Title

Assessing Automated Speed Enforcement in California

Authors

Chan, Ching-Yao
Li, Kang
Lee, Joon-Ho

Publication Date

2010-04-01

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Assessing Automated Speed Enforcement in California

Ching-Yao Chan, Kang Li, Joon-Ho Lee

California PATH Research Report
UCB-ITS-PRR-2010-21

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Order 6212

April 2010

ISSN 1055-1425

Task Order 6212 Final Report

Assessing Automated Speed Enforcement in California

Authors

Ching-Yao Chan
Kang Li
Joon-Ho Lee

ACKNOWLEDGEMENTS

The authors would like to thank Duper Tong, Clint Gregory, Joe Silvy of Caltrans District 10 and Asfand Siddiqui of Caltrans Headquarters Division of Research and Innovation for their support and assistance through the project. We also wish to thank our PATH colleagues Thang Lian, Jeff Ko, Susan Dickey, and David Nelson for their participation and execution of technical work in the project.

ABSTRACT

Speeding is known to be related to a significant portion of highway collisions. As part of the efforts to seek safety improvements of the California highway network, the California Department of Transportation (Caltrans) is exploring the implementation issues of automated speed enforcement (ASE). This report provides an overview of Task Order 6212 undertaken by California PATH to assess various issues associated with ASE systems.

An ASE system designed for use in work zones was acquired and tested in several field experimental sites, along with several other commercially-off-the-shelf traffic monitoring devices. The objective of the study is to examine the field performance of the equipment in a real-world setting, when evaluated against other comparable traffic devices. The results from the field experiments revealed that traffic speed measurements are likely to yield discrepancies. For considerations of future deployment of ASE, the technologies can be expected to be advanced further. Since all types of sensing devices are susceptible to certain levels of interference and noises in the field, a consistent and robust method of verification and calibration for sensors used for ASE will be essential. From the design point of view, extra measures or techniques can be taken to ensure the robustness and accuracy of ASE systems.

The assessment of technical performance of ASE as carried out in this project can provide insights in the process of validating functional characteristics and seeking performance enhancements. The outcome of this study, in conjunction with the experience and knowledge gained by other agencies in their development and implementation of work-zone and general ASE systems will offer valuable support for future ASE implementation.

KEYWORDS

Automated Speed Enforcement, Speed Radar, Doppler Radar, Traffic Monitoring, Field Observation, Highway Safety

EXECUTIVE SUMMARY

This PATH Research Report covers the assessing Automated Speed Enforcement (ASE) in California (Task Order 6212) efforts from May 2007 – September 2009. This part of TO 6212 addresses the technical aspects of ASE equipment in the field and it follows a predecessor project that was focused on institutional and legal aspects of ASE.

Automated speed enforcement programs have been widely applied outside of the U.S. to effectively address speeding-related safety problems. As of March 2009, 26 states and 48 communities in US uses speed enforcement cameras and more than 400 municipalities or cities use red-light running cameras as part of their safety measures. Studies have evaluated crash effects of automated speed enforcement, which have proven to be quite effective. A 2005 review analyzed data from 14 studies and found crash reductions in the immediate vicinities of camera sites, ranging from 5 to 69 per-cent for all crashes, 12 to 65 percent for injury crashes, and 17 to 71 percent for fatal crashes. A 2006 review analyzed data from 21 studies and found reductions ranging from 14 to 72 percent for all crashes, 8 to 46 percent for injury crashes, and 40 to 45 percent for crashes involving fatalities and serious injuries.

With the advancements in sensing and communication technologies, a variety of traffic monitoring devices are becoming more affordable and feasible. For the purpose of implementing ASE as well as traffic monitoring devices, it is important for highway operators and enforcement agencies to define and to understand the performances of such equipment. More importantly, select components and sub-systems can potentially be integrated to provide traffic enforcement and management functions more economically and effectively. Therefore, one major objective in the current study is to conduct a comparative evaluation of several candidate traffic monitoring systems so that their field performance can be fairly and thoroughly investigated.

The results from the field experiments revealed that traffic speed measurements would likely yield discrepancies among different devices. Since speed measurement consistency and accuracy are major concerns in the implementation of speed enforcement systems, it is critical that the operation of enforcement take into account the characteristics of field performance of such devices and set speeding thresholds accordingly. For a more robust and reliable system, it will also be desirable to utilize technical approaches to offer supplementary speed measurements.

Data processing techniques, including synchronization and association, were adopted to investigate in depth the speed measurement discrepancies between the selected ASE equipment and other traffic measuring devices, particularly compared against a ground data station that was used as the baseline. The speed enforcement unit tends to yield a lower measured value of speed measurement, with a mean differential of less than 1 mph. The standard deviation of the speed differential is between 3 to 4 mph. From this single measure, the ASE equipment has performed adequately. However, there are incidences where erroneous data points have occurred due to the unavoidable field noises and interference from various factors.

Additionally, steps were taken to compare the speed measurement discrepancies between the selected ASE equipment and the tracking radar system EVT-300. Although two radar systems have different signal ranges and coverage and functional features, the performance of speed

measurements are comparable, in particular, for the high-speed moving target. It was found that EVT-300 tended to report a smaller speed value than the RWASS speed measurement. However, the speed data of two systems are fairly consistent. At one study site on an interstate freeway, the mean of speed differential is around -1.09~-1.20 mph, and the standard deviation is between 2.2~2.3 mph. At another site on a local state route, the mean of speed differential is 0.48 mph and the standard deviation is 2.69 mph. Since the tracking radar EVT-300 can provide a sequence of range, speed, and heading measurements of the tracked targets, it has the potential to provide secondary measurements for an enhanced ASE system.

For considerations of future deployment of ASE, the technologies can be expected to be advanced further. Since all types of sensing devices are susceptible to certain levels of interference and noises in the field, a consistent and robust method of verification and calibration for sensors used for ASE will be essential. From the design point of view, extra measures or techniques can be taken to ensure the robustness and accuracy of ASE systems.

The assessment of technical performance of ASE as carried out in this project can provide insights in the process of validating functional characteristics and seeking performance enhancements. The outcome of this study, in conjunction with the experience and knowledge gained by other agencies in their development and implementation of work-zone and general ASE systems will offer valuable support for future ASE implementation.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1. INTRODUCTION

This PATH Research Report covers the Assessing Automated Speed Enforcement (ASE) in California (Task Order 6212) efforts from May 2007 – September 2009. This part of TO 6212 addresses the technical aspects of ASE equipment with an emphasis of experimental evaluation in the field and it follows a predecessor project that was focused on institutional and legal aspects of ASE.

It is organized to provide the background and objectives of the project (Section 1), the highway setting that was used as a case study for potential target applications (Section 2), then describes the field experiments that were carried out to investigate the performance of ASE equipment in the field (Section 3) and finally offer conclusions on the status and characteristics of ASE technologies for deployment considerations (Section 4).

Speeding is known to be related to a significant portion of highway collisions. As part of the efforts to seek safety improvements of the California highway network, the California Department of Transportation (Caltrans) is exploring the implementation issues of automated speed enforcement (ASE) and sponsoring a project conducted at California PATH[1], University of California at Berkeley.

Automated speed enforcement programs have been widely applied outside of the U.S. to effectively address speeding-related safety problems. As of March 2009, 26 states and 48 communities in US uses speed enforcement cameras and more than 400 municipalities or cities use red-light running cameras as part of their safety measures.

In a recent statement to the Maryland Senate committee [1], Insurance Institute for Highway Safety (IIHS) presented a comprehensive review on automated speed enforcement. Speeding is a major factor in motor vehicle crashes, especially those resulting in serious injuries [2]. In the United States, speeding — as defined on police crash reports as driving too fast for conditions, exceeding posted speed limits, or racing — was a contributor in about 32 percent of crash deaths in 2007, resulting in more than 13,000 fatalities [3]. Although speeding often is associated with interstates and other high-speed roads, 88 percent of speeding-related fatalities occur on roads other than interstate highways. In 2007, 24 percent of all speeding-related fatalities occurred on streets with speed limits of 35 mph or less.

In 2007 IIHS conducted an evaluation of the Montgomery County program using speed cameras to enforce limits on residential roads with speed limits of 35 mph or lower and in school zones [4]. The study indicates that the program is helping to reduce speeding. Researchers meas-ured traffic speeds approximately 6 months before and 6 months after camera enforcement be-gan in May 2007. The proportion of vehicles traveling more than 10 mph above posted limits fell by 70

---

[1] www.path.berkeley.edu

percent on roads where cameras were operational and by 39 percent on roads with signs warning of enforcement but where cameras were not yet in place.

The Institute also evaluated the effect of a pilot speed-camera enforcement program begun in 2006 in Scottsdale, Arizona [5]. Cameras photographed vehicles going more than 10 mph above the 65 mph speed limit on Loop 101, a six-lane freeway encircling the Phoenix metro area. Speeding in the city's camera enforcement zone decreased among both passenger vehicles and large trucks, with the combined proportion of vehicles exceeding 75 mph dropping from 15 percent before camera enforcement to 1-2 percent while cameras were in use. By comparing Loop 101 speeds with those observed on nearby freeways that did not have cameras, re-searchers concluded that the Scottsdale program was associated with as much as a 95 percent decrease in the odds that drivers would surpass 75 mph.

Studies have evaluated crash effects of automated speed enforcement. Evaluating a program in British Columbia that involved 30 cameras, researchers found a 7 percent decline in crashes, a 10 percent decline in daytime crash injuries, and up to 20 percent fewer deaths during the first year cameras were used. [6] The Transportation Research Board and others have reported the following examples of the successful use of speed cameras:

- Victoria, Australia, launched a speed camera program in 1989. A little more than a year later, the frequency of crashes involving injuries or deaths had decreased by about 30 percent. [7]
- On a stretch of Autobahn A3 between Cologne and Frankfurt, Germany, where speed cameras were deployed, total crashes dropped from about 300 per year to fewer than 30. Injury crashes decreased by a factor of 20. [7]
- Speed cameras were deployed on 64 roads in Norway, producing a 20 percent reduction in injury crashes. [7]
- An evaluation of fixed speed cameras on 30 mph roads in the United Kingdom found the average effect was a 25 percent reduction in injury crashes. [8]

The effects of automated speed enforcement on crashes also have been summarized in two systematic reviews of the international literature. A 2005 review analyzed data from 14 studies and found crash reductions in the immediate vicinities of camera sites, ranging from 5 to 69 percent for all crashes, 12 to 65 percent for injury crashes, and 17 to 71 percent for fatal crashes. [9] A 2006 review published by the Cochrane Collaboration (an international organization that conducts systematic reviews of the scientific literature on public health issues) analyzed data from 21 studies and found reductions ranging from 14 to 72 percent for all crashes, 8 to 46 percent for injury crashes, and 40 to 45 percent for crashes involving fatalities and serious injuries. [10]

An earlier phase of the project was carried out and concluded with an extensive literature review and an examination of various institutional and legal issues involved in the implementation of ASE [11]. In the earlier report, the legal restrictions to the implementation of automated speed enforcement in the U.S. were outlined. An evaluation of key program design choices was also provided, encompassing a variety of issues. In the current, second phase of the project, the focus is placed on the technological evaluation of ASE equipment. An ASE system designed for use in work zones was acquired and tested in several field experimental sites, along with several other commercially-off-the-shelf traffic monitoring devices. The objective of the study is to examine the field performance of the equipment in a real-world setting, when evaluated against other traffic sensing devices. This report provides a description of the rationale behind the study, the equipment included in the study, and the findings from the field experiment.

2. A CASE STUDY OF RURAL HIGHWAY SAFETY

While speed-enforcement programs are potentially applicable as safety countermeasures for high-risk areas where speeding is identified as a major contributor of collisions, a specific highway was evaluated during the course of this project to investigate in depth the traffic patterns of speeding and the locations where this type of safety systems can be adopted. A state highway (SR-12) in Northern California was chosen as a case study for this project. This highway is a rural roadway, which serves as a corridor connecting several counties and two interstate highways and one major state highway. It spans over 185 kilometers (115 miles), with one lane in each direction during a majority of its length and two lanes in each direction where it is closer to the junctions with other highways. The traffic pattern exhibited a high percentage of speeding vehicles and frequent serious collisions. In order to understand the contributing factors and the collision patterns, the historical data of crash records were analyzed for a 5-year period of 2002-2006. The distribution of crashes along the route and their primary collision factors are plotted and shown in the following figures.

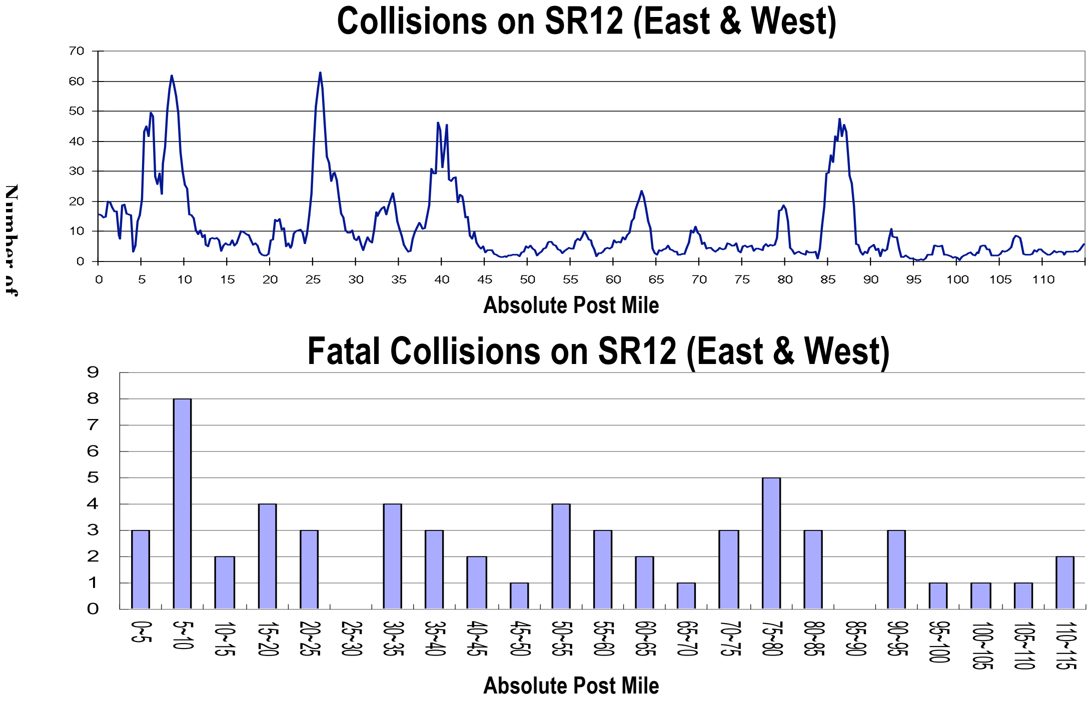


Figure 1 All Collision and Fatal Collisions along SR-12, 2002-2006

Figure 1 depicts the distribution of all and fatal collisions along the whole stretch of SR-12 over the 5-year period. Figure 2 shows the counts of collisions by the primary collision factors as reported in police reports in the same period. Unequivocally, speeding is an apparent cause of many crashes. In conjunction with the collision data analysis described above, a recent traffic survey was carried out in October 2007 by using on-site surface traffic sensors to acquire traffic counts, speed and vehicle class distribution. Figure 3 displays the exemplar data of vehicle speed and class distribution in a 24-hour period.

