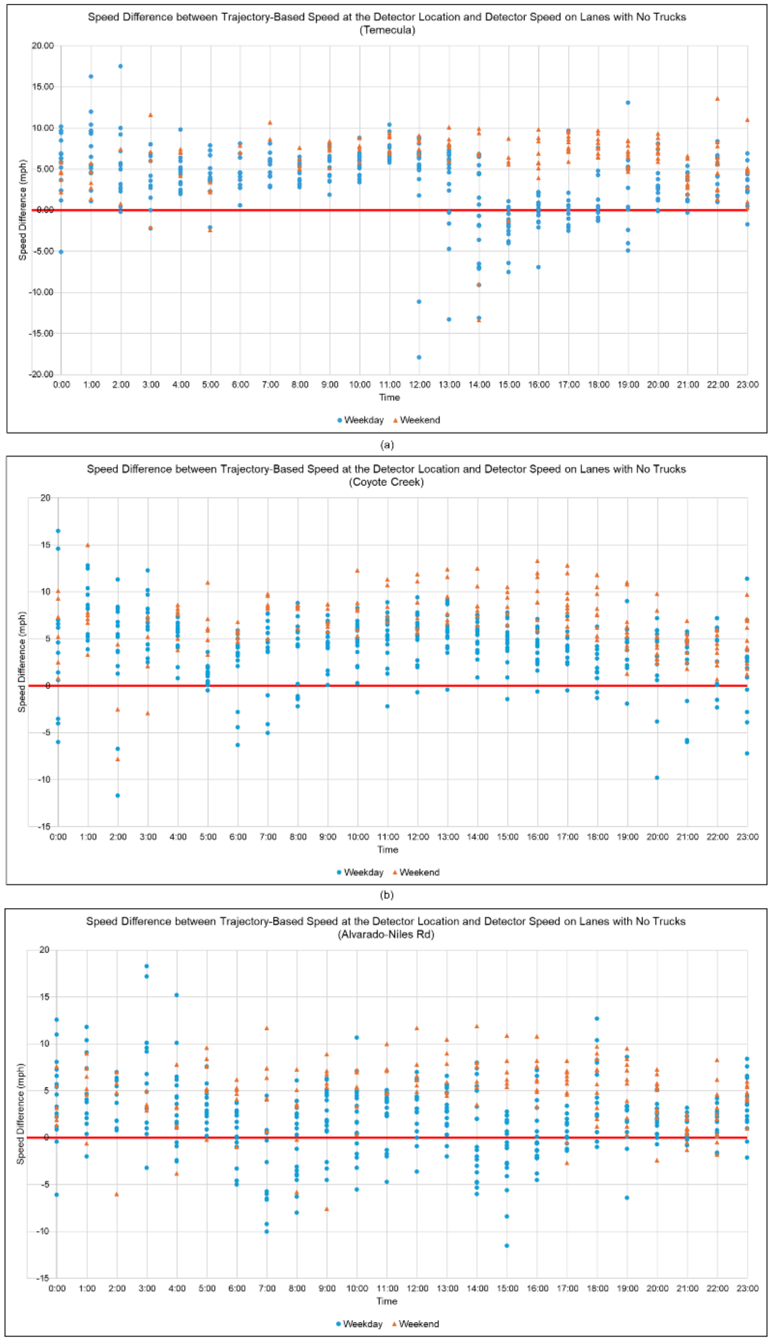


Figure 5 Speed Mismatch Patterns on Lanes with No Trucks: (a) Temecula, (b) Coyote Creek, and (c) Alvarado-Niles Rd

The above analysis indicated that speed mismatch patterns varied by spots and detector types. PVTD can serve as a useful data source to verify the accuracy of detector speeds on lanes with no trucks and provide insight into identifying speed mismatch patterns.

Relationship between Lane-by-lane Speed Differences and Lane-by-lane Truck Proportions

It was observed from Figure 4 that the existence of trucks had impacts on the speed difference. Because very few trucks were observed on Auburn Oaks, speed and truck proportion data was obtained from Sierra Point Pkwy and

Yale Ave. Figure 6 was generated to explore the relationship between the lane-by-lane speed difference (trajectory-based speed at the detector location – detector speed) and the lane-by-lane truck proportion.