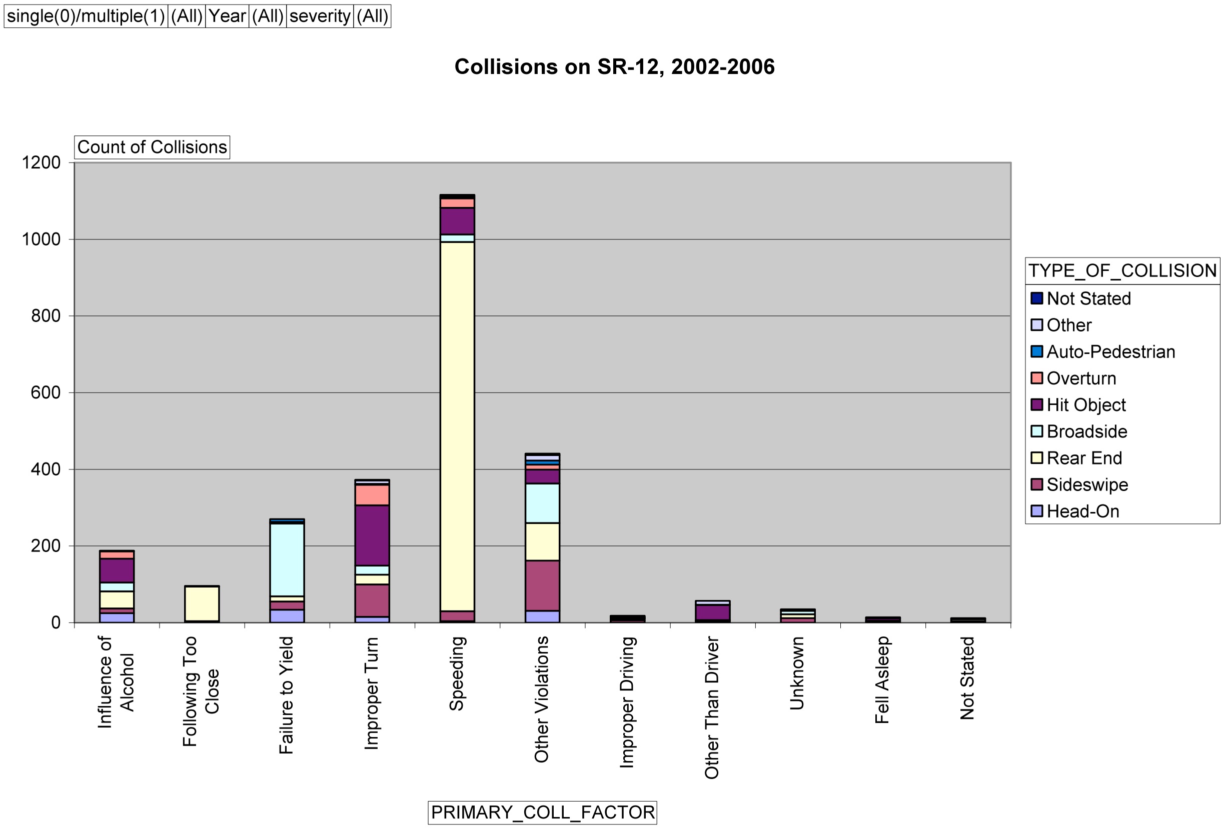


Figure 2 Primary Collision Factors and Collision Types of SR-12, 2002-2006

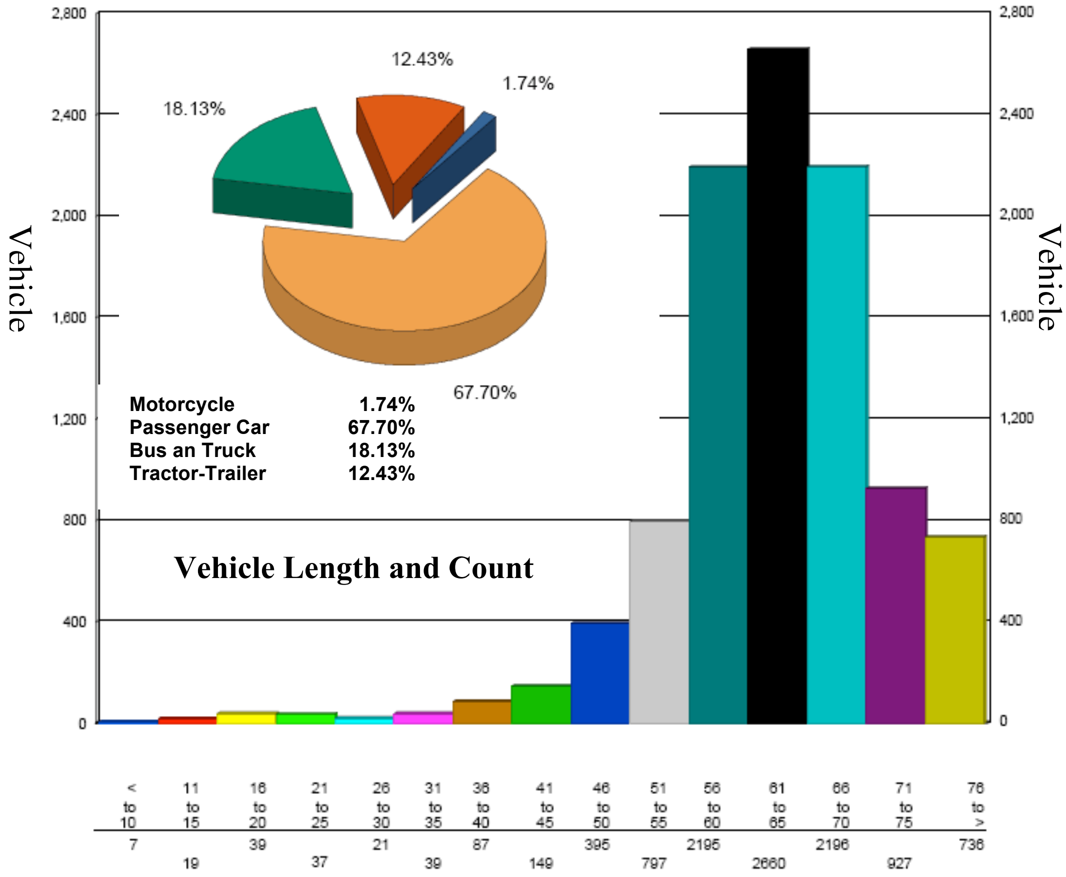


Figure 3 Vehicle Class and Speed Distribution in a One-Day Period on SR-12

Section 2.1 discusses the data used for the analysis. Section 2.2 summarizes results of spatial analysis on the data, and Section 2.3 presents linear regression approach to identify effects of geometric configurations (i.e., left shoulder width, right shoulder width, and median width) of the freeway. Section 2.4 summarizes results from categorical analysis on the collisions on east and west directions

2.1 Overview of Collision Data

To compare identify collision patterns on the freeway, a variety of data were gathered at the nine study sites where auxiliary lanes were constructed. Data sources and severity of collision data by districts are presented below.

- Collision data source: Route 12 in Districts 3, 4, and 10 between years 2002 and 2006 from TASAS
- Annual Average Daily Traffic (AADT) data source: data between years 2002 and 2006 from Caltrans Traffic Data Branch

- Geometry data source: most recent changes up to 2006 from California Highway Performance Monitoring System (HPMS)

Table 1 Summary of collisions by district and severity

District	Fatality	Injury	PDO	District Total
3	2	58	89	**149**
4	38	1158	1825	**3021**
10	18	401	637	**1056**
Severity Total	**58**	**1617**	**2551**	**4226**

Based on table 1, fatal collisions are relatively rare events (approximately 10 per year) on the freeway.

2.2 Spatial analysis of collisions

Figure 4 shows 1 mile moving averages of collision profiles of eastbound and westbound directions. Y-axis in the figure represents the number of collisions per mile per year, and x-axis indicates corresponding absolute post-mile. In the figure, the locations of I-80 and I-5 are shown with dotted vertical lines. For readers' convenience, locations of major junctions with freeways and county boundaries on route 12 are summarized in table 2.

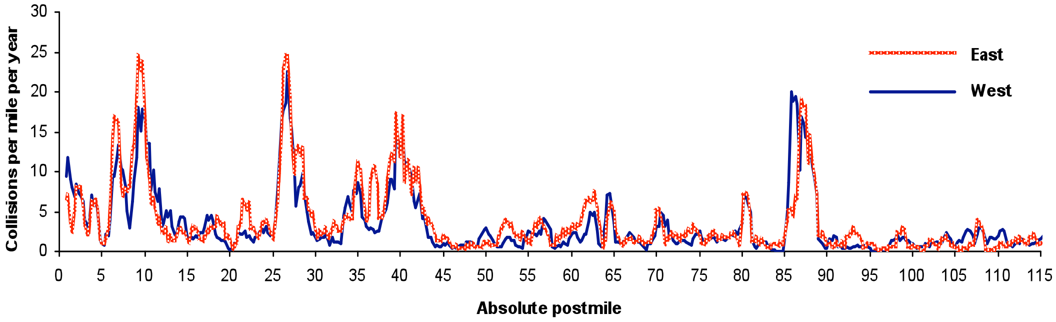


Figure 4 Collisions on Route 12 - Fatality, Injury, and PDO

Table 2 Locations of county lines and freeway junctions

District	Route	County	Postmile	Abs Postmile	Description
4	12	SOL	0.000	37.179	SOL/NAPA County Line
4	12	SOL	1.801	38.980	JCT. RTE. 80
4	12	SOL	19.169	56.348	JCT. RTE. 113 NORTH
4	12	SOL	26.276	63.455	JCT. RTE. 84 NORTH
3	12	SAC	0.000	63.596	SOL/SAC County Line
3	12	SAC	0.571	64.167	JCT. RTE. 160
3	12	SAC	6.200	69.796	SAC/SJ County Line
10	12	SJ	10.167	79.963	JCT. RTE. 5

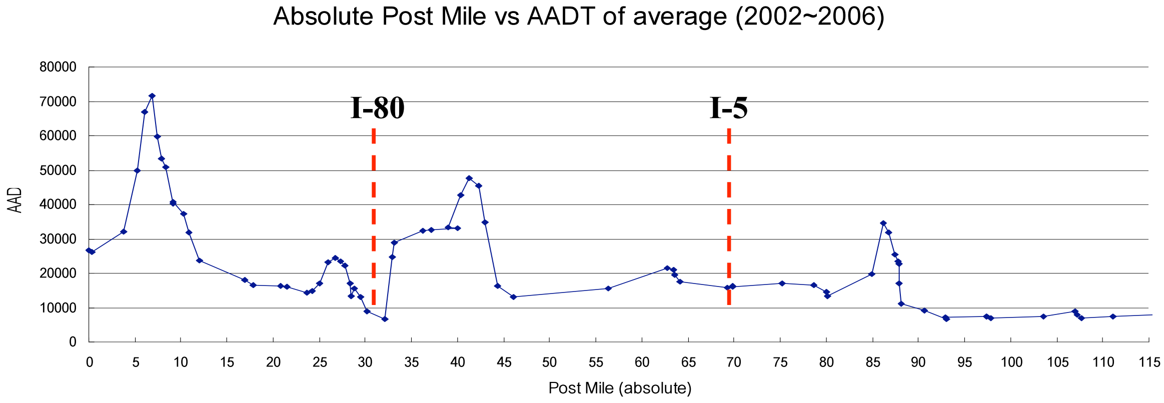


Figure 5 Average AADT from 2002 to 2006

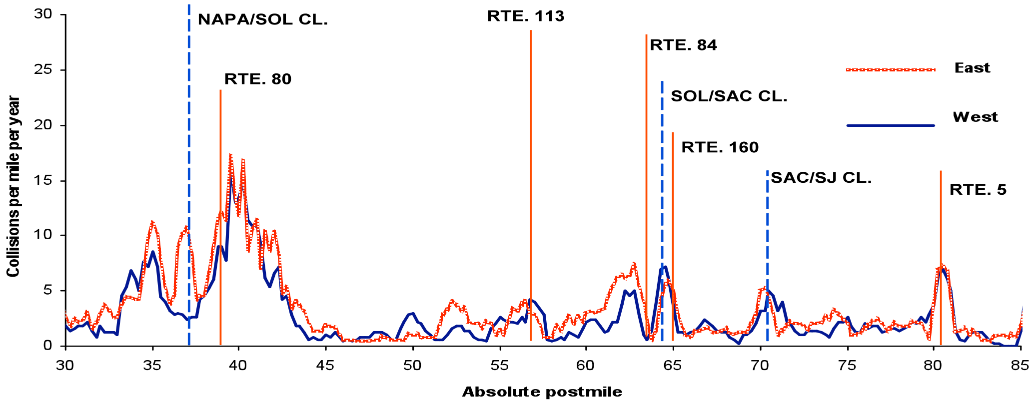


Figure 6 Collisions between I-80 and I-5

Figure 5 shows AADT along the stretch of the freeway. Notice that the peaks of collisions in figure 1 generally coincide with the peaks of AADT in figure 2. Figure 6 shows collisions between I-80 and I-5. The figure shows that collision concentrations tend to occur near junctions with highways.

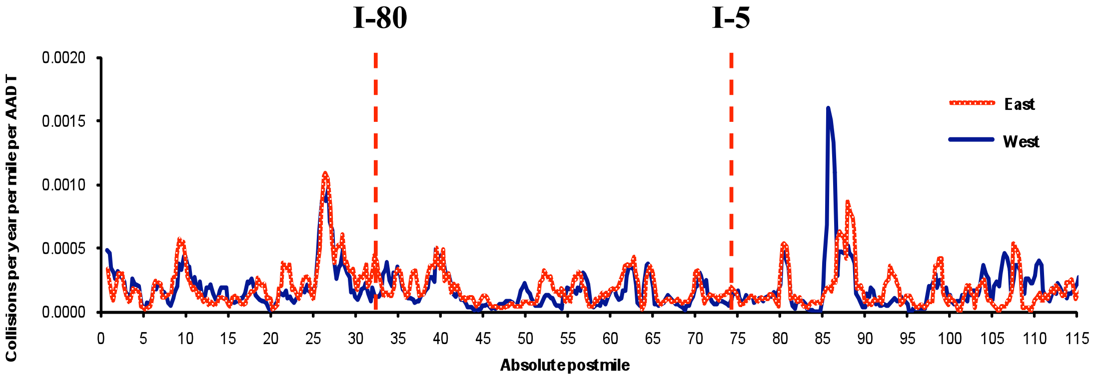


Figure 7 Collision rates on Route 12 - Fatality, Injury, and PDO

Figure 7 show collision rates along the freeway, the number of collisions per year per mile per AADT, and Figure 8 show collision rates between I-80 and I-5. Note that these figures show peaks at the same locations as figures 1 and 3. However, peaks between absolute postmile (APM) 5 and 10 and peaks near APM 40 disappear in the formers, indicating that the number of collisions is relatively insignificant as compared to the traffic volume of the location. Two major high concentration collision locations (HCCL) identifiable from figure 4 are near APM 27 and 88.

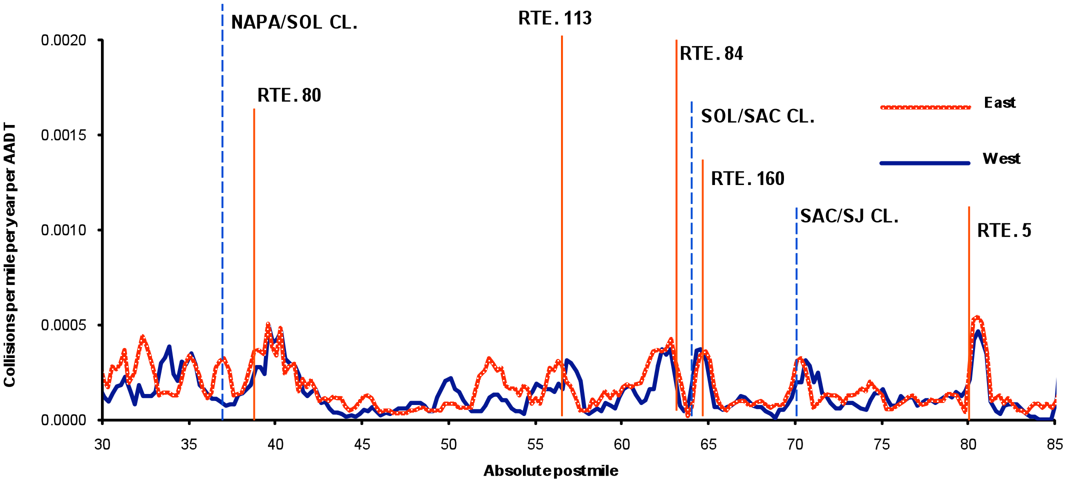


Figure 8 Collision rates between I-80 and I-5

2.3 Linear regression analysis on collisions

The purpose of linear regression analysis is to identify the effects of geometric configurations on the number of collisions. A dependent variable is the number of collisions per year per lane per 0.25 mile. There are four explanatory variables included in this analysis: i) width of left shoulder, ii) width of right shoulder, iii) width of median, and iv) AADT per lane.

$$\begin{aligned}\text{Collisions per Year per Lane} = {} & b_0 + b_1 * \text{left shoulder width} + \\ & b_2 * \text{right shoulder width} + \\ & b_3 * \text{median width} + \\ & b_4 * \text{AADT per lane}\end{aligned}$$

The outputs of the regression analysis for eastbound and westbound traffic are presented respectively in Table 3 and Table 4. T-stat in the tables is the ratio of the coefficients to their standard errors. This can be tested against a t distribution to determine how probable it is that the true value of the coefficient is really zero. This probability of being zero is shown by p-values. As the p-values become smaller, the values of the coefficients turn out to be more statistically significant.

Results in both directions indicate that the increase in AADT per lane results in the increase in the number of collisions, while increases in the length of left shoulder reduce the number of collisions. In contrast, the length of right shoulder does not demonstrate a significant relation with the number of collisions. Interestingly, the median width and the number of collisions show a positive relation. Much detailed analysis with additional explanatory variables is required to verify the findings from the regression analysis.

Table 3 Regression analysis on eastbound geometric data

Eastbound	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Intercept	-0.0527	0.5475	-0.0963	0.9233
Left Shoulder Width	-0.6061	0.2723	-2.2253	0.0265
Right Shoulder Width	-0.0835	0.0672	-1.2435	0.2143
Median Width	0.0830	0.0277	2.9924	0.0029
AADT per lane	0.0002	0.0000	8.9850	0.0000

Table 4 Regression analysis on westbound geometric data

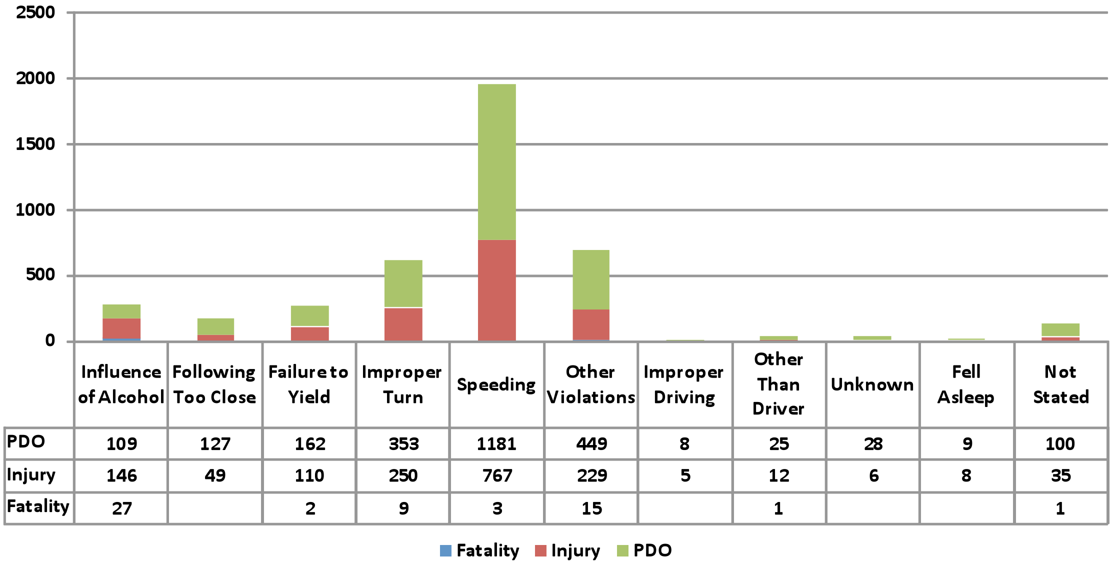
Westbound	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Intercept	0.1146	0.5779	0.1983	0.8429
Left Shoulder Width	-0.6265	0.2942	-2.1297	0.0337
Right Shoulder Width	-0.0014	0.0745	-0.0185	0.9853
Median Width	0.0934	0.0300	3.1079	0.0020
AADT per lane	0.0002	0.0000	6.1627	0.0000

2.4 Categorical analysis on collisions

Detailed breakdown of collision patterns summarized in both directions and each direction are presented in this section. The results can be summarized as follows:

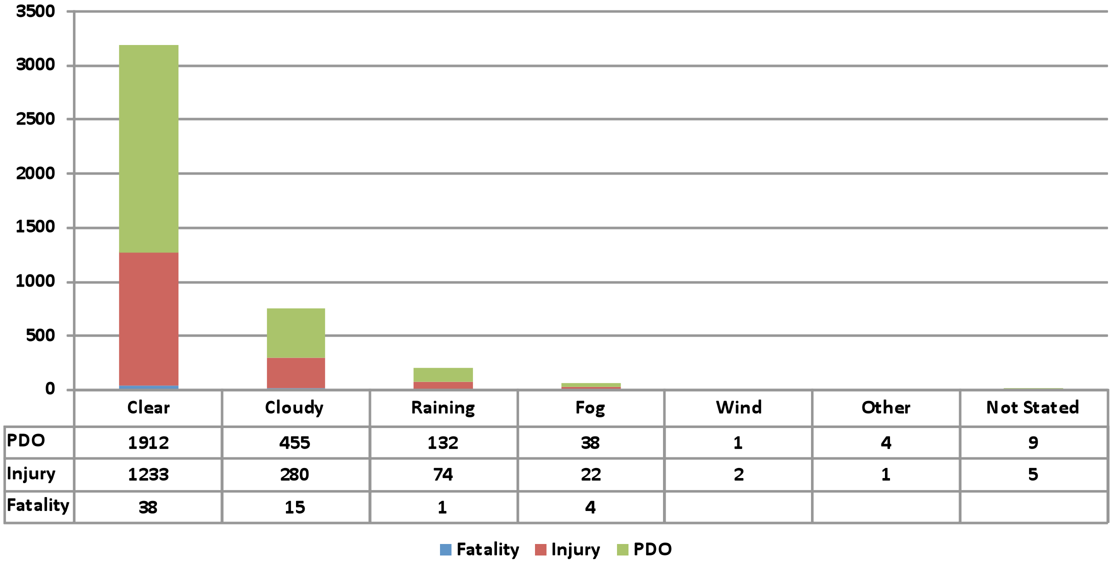
- Speeding is the primary factor for all collisions, while DUI (drunken under the influence) is a major factor in fatal collisions (27 out of 58 fatal collisions).
- There are no visible differences in eastbound and westbound directions.
- Adverse weather does not seem to influence the likelihood of collisions. Most of collisions and fatal collisions (38 out of 58 fatal collisions) occurred in clear weather.
- The primary type of collisions for fatal injuries is head-on (27).
- Hit object type (14) is also related to significant portions of fatal collisions.
- Most of fatal collisions took place in right lanes as well as right and left shoulders. Note that a main stretch of this highway has only one lane in each direction, therefore right lane is equivalent to the only lane in either traveling direction. Collisions in right shoulder lane shows significant fatality, and it is conjectured that these are related to hit object type collisions.
- Most of vehicles were travelling straights, before they ran into collisions, but higher portion of ran-off-road movements resulted in fatal injuries. It is assumed that they are associated with hit-object collisions on the right shoulder.
- Collisions peak during evening commute between 15:00 and 17:00, but fatal collisions are evenly distributed throughout the day.

A sampling of the results of categorical analysis is presented in the figures below. Figure 9 shows the primary collision factor and Figure 10 weather conditions for crashes in both directions.



	Influence of Alcohol	Following Too Close	Failure to Yield	Improper Turn	Speeding	Other Violations	Improper Driving	Other Than Driver	Unknown	Fell Asleep	Not Stated
PDO	109	127	162	353	1181	449	8	25	28	9	100
Injury	146	49	110	250	767	229	5	12	6	8	35
Fatality	27		2	9	3	15		1			1

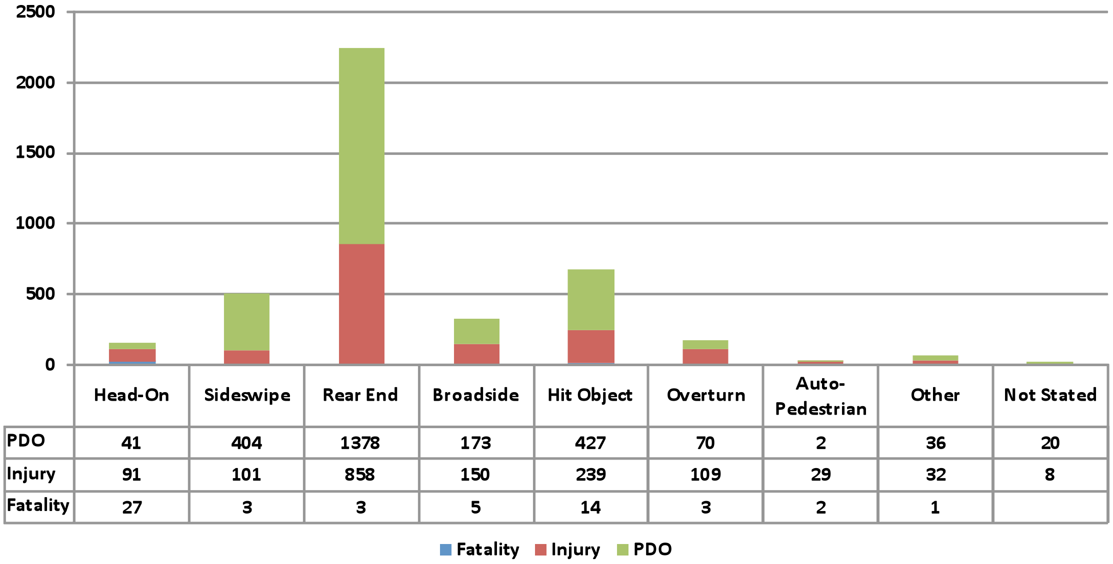
Figure 9 Primary Collision Factor, Both Directions



	Clear	Cloudy	Raining	Fog	Wind	Other	Not Stated
PDO	1912	455	132	38	1	4	9
Injury	1233	280	74	22	2	1	5
Fatality	38	15	1	4			

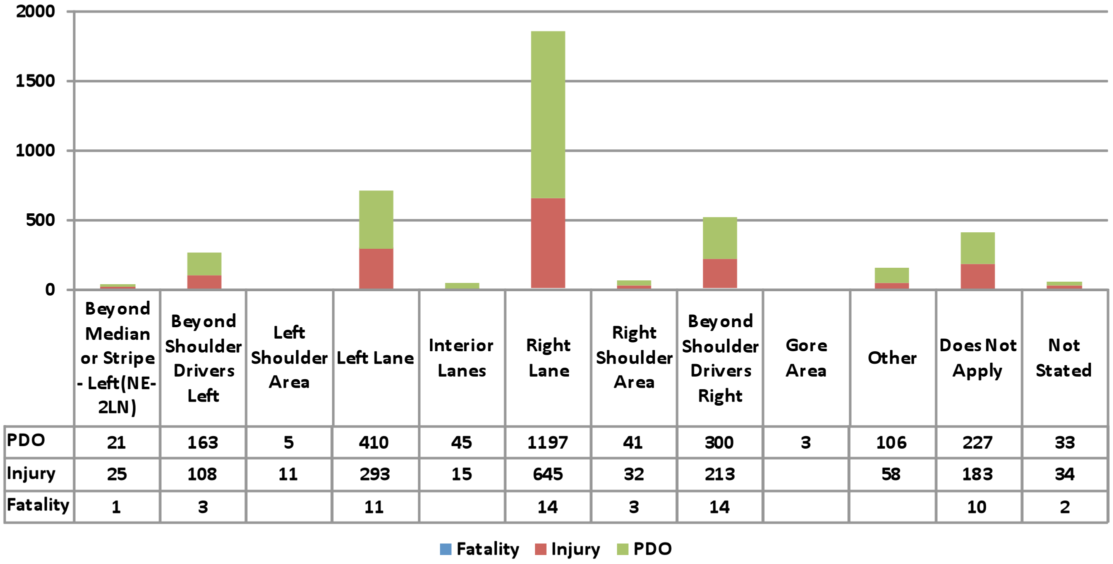
Figure 10 Weather, Both Directions

Figure 11 shows the types of collisions and Figure 12 collision locations for crashes in both directions.



	Head-On	Sideswipe	Rear End	Broadside	Hit Object	Overturn	Auto-Pedestrian	Other	Not Stated
PDO	41	404	1378	173	427	70	2	36	20
Injury	91	101	858	150	239	109	29	32	8
Fatality	27	3	3	5	14	3	2	1	

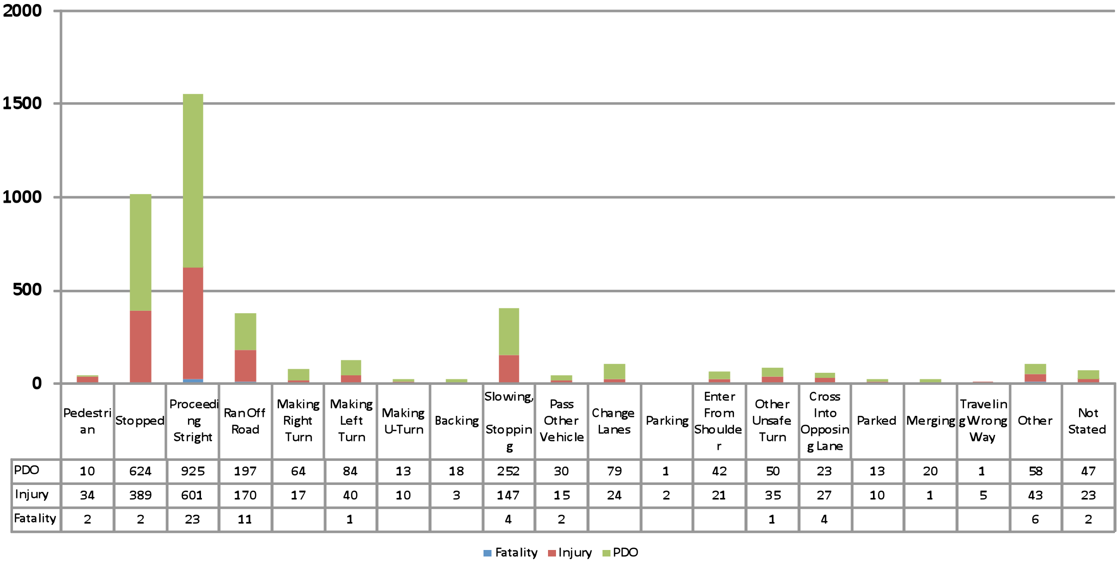
Figure 11 Type of Collision, Both Directions



	Beyond Median or Stripe - Left(NE-2LN)	Beyond Shoulder Drivers Left	Left Shoulder Area	Left Lane	Interior Lanes	Right Lane	Right Shoulder Area	Beyond Shoulder Drivers Right	Gore Area	Other	Does Not Apply	Not Stated
PDO	21	163	5	410	45	1197	41	300	3	106	227	33
Injury	25	108	11	293	15	645	32	213		58	183	34
Fatality	1	3		11		14	3	14			10	2

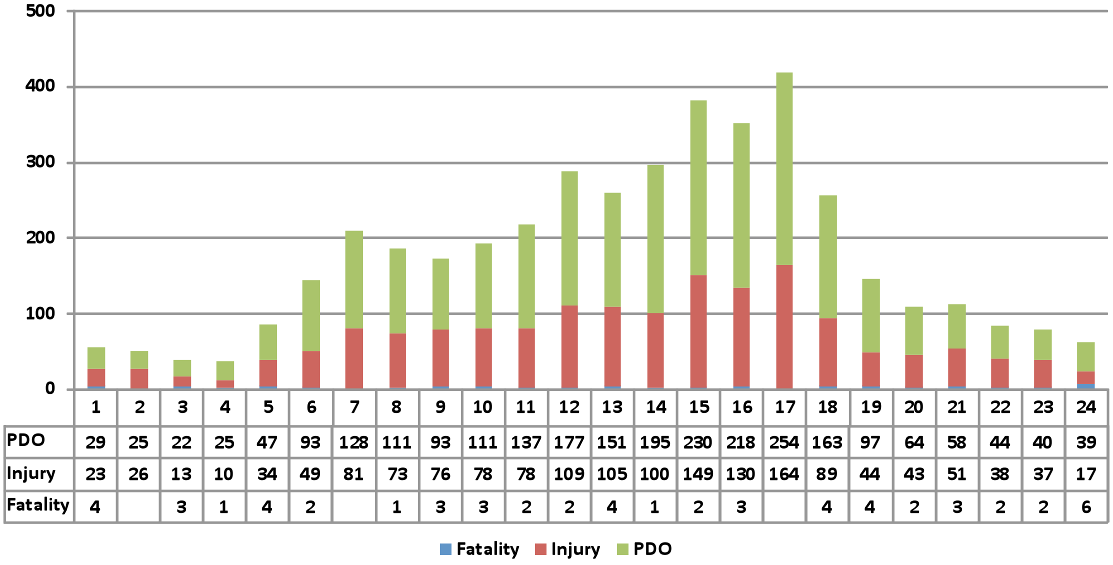
Figure 12 Collision Locations, Both Directions

Figure 13 shows the vehicle movements preceding collisions and Figure 14 time of collisions for both directions.