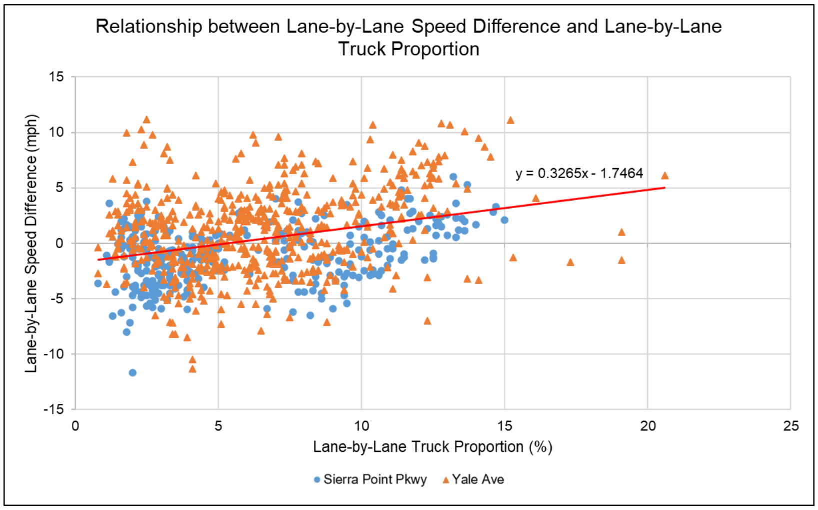


Figure 6 Relationship between Lane-by-Lane Speed Differences and Lane-by-Lane Truck Proportions

In Figure 6, the horizonal axis represents the lane-by-lane truck proportion, and the vertical axis represents the lane-by-lane speed difference. To reduce biased speed comparison, a minimum of 15 vehicles per hour per lane was used as a threshold to determine comparison periods. Each point was generated based on an hourly lane-by-lane truck proportion and the corresponding hourly lane-by-lane speed difference with blue circles and orange triangles for Sierra Point Pkwy and Yale Ave, respectively. It can be found that points cluster above and below 0 on the vertical axis because of sampled vehicle trajectory data. The red trendlines with positive slopes indicate that the lane-by-lane speed difference tends to increase as the lane-by-lane truck proportion increases.
Therefore, it was concluded that the lane-by-lane speed difference between trajectory-based speeds at the detector location and detector speeds cannot be ignored for lanes with trucks and tends to increase as the lane-by-lane truck proportion increases.

Conclusions

Motivated by the challenge of verifying the accuracy of lane-by-lane speeds measured by freeway detectors, this research explores the use of PVTD to verify the accuracy of lane-by-lane speed measured by freeway detectors. A calculation framework for trajectory-based speeds from PVTD is proposed and applied to six detector stations with different types of detectors on different freeways in California. Based on comparisons between trajectory-based speeds and detector speeds, the following conclusions are drawn from this research:
(1) PVTD can be utilized as a useful data source to verify the accuracy of freeway detector speeds on lanes with no trucks and provide insight into identifying speed mismatch patterns.
(2) PVTD is found to be less representative on lanes with trucks. The lane-by-lane speed difference between trajectory-based speeds at the detector location and detector speeds tends to increase as the lane-by-lane truck proportion increases.
As this research is mainly focused on utilizing PVTD to verify the accuracy of lane-by-lane detector speeds with detector quality of 100% observed, further research can be expanded to explore the capability of PVTD to fill data gaps caused by malfunctioning detectors to by comparing trajectory-based speeds and imputed speeds in the PeMS. Additionally, it was found that the lane-by-lane speed difference between PVTD (passenger cars) and freeway detector data cannot be ignored for lanes with trucks in this research. As probe truck telematics data (PTTD) becomes increasingly available[51,52,53], the combination PVTD and PTTD should be taken into consideration for performing a more comprehensive and reliable speed comparison at the detector location to verify the accuracy of speeds for lanes with trucks.

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