	Pedestrian	Stopped	Proceeding Stright	Ran Off Road	Making Right Turn	Making Left Turn	Making U-Turn	Backing	Slowing/ Stopping	Pass Other Vehicle	Change Lanes	Parking	Enter From Shoulder	Other Unsafe Turn	Cross Into Opposing Lane	Parked	Merging	Traveling Wrong Way	Other	Not Stated
PDO	10	624	925	197	64	84	13	18	252	30	79	1	42	50	23	13	20	1	58	47
Injury	34	389	601	170	17	40	10	3	147	15	24	2	21	35	27	10	1	5	43	23
Fatality	2	2	23	11		1			4	2				1	4				6	2

Figure 13 Movement Preceding Collisions, Both Directions



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
PDO	29	25	22	25	47	93	128	111	93	111	137	177	151	195	230	218	254	163	97	64	58	44	40	39
Injury	23	26	13	10	34	49	81	73	76	78	78	109	105	100	149	130	164	89	44	43	51	38	37	17
Fatality	4		3	1	4	2		1	3	3	2	2	4	1	2	3		4	4	2	3	2	2	6

Figure 14 Time of Collisions, Both Directions

2.5 Safety Countermeasures in Route 12

A list of safety countermeasures that have been implemented or being planned by the local Caltrans districts is tabulated below for reference.

Table 5 List of safety countermeasures applied and scheduled to be applied

District	Start Date	Finish Date	Description
3	-	7/2000	Placed a rumble strip using black markers (Type A) on centerline between existing striping
3	-	8/2002	Placed shoulder rumble strip
3	Under construction		At the intersection of Brannan Island Rd and Rte12, Widen intersection to install EB acceleration lane on Rte 12
3	Upcoming project		Place ground-in centerline rumble strip under existing stripe from County line to County line
4	-	12/2007	Median k-rail & left turn channelization, median channelizers, from west of Scally Road to Currie Road
4	-	7/2007	Median soft barrier, rt. shoulder rumble strips, median channelizers, from Currie Road to Drouin Drive
4	Scheduled in 2010		shoulder widening & left turn channelization, from Azevedo Road to Liberty Island Road
4	Scheduled in 2010		Pavement rehab, median soft barrier, shoulder widening, rt. shoulder rumble strips, horizontal & vertical alignment, left-turn channelization, from east of Walters Road to Currie Road
12	-	Summer 2007	Installed enhance public service advisory signs
12	-	5/2007	Eliminated 2 miles of passing zone and installed additional no passing signing package
12	-	5/2007	Conducted extreme maintenance to enhance traffic safety such as refresh striping, repair guardrail, install signing and repair pavement
12	-	7/2007	Installed solar power red flasher at De Vries Rd.
12	Scheduled in summer 2009		Install Permanent Radar Speed Feedback signs with CHP coordination
12	-	10/2007	Install Soft Barrier "Centerline Rumble Strips", EA 0K450
12	-	12/2007	Install Traffic Signal at Davis Road, EA 0L390
12	Under construction		Install Intersection Safety Lighting and Permanent red flashers at De Vries Road, EA 0Q850
12	Scheduled in summer 2009		Install Traffic Signal at De Vries Road, EA 0Q890
12	Scheduled in 2012		Bouldin Island Rehabilitation, EA 0G800
12	Candidate 2008 SHOPP		Lodi Rehabilitation, EA 28150
12	Scheduled in 2011		Operational Improvement, EA 0A840, Realign Tower Parkway under Potato Slough Bridge connect to Glasscock Rd, and Install left turn pockets at Correia Road and Guard Road

2.6 Conclusions & Findings

The present study analyzed collision patterns between years 2002 and 2006 along route 12 in districts 3, 4, and 10. The spatial analysis on the data reveals that high concentration collision locations (HCCL) are generally located near junctions with major highways. There are two major locations with high collision rates: i) APM 28 (pm 36) in Sonoma county, which is near downtown Sonoma, and ii) APM 88 (pm 18) in San Joaquin county, which is near a junction between route 12 and route 99 in Lodi.

Regression analysis on the data was performed to identify the effects of geometric features on collisions in the study sites. There are four variables included in the linear regression model: i) width of left shoulder, ii) width of right shoulder, iii) width of median, and iv) AADT per lane. Results of the regression analysis indicate that the number of collisions tends to increase with higher AADT per lane and shorter width of left shoulder. In contrast, the width of right shoulder does not demonstrate a significant effect on collisions. Interestingly, the median width shows a positive relation with the number of collisions. Much detailed analysis with additional explanatory variables is required to verify the findings from the regression analysis.

Categorical analysis on collisions is also included in this present study. The results indicate that speeding is the primary factor for all collisions, while DUI is a major factor in fatal collisions (27 out of 58 fatal collisions). There are no visible differences in eastbound and westbound directions. In addition, adverse weather does not seem to influence the likelihood of collisions. Most of collisions and fatal collisions (38 out of 58 fatal collisions) occurred in clear weather. The primary type of collisions for fatal injuries is head-on (27). Hit object type (14) is also related to significant portions of fatal collisions. Most of fatal collisions took place in right lanes as well as right and left shoulders. Many fatal collisions took place in right shoulder lane, and it is conjectured that these are related to hit object type collisions. A majority of vehicles were travelling straights, before they ran into collisions, but higher portion of ran-off-road movements resulted in fatal injuries. It is assumed that they are associated with hit-object collisions on the right shoulder. Collisions peak during evening commute between 15:00 and 17:00, but fatal collisions are evenly distributed throughout the day.

3. TECHNICAL EVALUATION OF ASE EUIPMENT

With the advancements in sensing and communication technologies, a variety of traffic monitoring devices are becoming more affordable and feasible. For the purpose of implementing ASE as well as traffic monitoring devices, it is important for highway operators and enforcement agencies to define and to understand the performances of such equipment. More importantly, select components and sub-systems can potentially be integrated to provide traffic enforcement and management functions more economically and effectively. Therefore, one major objective in the current study is to conduct a comparative evaluation of several candidate traffic monitoring systems so that their field performance can be fairly and thoroughly investigated. Preliminary results of traffic data gathered with several commercially-off-the-shelf products have been documented and reported in previous efforts [12-14] and were used as the basis of conducting a market survey and the selection of candidate devices. A brief summary of the equipment used in the field experiments is given below.

3.1 Experimental Data Collection Plans

In a separate project, the research team has surveyed and tested a number of commercially-off-the-shelf traffic monitoring devices for a different application [12-14]. Based on previous experience of evaluating such products, a select set of candidate products were acquired and developed for the current task.

Commercially-off-the-shelf traffic sensors were selected that could potentially offer comparative output for the evaluation of ASE equipment. The combined sensor suite was deployed at selective locations along the case-study highway. The data collection sites were chosen preferably to allow field data collection with variations in setup configurations and traffic patterns. At each location, the data collection process continued for approximately one week. During the course of the field observation, data were collected for comparative evaluation but no enforcement function was executed.

3.1.1 Caltrans Traffic Data Station (Courtesy of Clint Gregory of Caltrans District 10)

Caltrans has a traffic monitoring station near Post-Mile 5.6 of Route 12, close to one data collection site. At this station, a pair of in-ground loops is spaced by 12 feet (3.6 meters) with a piezoelectric sensor in between. The double loops and the piezoelectric sensor are combined to provide vehicle count, speed measurement, vehicle length, and axle spacing for each passing vehicle. The Caltrans Traffic Data Station is considered a reliable data source because the station was calibrated during installation and the results across multiple data show consistent output. Given its combination of double loop construction, at least the vehicle count measurement should be fairly accurate. The collected data from this station were used as the baseline to compare to those measured by other sensing devices on the eastbound lane.

The traffic data station was a joint effort between InfoTek Wireless[2] and Caltrans District 10. They created a customized solution combining the InfoTek Wizard hardware, its Intelligent Loop Detection Application (ILDA) firmware, and data collector middleware to solve its several identified problems and to provide near real-time performance measurement data.

The new low-cost platform enabled District 10 to provide near real-time data directly for the Freeway Performance Measurement System [15-16], developed in cooperation with the University of California at Berkeley and other partners; it allowed for data sharing with Traffic Census, not previously achievable; it facilitated the capture of much more detailed and extensive traffic data; it made possible the archiving of traffic data; and it provided an upgrade to the Caltrans Automated Warning System (CAWS). The project was undertaken as a long-term solution with a projected life of at least ten years.

Caltrans District 10's rollout of the InfoTek Wizard platform advances its use of a cutting edge, bi-directional GPRS intelligent modem for wireless data collection and M2M communication, its ILDA software and middleware for collecting, analyzing and archiving more precise data (including actual speed, occupancy, and classification of individual vehicles on a lane-by-lane basis), and its Web-based, user-intuitive GUI interface—all rolled out over existing infrastructure.

By using existing infrastructure down to the cabinet level, significant cost savings were realized, and the solution was able to be implemented very quickly, requiring minimal installation procedures and, being a wireless solution, no laying of costly cable or complex wiring. Once the new data was in place, it immediately began providing data that helped the Caltrans meet its PLAP (Program Level Action Plan) goals for improving safety and mobility for California's travelers.

With the InfoTek Wizard platform, Caltrans District 10 is achieving a level of performance not possible with the previous system. First, the system allows for the capture of a much higher level of detail in traffic data. Then, that traffic data is now archived and is being analyzed to improve safety and mobility within the system. Finally, in addition to capturing traffic data, the system monitors the health of the components. When a component fails, rather than sending a field engineer to examine 15 miles of highway until he determines which site and which component is faulty, the InfoTek Wizard platform detects the faulty component and almost instantly notifies the specified Caltrans District 10 employees by email and pager. The engineer can often even repair the failed component remotely. The result is significantly shorter downtime, and a reduced number of and reduced duration for field service trips. The bottom line is exponential cost savings, time savings and increased efficiency.

In addition to the projected benefits of implementing this system, Caltrans District 10 experienced some unanticipated side benefits. The cutting-edge Java-based technology employed by the InfoTek Wizard hardware means that more than 12 InfoTek Wizard units can be deployed in the space formerly occupied by one 170 collector. This saves storage space, as well as time and effort for installation and maintenance personnel. Further, Caltrans District 10 has achieved

---

[2] http://www.infotekwireless.com/

substantive, measurable power savings of up to 50% by employing the InfoTek Wizard platform, which uses only milliamps per unit, compared to the old hardware that used several amps per unit.

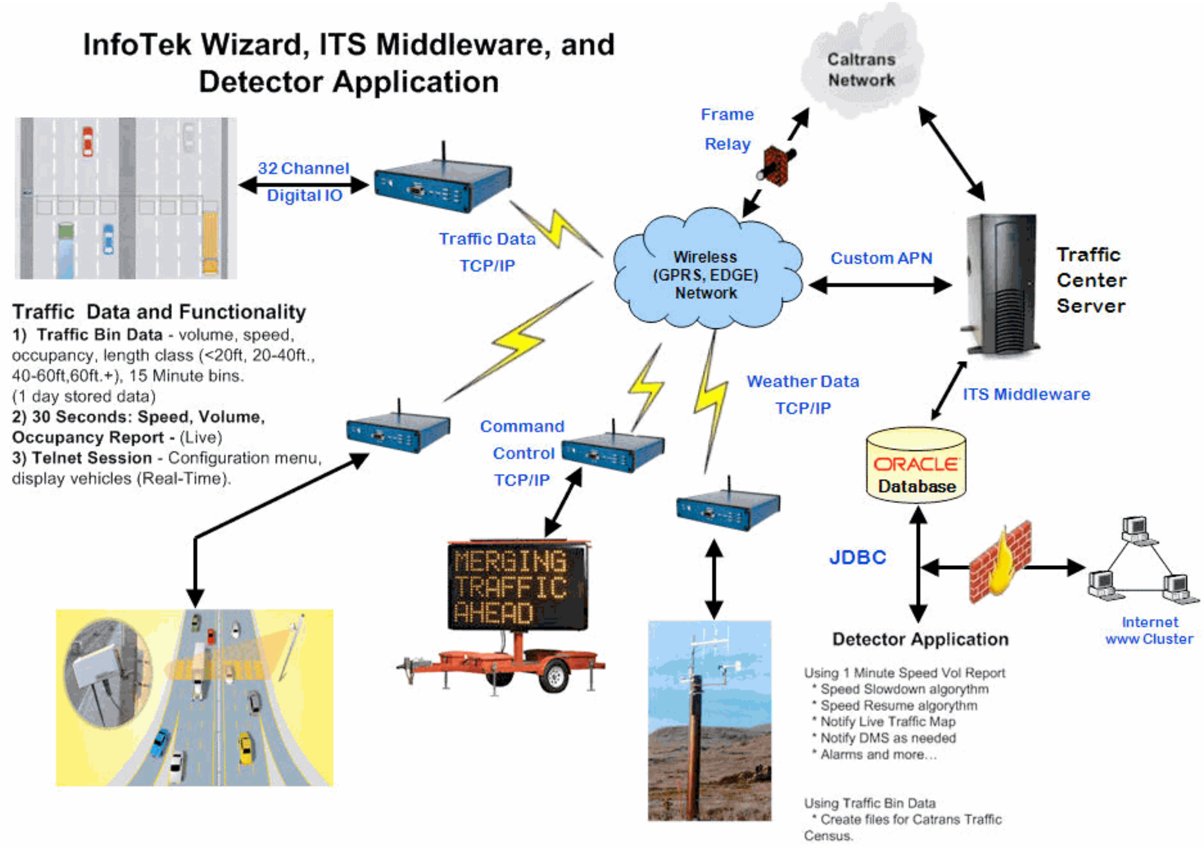


Figure 15 Schematic diagram Infotek Wizard in an Integrated System

The schematic diagram in Figure 15 depicts the interaction of Infotek Wizard with other system components in an integrated system (Courtesy of Mike Poursartip of Infotek Wireless)

3.1.2 3.3 Traffic Monitoring Devices

RWASS *EVT-300* *NC-200* *Trans-Q*

Figure 16 Devices Used in Data Collection for Technical Evaluation

For the data collection task, an industrial computer (PC-104) system was developed and interfaced with a traffic monitoring radar and an ASE equipment to record synchronized data. Four different types of sensors shown in Figure 16 were jointly used in the field experiments [17-18].

The sensor suite used in the filed included:

- Road Working Area Safety System (RWASS manufactured by *Sensys Traffic*[3] *AB, Sweden,* and provided by Road-Tech, a subcontractor to California PATH in this project.
    - The Road Working Area Safety System (RWASS) is designed to operate in a work zone, based on the Mobile Speed Safety System.
    - It warns drivers for excess speeding, alarms road workers of potentially dangerous situations, and enforces should the speeding driver choose not adapt to the applicable speed limit.
    - It reports the time, speed, distance, and direction of the target. Besides using a radar sensor to detect speeding targets, it is also equipped with a camera to capture the image of violators.
    - RWASS is equipped with photograph capabilities to record events triggered by speeding vehicles. However, **the camera was disabled** during the field tests to alleviate privacy concerns. The triggering signal was kept active to provide synchronization pulses to the PC-104 for the data-acquisition process.
- EVT-300 TM (*Eaton-Vorad Technologies*)[4] Tracking Radar
    - The 24-GHz EVT-300 is offered by Eaton-Vorad that utilizes mono-pulse radar technology in conjunction with state-of-the-art digital signal processing.
    - This is target-tracking radar functioning as part of a forward-looking collision warning system. It is mainly developed and used by freight vehicles to alert drivers of imminent collisions. In the year of 2007, a newer version of radar, VS-400, came to the market and the older version is no longer available off the shelf. In this study, it is still applicable and the radar was included to acquire target data to be compared with those outputs by RWASS.
- Nu-Metrics NC-200 TM (*Quixote Technology*)[5] Traffic Sensors
    - NC-100/200 is a portable traffic analyzer designed to be placed directly in the traffic lanes to provide traffic data.
    - The NC-100/200 utilizes Vehicle Magnetic Imaging to detect vehicle count, speed and classification.
- Trans-Q TM (*Quixote Technology*)[6] Radar Traffic Classifier
    - The *trans*-Q is designed for non-contact measurement of traffic flows.
    - It utilizes a Doppler radar to detect traffic count, speed, and length.
    - It is capable of reporting traffic data for two-direction roadways with one lane in each direction.

---

[3] http://www.sensys.se/

[4] http://www.roadranger.com/Roadranger/productssolutions/collisionwarningsystems/index.htm

[5] http://www.qttinc.com/pages/nc200.html

[6] http://www.qttinc.com/newproducts/trans-Q.html

3.1.3 Equipment Configuration and Layout

A schematic diagram in Figure 17 depicts the arrangement of equipment.

- The Caltrans traffic data station is located 250 feet (75 meters) upstream of the RWASS location.
- RWASS and EVT-300 were set up on roadside with the radar antennas oriented to the upstream direction to cover oncoming traffic.
- A trailer equipped with solar panels and batteries was located further from traffic lanes to provide power supplies for RWASS and EVT-300.
- Trans-Q was mounted on a pole attached to the trailer. This unit is oriented in a 45-degree direction opposite from the other radar. The trans-Q lateral position was located within 30 feet from the centerline of the near traffic lane.
- Four NC-200 devices were installed on the near lane using adhesive tapes. The four sensors were arranged sequentially to acquire data at different distances relative to the radar location.
- A data acquisition computer was stored inside the trailer box. A synchronization signal is provided by RWASS to EVT-300 data computer whenever RWASS was triggered by a speeder traveling over the pre-determined threshold.

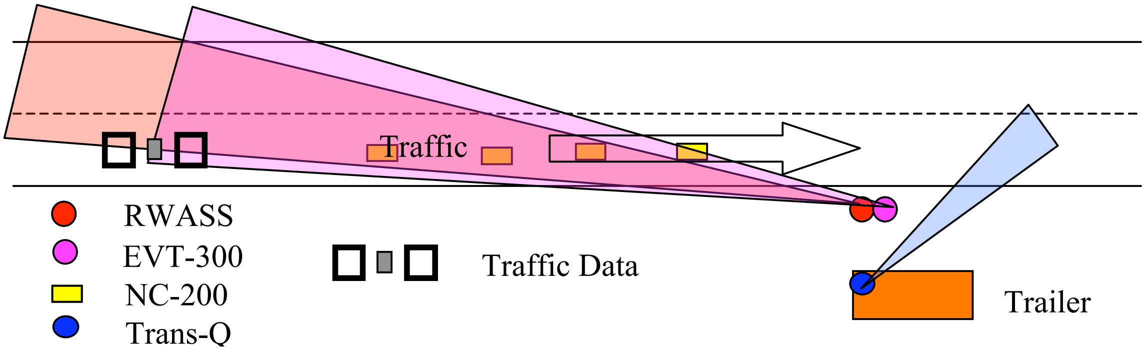


Figure 17 Layout of Equipment Setup at Data Collection Site

3.2 Summary of Data Comparison among Different Devices

A preliminary account of traffic data collected from the Caltrans data station and other traffic monitoring devices has been reported in an earlier publication [17]. This section first provides a review of the results and the conclusions reached from field observations in July 2008 on State Route 12. This roadway has a posted speed limit of 55 mph, while the threshold for screening for high-speed traffic was set at 65 mph in the following sample data.

3.2.1 SR-12 Caltrans Traffic Station

Caltrans has a traffic monitoring station near Post-Mile 5.6 of Route 12, close to the data collection site. At this station, a pair of in-ground loops is spaced by 12 feet (3.6 meters) with a piezoelectric sensor in between. The double loops and the piezoelectric sensor are combined to provide vehicle count, speed measurement, vehicle length, and axle spacing for each passing vehicle. The data collected data from this station were used to compare to those measured by other sensing devices on the eastbound lane.

An exemplar set of data from one day (July 16) is illustrated below. Figure 18 displays the measured speed of each passing vehicle on the left chart and the speed distribution on the right. For this particular day, 274 out of 8499 (3.22%) vehicles were passing at speed higher than 65 mph (29.1 m/sec).

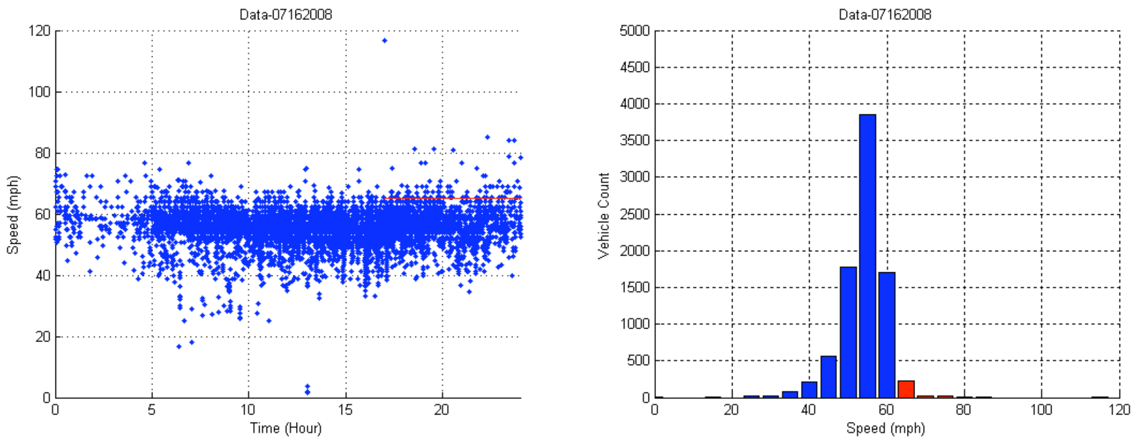


Figure 18 Caltrans - Speed of Passing Vehicles in One Day and Overall Distribution

Figure 19 displays the data from the same day the measured vehicle length of each passing vehicle on the left chart and the length distribution on the right. For this particular day, 1550 out of 8498 (18.24%) vehicles were has a length greater than 40 feet (12.2 m/sec), indicating a significant ratio of heavy-duty vehicles on this route.

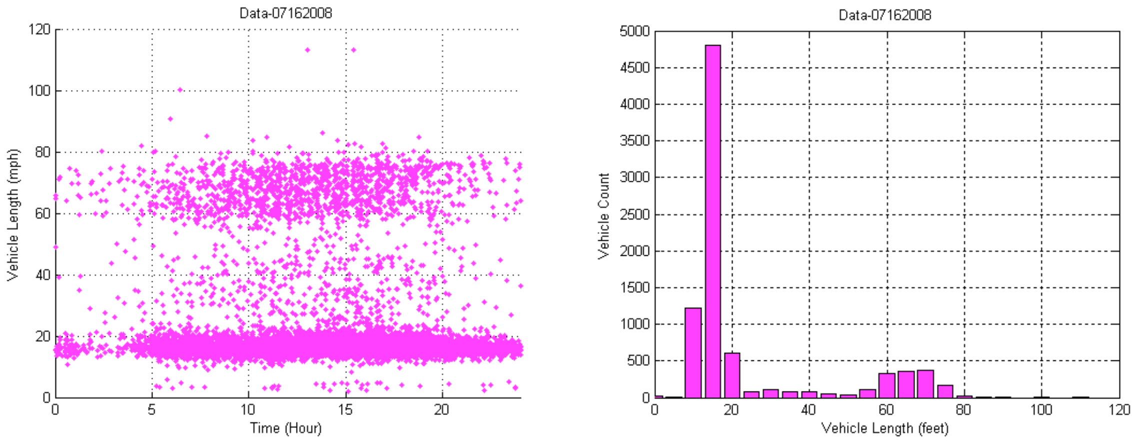


Figure 19 Caltrans - Length of Passing Vehicles in One Day and Overall Distribution

The Caltrans traffic station was activated throughout the study period, but was intermittently turned off for maintenance reasons for the later part of the week. Table 3 shows the vehicle counts and the percentage of speeders for 5 consecutive days. Note that in the last two columns, for July 19 (Saturday) and July 20 (Sunday), the percentages of speeding vehicles are much higher than the other days. In particular, the ratio of speeding vehicles is the lowest on Friday, when the traffic was the heaviest. Additionally, the total and speeder counts are also listed for the night time hours, midnight o 6 in the morning. There is a significant increase in the ratio of speeding vehicles during this period.

Table 6 Caltrans Data Station Data Summary

Date	07-16	07-17	07-18	07-19	07-20
Vehicle Count	8499	8861	9732	8898	7127
Vehicle Counts of Speed > 65 mph	274	272	243	452	366
Percentage of Counts > 65 mph	3.22%	3.07%	2.50%	5.08%	5.14%
Night time (Hours 0-6)					
Vehicle Count	466	454	515	408	350
Vehicle Counts of Speed > 65 mph	57	46	57	69	62
Percentage of Counts > 65 mph	12.23%	10.13%	11.07%	16.91%	17.71%

3.2.2 RWASS

RWASS was activated throughout the collection period of one week. However, only 4-plus days of data were collected due to vandalism and loss of power supply. The triggering threshold for RWASS was set at 65 mph, 10 mph higher than the speed limit, to take into account that the traffic flow in this region generally moves at a speed higher than the speed limit. Out of 22,849 targets detected by RWASS, the system registered 671 times (2.9%) of speeding records for vehicles traveling at 65 mph or higher.

Figure 20 shows the measured speed of targets detected by RWASS on July 16. The left chart plots the instantaneous speed of each passing target when the target is 32 meters (106 feet) from the radar antenna. Generally, RWASS begins tracking targets from a range of 100 meters. The right chart depicts the distribution of speeds among all targets on the same date.

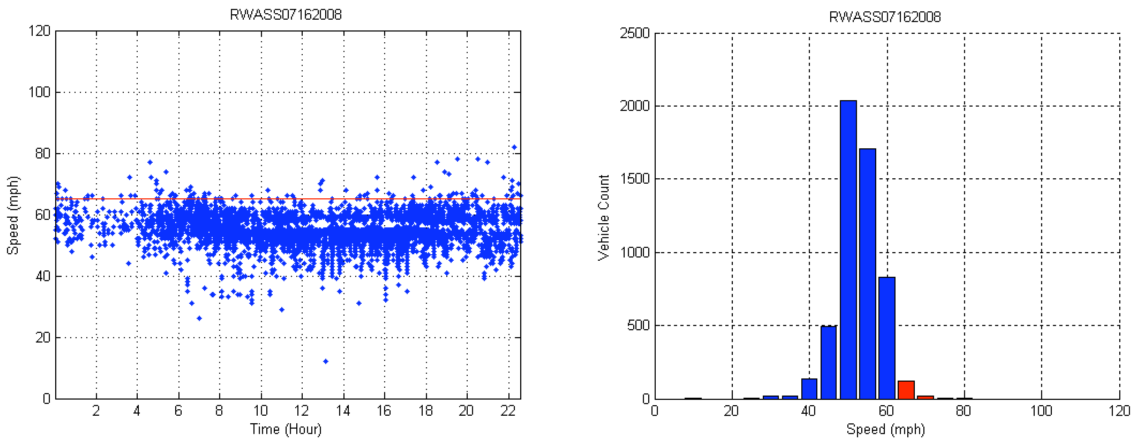


Figure 20 RWASS - Speed of Passing Vehicles in One Day and Overall Distribution

Table 7 RWASS Data Summary

Date	07-16	07-17	07-18	07-19	07-20*
Vehicle Count	5373	5471	6124	5560	321*
Vehicle Counts of Speed > 65 mph	144	130	131	221	45*
Percentage of Counts > 65 mph	2.68%	2.38%	2.14%	3.97%	14.00%*
Night time (Hours 0-6)					
Vehicle Count	402	380	406	308	273
Vehicle Counts of Speed > 65 mph	32	27	38	41	38
Percentage of Counts > 65 mph	7.96%	7.11%	9.36%	13.31%	13.92%*

Table 7 lists the total vehicle counts for 5 days and the percentage of speeders. Note that on the column of July 20 (Sunday), the system was only powered for the midnight and early morning hours, thus the vehicle count was low. However, the ratio of speeders in this nighttime period was quite high.

3.2.3 NC-200

Four NC-200 surface sensors were mounted in sequence on the eastbound lane at the test site at Positions A-D. Position A was approximately 10 meters west of RWASS, and B, C, And D are further upstream along the approaching traffic lane in approximately equal spacing. Sensor D was damaged during the experiment, thus only data from the other three are shown. Among the three sensors, Sensor B appears to contain abnormal and offset data, probably due to installation errors or device malfunctioning. Position C was found to have the most consistent and best matching data when compared with the Caltrans Data Station.

Table 8 NC200 – Position C Data Summary

Date	07-16	07-17	07-18	07-19	07-20
Vehicle Count	8457	8769	9658	8793	7739
Vehicle Counts of Speed > 65 mph	271	255	222	368	333
Percentage of Counts > 65 mph	3.20%	2.91%	2.30%	4.19%	4.30%

Table 8 shows the vehicle counts and percentage of speeders with data from Sensor C for 5 days. The ratio of vehicles traveling at 65 mph or higher ranges between 2.30% to 4.30%. The weekend days have higher ratios, and Friday again exhibits the lowest ratio with the highest traffic volume.

In Figure 21, the distribution of measured speeds and vehicle lengths are given for July 16, the same day as those illustrated in the section above. Among the three sensors, Sensor B appears to contain abnormal and offset data, probably due to installation errors or device malfunctioning. Position C was found to have the most consistent and best matching data when compared with the Caltrans Data Station.

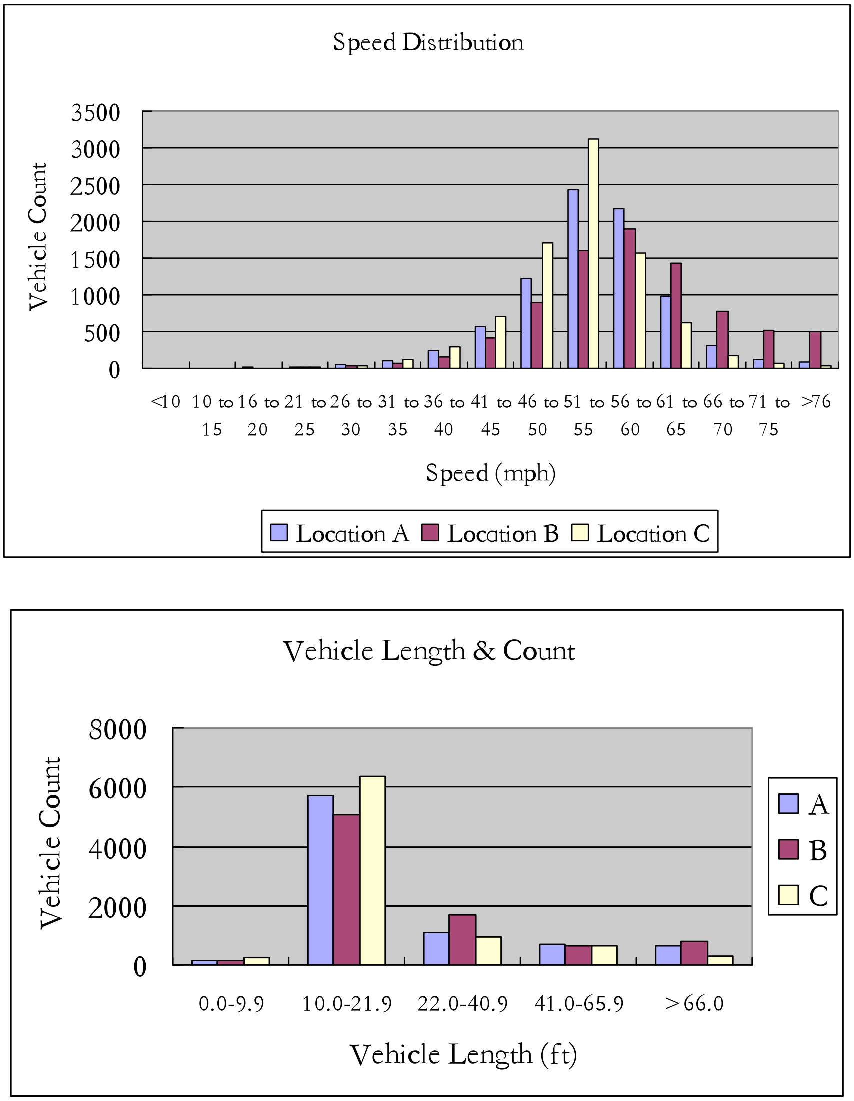


Figure 21 NC200 - Distribution of Vehicle Speed and Length in One Day

3.2.4 Trans-Q

Trans-Q is capable of detecting traveling targets in two directions in a two-lane highway. During the field experiment, Trans-Q was oriented in an opposite direction from RWASS to avoid electro-magnetic interference. Overall, Trans-Q appeared to have under-estimated the speeds of passing vehicles, and the speed distribution is shifted to the left side of the scale.

Table 9 shows the vehicle counts and percentage of speeders with eastbound-lane data from Trans-Q for 5 days. The ratio of vehicles traveling at 65 mph or higher ranges from 0.35% to 0.88%. This range is considerably lower than those from the other measurement systems. However, the weekend days still have higher ratios, and Friday again exhibits the lowest ratio with the highest traffic volume.

Table 9 TransQ Data Sumamry

Date	07-16	07-17	07-18	07-19	07-20
Vehicle Count	8610	8941	9844	8967	7814
Vehicle Counts of Speed > 65 mph	56	42	34	74	69
Percentage of Counts > 65 mph	0.65%	0.47%	0.35%	0.83%	0.88%

In Figure 22, the data of July 16 as those in previous sections are plotted for both eastbound and westbound lanes. The eastbound data from Trans-Q correspond to those measured by the other devices.

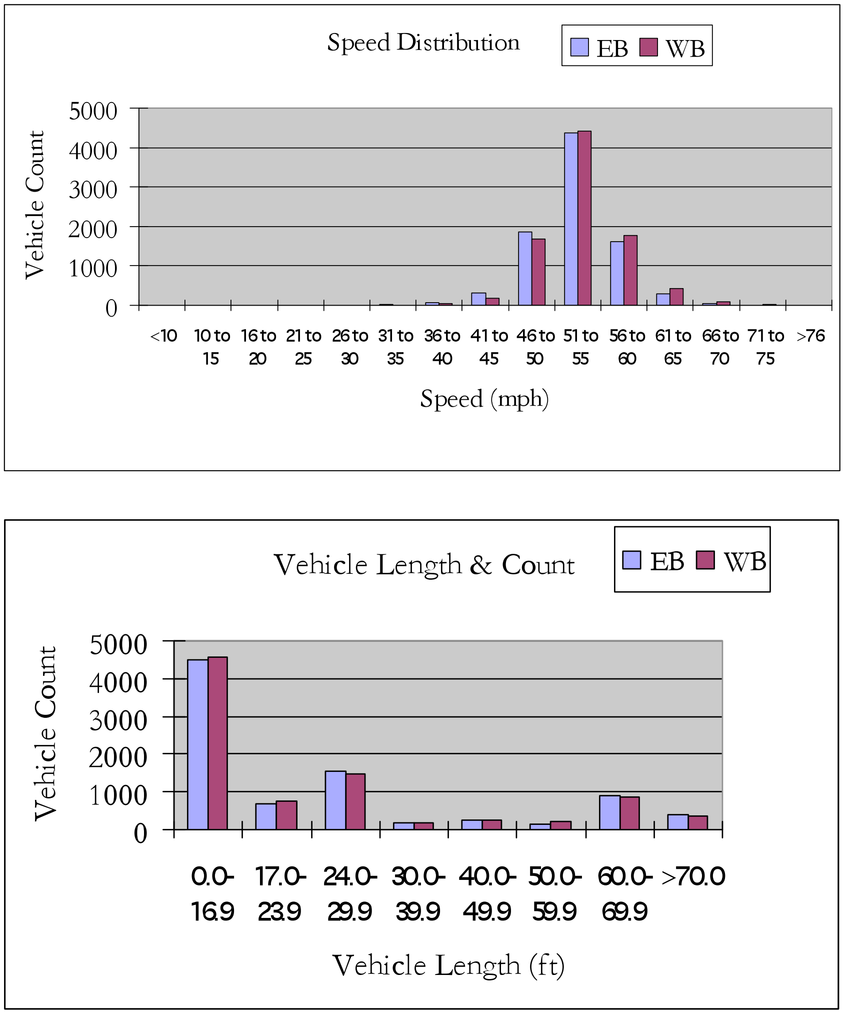


Figure 22 TransQ - Distribution of Vehicle Speed and Length in One Day

3.2.5 Summary of Data Analysis and Performance of Sensor Suite

Based on an overall review of data from various traffic monitoring systems, the following observations were made:

(1) The Caltrans Traffic Data Station is considered the most reliable data source and used as the baseline for comparative analysis.
(2) The other surface-based sensing devices, NC-200, have vehicle counts most compatible with the Traffic Station.
(3) RWASS underestimates the count of passing vehicles due to its relatively low mounting position at approximately one meter and occlusion of some vehicles in traffic streams.
(4) Trans-Q has vehicle counts compatible with Traffic Station and NC-200, but it appears to have underestimated speed measurements.
(5) Despite the differences in vehicle counts, several data sources provided very compatible estimates of speeder population in the range of 2-3 % on weekdays and 4-5% on weekends.
(6) During the nighttime hours, the ratio of vehicles increased several folds to the range of 7-10 % on weekdays and 14-17% on weekends.

3.3 Data Association and Comparative Analysis of Speed Measurements

This section describes the work that carried out for in-depth investigation of speed measurements with different sensing devices. The techniques of signal processing and statistical analysis are applied to the data described in the previous section to investigate the performance of speed measurements provided by RWASS, with the Caltrans data station serving as the baseline. There are mainly two tasks performed in order to analyze and compare the RWASS and Caltrans loop sensor data. One is data synchronization and the other is data association. Descriptions of the techniques and the results are given in the following sections.

3.3.1 Synchronization and Association of Data Series

Since the time stamps of data sequence for RWASS and Caltrans loop sensors were set separately in experiments, the data of the two systems need to be synchronized through post-processing. After synchronization, data association between the two data sets can be performed for further data analysis.

Although the RWASS and loop sensor have quite different sensor characteristics in terms of accuracy, sensitivity, robustness, and sampling rate, etc. due to the sensors' intrinsic properties, the two data sets should exhibit similar traffic pattern/dynamics. Based on this concept, cluster analysis and pattern recognition were conducted to identify the time lag between the two data sets. An example of the synchronization result is shown in Figure 23. Figure 23 (a) and (b) show the speed versus time data before and after synchronization, respectively. It can be observed that without synchronization, the two data series do not match in time. On the other hand, the synchronized data sequences have corresponding data points that line up reasonably well side by side.

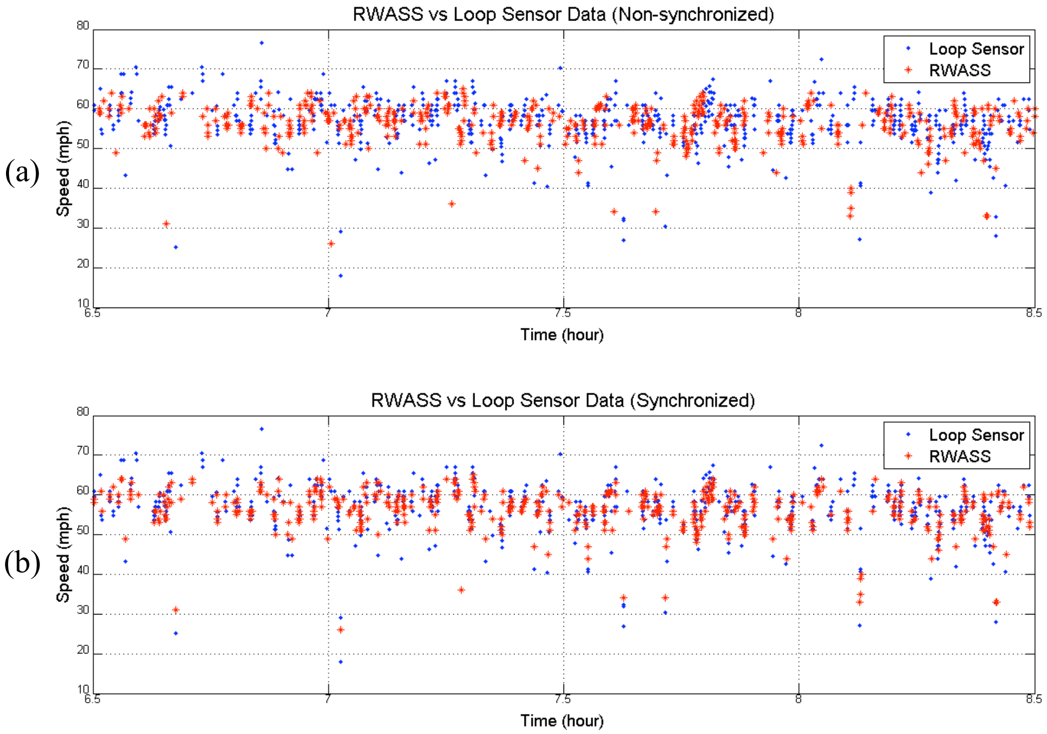


Figure 23 RWASS and Caltrans Loop Sensor Data: (a) Non synchronized (b) Synchronized.

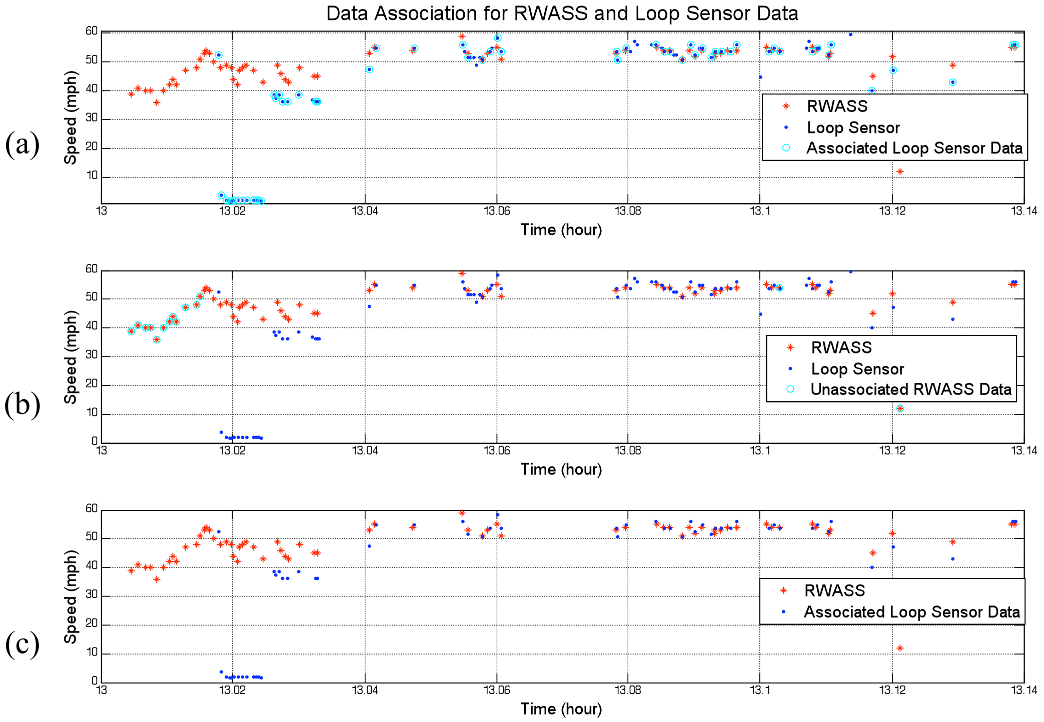


Figure 24 Data Association for RWASS and Caltrans Loop Sensor Data.

Figure 24 shows an example of the data association for RWASS and loop sensor. Theoretically, the missed detection rate of RWASS is higher than the Caltrans loop sensor due to missed targets that were occluded by leading vehicles. Therefore, the total vehicles detected by RWASS can be regarded as a subset of the total vehicles detected by Caltrans loop sensor. Also, each data value represents a different vehicle. As a result, for each RWASS data value, there exists only one corresponding value in the loop sensor data.

After data synchronization, data association between RWASS and loop sensor data is carried out based on the proximity in time. Namely, for each RWASS data point, the closest (in time) loop sensor data point is chosen as the "associated" loop sensor data point representing the same vehicle detected by RWASS and loop sensor. As shown in Figure 24(a), the light blue circles represent the loop sensor data that have been associated with the RWASS data. Figure 24(b) shows the same data association result, but the light blue circles represent the RWASS data which are not able to be associated with any loop sensor data. The lack of associated loop sensor data for the RWASS data might be due to either the missed detection of the loop sensor or the sensor error of the RWASS. Thus, these RWASS data are excluded in our data analysis. Figure 24 (c) shows all RWASS and associated loop sensor data. It can be seen that the occurrences of the associated loop sensor data points and their corresponding RWASS data points match quite well although there are some RWASS data not being able to be matched to any loop sensor data.

3.3.2 Speed Differential Distribution

More in-depth analysis of the data from RWASS and ground-loop data station was conducted. The following figures use the sample set from July 19 as a case study to illsutrate the results from the analysis. Figure 25 provides an hour-by-hour count of data points for the two data series from RWASS and Caltrans data station. It can be seen that the RWASS consistently lags in vehicle counts, and it is most obvious during the day time when traffic is heavy.

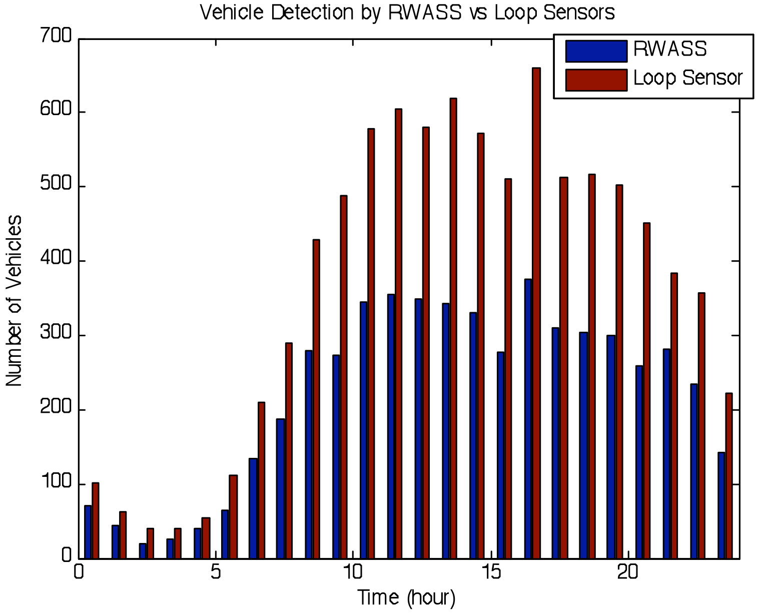


Figure 25 Vehicle Detection Counts by RWASS and Loop Sensor

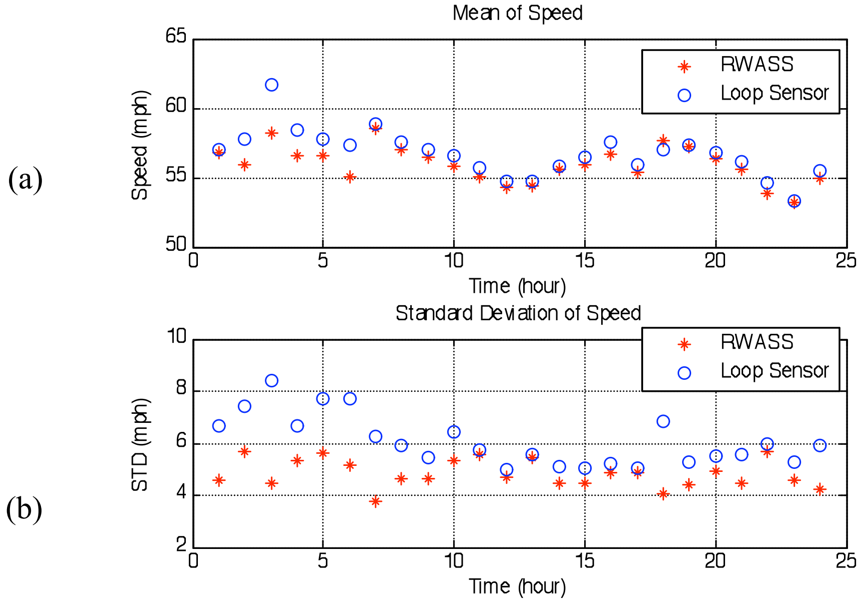


Figure 26 RWASS and Loop Sensor Speed Data Analysis. (a) Mean Value of Speed (b) Standard Deviation of Speed.

Once data association is carried out on the two sequences, the speed differential can be obtained for each associated pair. The statistical mean and standard deviation (STD) for the data sets in each one-hour period are then calculated. Figure 26 plots the mean and STD values for the 24-hour period. The mean values for the two data sources are quite close, especially in the day-time period. However, it can still be observed that the loop-based data have a slightly higher mean values. The differential becomes more amplified in the midnight hours. The standard deviations for the loop-based data also have a higher value than RWASS, which means that the range of values is wider for the loop-based data station.

Figure 27 shows the relation between Speed Difference and Vehicle Class, where Speed Difference is defined as (RWASS speed – Loop Sensor speed), and Vehicle Class is determined based on vehicle length estimated by Caltrans data station. Vehicle length is shortest for Class 1 and longest for Class 4. Figure 27(a) plots the speed differential for all associated pairs for the 24-hour period. Figure 27(b) and 27(c) shows the mean and STD of speed differential for this data set. It can be seen that both the mean and STD decrease as the vehicle class/vehicle length increases.

Figure 28 shows the relation between Speed Difference and the measured vehicle speed. It appears that the discrepancy between the RWASS and Loop Sensor speed measurements is larger at extreme low speeds. In other words, it is possible that the measurements of either RWASS or loop-based stations become unstable at the very low-speed range.

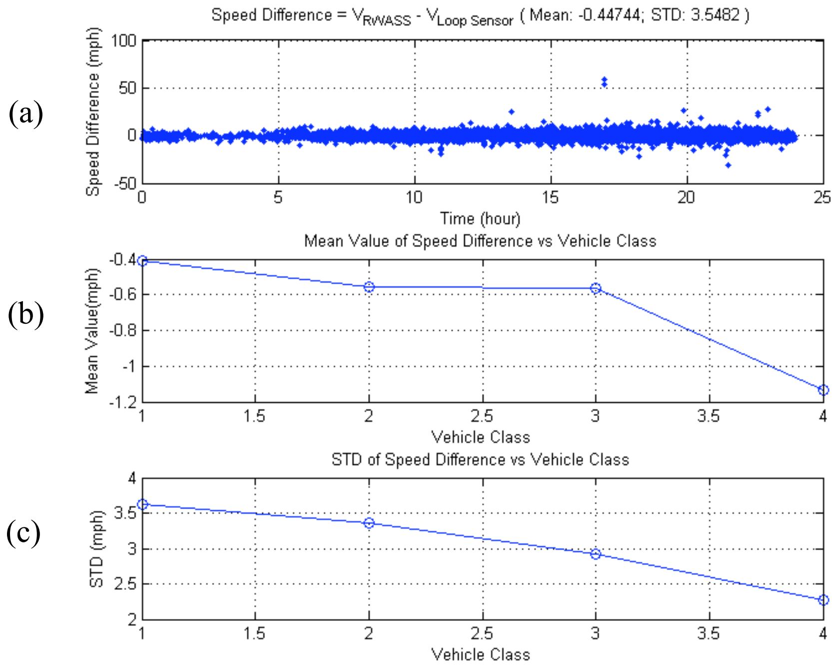


Figure 27 Analysis of Speed Difference versus Vehicle Class. (a) Speed Difference (b) Mean of Speed Difference (c) Standard Deviation of Speed Difference.

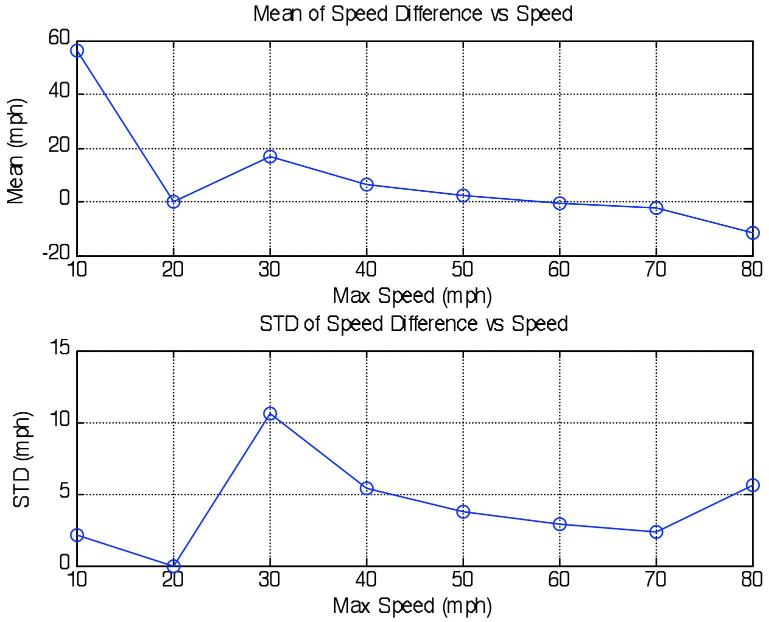


Figure 28 Analysis of Speed Difference versus Speed. (a) Mean of Speed Difference (b) Standard Deviation of Speed Difference.

Table 10 lists the parameters of data sets from four complete days of filed experiments. The range, maximum, minimum, mean and standard deviations are given. It can be seen that the results of analysis are consistent and stable across multiple data sets, which supports the validity of the approaches taken in data processing.

Table 10 Data Comparison of RWASS and Loop-Based Data Sets

Date (July 2008)	16th	17th	18th	19th
Number of Total RWASS Data	5230	5345	5996	5345
Number of Associated RWASS Data	5176	5312	5962	5316
Successful Association Rate (%)	98.97	99.38	99.43	99.46
Maximum Loop Sensor Speed (mph)	116.7	89.5	81.3	83.9
Minimum Loop Sensor Speed (mph)	1.7	2.3	15.3	4
Mean Value of Speed from Loop Sensor	55.61	55.72	54.41	56.2
STD of Speed from Loop Sensor	5.95	5.81	5.96	5.81
Maximum RWASS Speed (mph)	65	65	65	65
Minimum RWASS Speed (mph)	12	10	11	20
Mean Value of Speed from RWASS	54.49	54.72	53.48	55.72
STD of Speed from RWASS	4.91	5.09	5.58	4.98
Maximum Speed Difference (mph)	51.1	60.7	40.2	58.5
Minimum Speed Difference (mph)	-65.7	-33.9	-41.7	-31.6
Mean of Speed Difference (mph)	-0.53	-0.57	-0.34	-0.45
STD of Speed Difference (mph)	4.02	3.81	3.59	3.55
Mean Value of Associated Loop Sensor Speed (mph)	55.05	55.3	53.88	56.16
STD of Associated Loop Sensor Speed (mph)	6.31	5.99	6.27	5.87
Mean Value of Associated RWASS Speed (mph)	54.52	54.73	53.54	55.71
STD of Associated RWASS Speed (mph)	4.84	5.08	5.4	4.96

3.3.3 Concluding Remarks on Data Association and Analysis

Data processing techniques, including synchronization and association, were adopted to investigate in depth the speed measurement discrepancies between the selected ASE equipment and a ground-loop based data station, which was taken as the baseline with the consideration of its prior validation and calibration. The speed enforcement unit tends to yield a lower measured value of speed measurement, with a mean differential of less than 1 mph. The standard deviation of the speed differential is between 3 to 4 mph.

The results from the field experiments revealed that traffic speed measurements are likely to yield discrepancies. Since speed measurement consistency and accuracy are major concerns in the implementation of speed enforcement systems, it is critical that the operation of enforcement take into account the characteristics of field performance of such devices and set speeding thresholds accordingly. For a more robust and reliable system, it will also be desirable to utilize technical approaches to offer supplementary speed measurements.

4 FIELED EVALUATION OF RADAR-BASED SPEED MONITORING DEVICES FOR AN ENHANCED ASE SYSTEM

The last section describes the field evaluation of select ASE equipment, i.e., RWASS, carried out on the state highway (SR-12) in northern California. The results show that the RWASS tends to yield lower values of speed measurements than the speed data provided by Caltrans Traffic Data Station. However, the speed measurements of RWASS are quite consistent with Caltrans' data. The mean of speed differential is less than 1 mph, and the standard deviation is between 3 to 4 mph.

To further investigate the performance of select ASE system under different traffic conditions and the feasibility of enhancing ASE through system integration with additional traffic monitoring sensors, the tracking radar, EVT-300, was employed together with the RWASS in the field evaluation. Field experiments were conducted at study sites on two highways, Interstate 5 (I-5) and State Route 160 (SR-160), in northern California, where traffic conditions appeared to be different in terms of traffic volume, mean speed, posted speed limit, and number of lanes, etc. At the study site on I-5, the traffic volume is fairly high on the six-lane rural freeway, and speeding vehicles are frequently observed. Compared with the site on I-5, the mean speed, speed limit, and traffic volume are much lower at another study site on SR-160, where the roadway has only one lane in each direction.

Since the radar signals of traffic monitoring devices can be potentially affected by various environmental condition effects, the objective of this field evaluation is to assess the functional capabilities and limitations of select ASE equipment and tracking radar in different traffic conditions. The outcome of this study together with previous evaluations can provide recommendations and valuable information for further system enhancement of ASE equipment.

4.1 Technical Evaluation of Radar-Based Speed Monitoring Devices

With the advancements in sensing and communication technologies, a variety of traffic monitoring devices are becoming more affordable and feasible for massive deployment. Existing ASE systems generally consist of a radar or lidar speed detection unit and a camera that photographs vehicles exceeding a specified speed threshold. The speed detection unit must be able to detect a speeding target among a large group of vehicles. The high-accuracy Doppler radar speed sensor measures the speed of a vehicle by detection of the Doppler frequency shift, namely, the difference in frequency of the transmitted and received reflected signals. A lidar unit typically utilizes a narrow-beam laser to determine the range to an object by measuring the time delay between transmission of a pulse and detection of the reflected signal. The range rate, i.e., speed, of the target can thus be determined by using two consecutive range measurements.

In general, the radar unit is more susceptive to signal interference problems due to its greater beam width and the intrinsic property of radio waves. A laser beam is about 18-inch wide at 500 feet compared to a radar beam's width of some 150 feet. When using the Doppler effect to measure vehicle speeds, any moving object, not only the targeted vehicle, will generate a Doppler frequency shift. Another problem with the radar unit is signal reflections – the radar signals reflect on surfaces of static or moving objects and then return the same way back to the radar receiver. All these unwanted signals must be detected and filtered in real-time by the ASE system. Therefore, special signal processing algorithms are required to enhance the data integrity and accuracy of the ASE equipment. Moreover, advanced ASE systems utilize range and heading data to discriminate and to track different vehicles, so that the Doppler frequency based speed measurement can be validated by the range rate data.

Table 11 shows the technical data of adopted speed monitoring sensors. Compared with RWASS, EVT-300 can provide a larger range of distance measurements but a smaller range of speed measurements. Also, EVT-300 can measure the azimuth angles of tracked targets, which are not available from the RWASS, and this extra parameter can be potentially useful for improving the select ASE system. For example, it can be applied to removing the speed measurement error due to the "Cosine effect" and distinguishing the tracked speeding target from the surrounding vehicles.

Figure 29 illustrates the so-called "Cosine effect" in the radar speed measurements. Since the radar system measures the radial speed towards the receiver, the angle between the orientation of the radar beam and the vehicle's heading can result in a smaller speed measurement than the actual vehicle speed. Figure 29 (a) shows the raw speed data measured by EVT-300 versus the modified speed data by taking into account the Cosine effect. The measured azimuth angle ranges between -15 and +15 degrees (although the azimuth field of view claimed by the manufacturer is 12 degrees), and the resulting speed differential is between 0 to 4 mph as illustrated in Figure 29(b).

Table 11 Technical Data of Adopted Radar-Based Speed Monitoring Devices

	RWASS (RS240 Sensor)	EVT-300
Range of Speed Measurement	1.86-186 mph (3-300 km/hr)	0.25-100 mph
Operating Range: Arriving Vehicles	32.81-262.47 ft (10-80 m)	Average: 3-350 ft (Maximum: 500 ft)
Operating Range: Departing Vehicles	65.62-328.08 ft (20-100 m)	
Range Accuracy	N/A	5% ± 3 ft
Range Rate Accuracy	12.43-61.52 mph ± 0.62 mph (20-99 km/h ± 1 km/hr)	1% ± 0.2 mph
	62.14-186.41 mph ± 1% (100-300 km/hr ± 1%)	
Azimuth Field of View	N/A	12°
Azimuth Accuracy	N/A	± 0.2°
Transmitting Frequency	24.10 ± 0.025 GHz	24.725 GHz (1 MHz Bandwidth)
Transmitted RF Power	max 100 mW EIRP	3.0 mW (Typical)
Maximum Tracked Targets	8	20
Targets Per Updated Period	1	7
Target Update Frequency	47 ms	65 ms

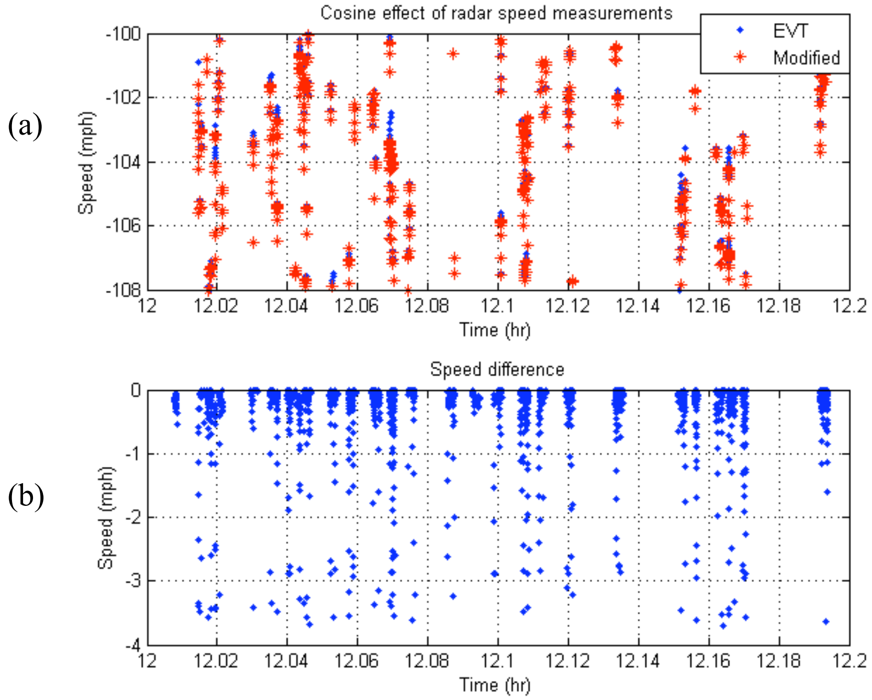


Figure 29 Cosine Effects of Radar Speed Measurements (a) Raw Speed versus Modified Speed Data and (b) Speed Differential

4.2 Equipment Configuration and Layout

Two field data collection sites were set up on the highways, I-5 and SR-160, as described below.

4.2.1 Field Data Collection Site on Interstate 5

On I-5, the study site was set up at the location close to a Caltrans Traffic Data Station. At this station, the duplex loops are combined to measure traffic data including the vehicle count, speed, vehicle length, and axle spacing for each passing vehicle. The Caltrans Traffic Data Station is considered a reliable data source because the station's data has been validated after installation. Even though no ground-truth measurements were available, the data provided by the Traffic Data Station were used as the baseline for evaluating the other traffic monitoring systems.

Figure 30 depicts the arrangement of the field experimental equipment at this study site, where the road has three lanes in each direction and the posted speed limit is 65 mph.

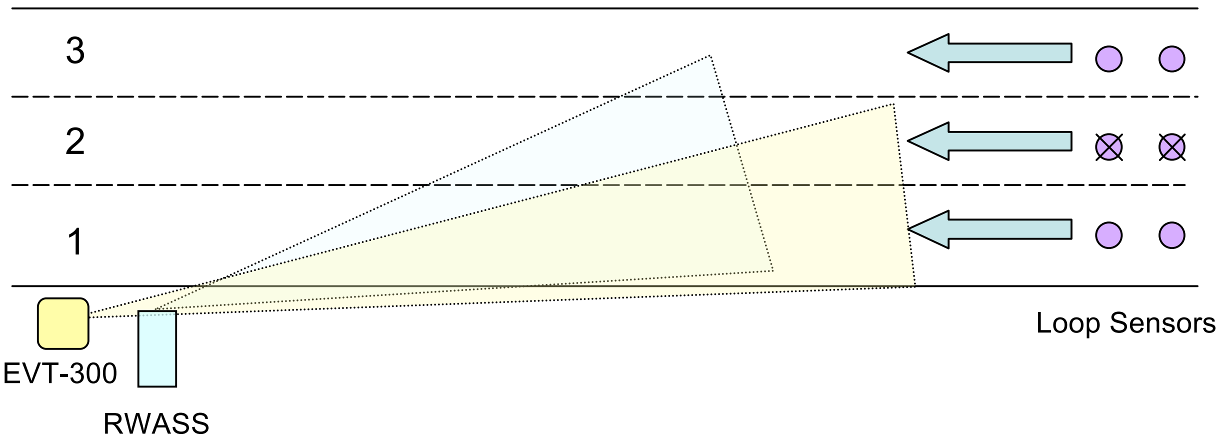
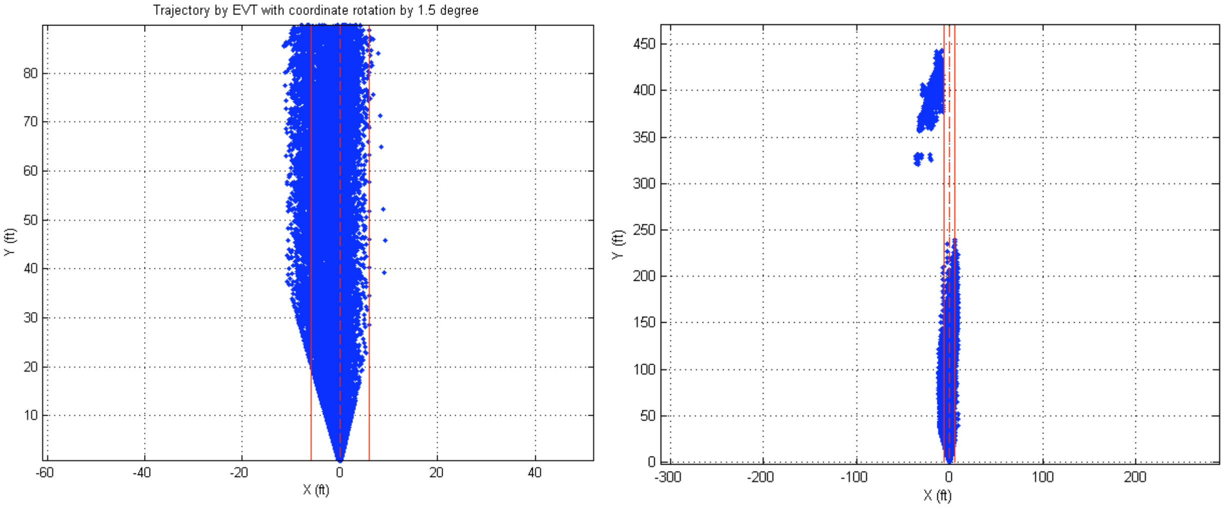


Figure 30 Layout of Equipment Setup at Data Collection Site on Interstate 5

- RWASS and EVT-300 were set up on the roadside, as close to the traffic lane as possible. The radar antennas were oriented to the upstream direction to cover the oncoming traffic.
- A data acquisition computer was used to record RWASS and EVT-300 data. A synchronization signal was provided by RWASS to record the corresponding EVT-300 data whenever RWASS detected a speeding vehicle traveling with a higher speed than the predetermined speed threshold.



(a) (b)

Figure 31 Vehicle Trajectories Recorded by EVT-300 (a) Lateral Range Coverage and (b) Longitudinal Range Coverage

Figure 31 shows the radar signal coverage of EVT-300. The solid and dashed lines stand for the boundaries and centerline of the inner lane, respectively. As illustrated in Figure 31(a), the radar signal covers the whole inner lane (lane 1) and the partial middle lane (lane 2) within the operation range, which can be as far as more than four hundred feet. However, due to the internal signal processing algorithm applied in the EVT-300 and the effect of antenna orientation with respect to the road heading, vehicle trajectories at the distance between 230 and 350 feet were not recorded as shown in Figure 31(b).

4.2.2 Field Data Collection Site on State Route 160

The second field data collection site was set up on California State Route 160. Figure 32 depicts the arrangement of field experimental equipment. RWASS and EVT-300 were set up on the roadside, as close to the traffic lane as possible. The antennas were oriented to the upstream direction to cover the oncoming traffic. A data acquisition computer was used to record the RWASS and EVT-300 data. In this field evaluation, RWASS only recorded one set of data (distance and speed) at one point in time for each speeding vehicle, but EVT-300 recorded a sequence of data (distance, speed, and heading) for all tracked vehicles. In addition, RWASS only reported speeding vehicles in the approaching direction (on lane 1) while EVT-300 reported tracked vehicles in both directions as illustrated in Figure 32.

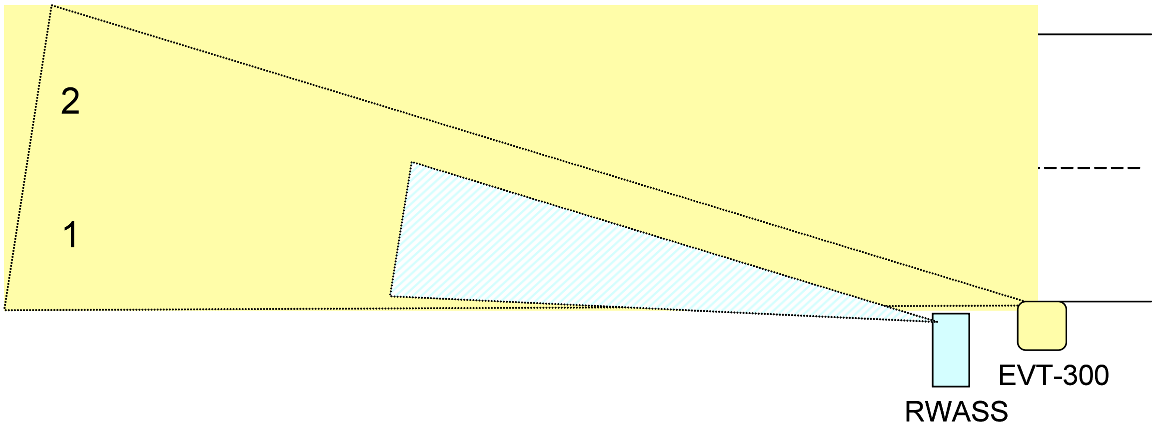


Figure 32 Layout of Equipment Setup at Data Collection Site on State Route 160

Figure 33 Data Collection Site on State Highway 160

Figure 33 shows the photo taken at this site, where the road has one lane in each direction and the posted speed limit is 30 mph.

4.3 Data Association and Comparative Analysis of Doppler Radar-Based Speed Measurements

Figure 34 shows the RWASS measurements recorded at the site on SR-160 on October 16, 2008, and Figure 35 illustrates EVT-300 data collected in the same day. As can be seen from the two figures, the signs of RWASS speed data are all negative, which indicates that reported vehicles were all approaching the radar antenna; however, the EVT-300 speed data include positive and negative values, and thus traffic in both directions were recorded.

As for the distance measurements, RWASS only reported a constant value, 106 feet, whereas the distance data of EVT-300 range from 0 to 500 feet depending on the actual target tracking range. Also, the azimuth angles measured by EVT-300 are between -0.1 and 0.25 radians. For each tracked target, an identification (ID) number is generated by EVT-300 and associated with other EVT-300 measurements. Therefore, the number of vehicles detected by EVT-300 is the number of different vehicle identification numbers.

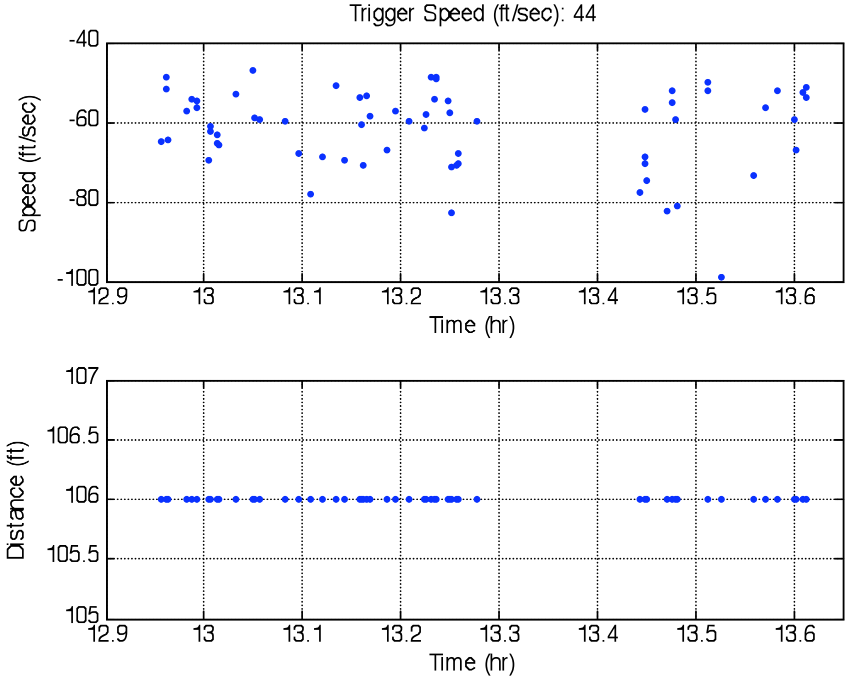


Figure 34 RWASS Measurements

Since the data of RWASS and EVT-300 were sent to the data acquisition computer separately and the two systems reported measurements at different frequency, data synchronization and association must be performed through post-processing for comparison. Novel sensor fusion techniques as described in the last section were applied in this evaluation.

The techniques of signal processing and statistical analysis are applied to evaluate and compare the performances of RWASS and EVT-300. Two main signal processing tasks are performed. One is data synchronization, and the other is data association. Descriptions of the techniques and analysis results are given in the following sub-sections.

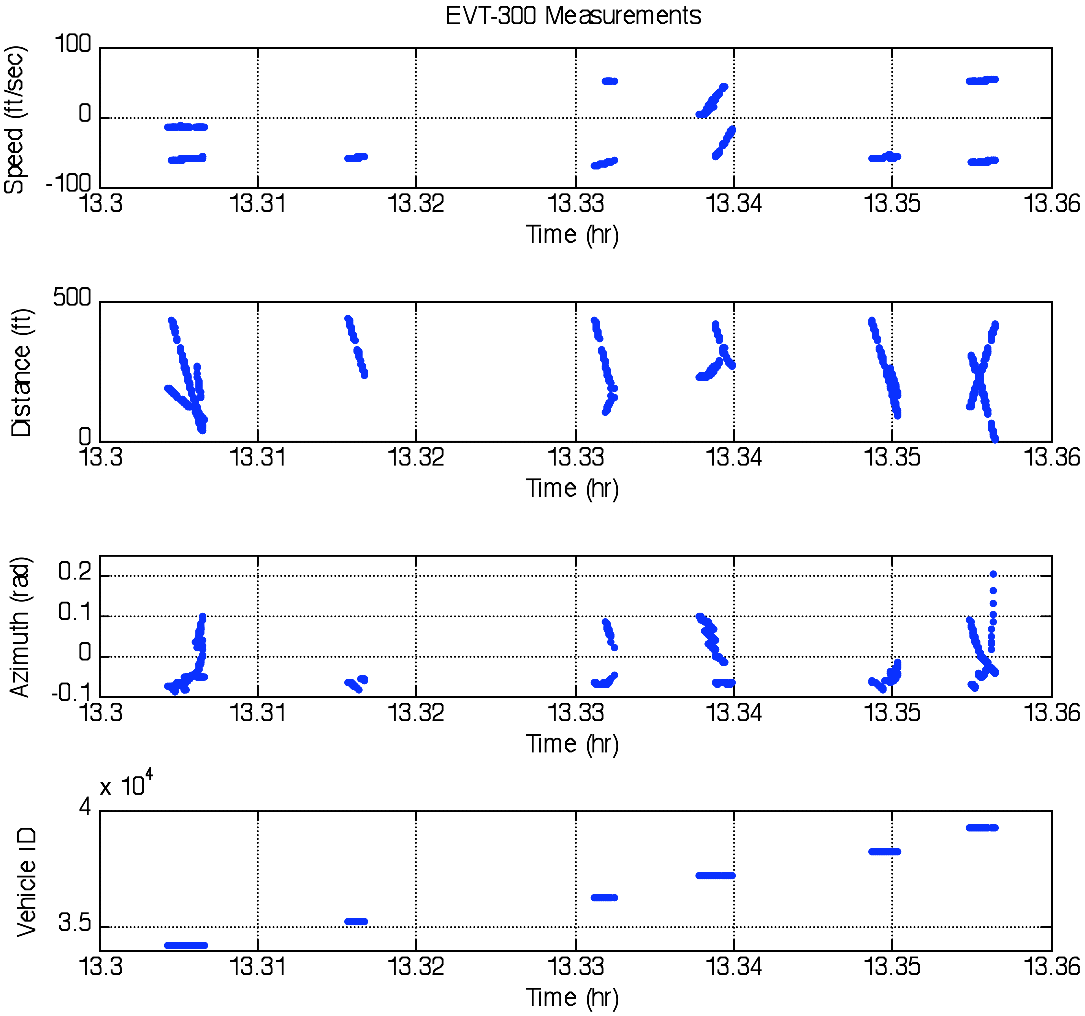


Figure 35 EVT-300 Measurements

4.3.1 Synchronization and Association of Data Series

Since the time stamps of RWASS and EVT-300 data were set independently in experiments, the data of the two systems need to be synchronized through post-processing. After synchronization, data association of the two data sets can be performed for further data analysis.

The data association algorithm developed in this work is based on the principle that two independent data series recorded by different sensors should exhibit similar traffic patterns or dynamics although the sensors may possess different functional characteristics. Therefore, through cluster analysis and pattern recognition the time lag between the two data sets can be identified. It should be noted that RWASS outputs only one speed measurement for each detected vehicle, but EVT-300 provides a sequences of speed data for the tracked target. Thus, the number of EVT-300 speed data for each tracked vehicle is much greater than that of RWASS speed data. Consequently, to identify the underlying traffic pattern and match the two data sets can be more difficult than the one-to-one mapping case.

An example of the data synchronization result is shown in Figure 36. The data were collected at the study site on I-5. Figure 36(a) and 36(b) shows the speed measurements versus time of two sensors before and after synchronization, respectively. It can be observed that the two data sets do not match in time without synchronization. The synchronized data sequences, however, appear to have corresponding data points that match each other reasonably well.

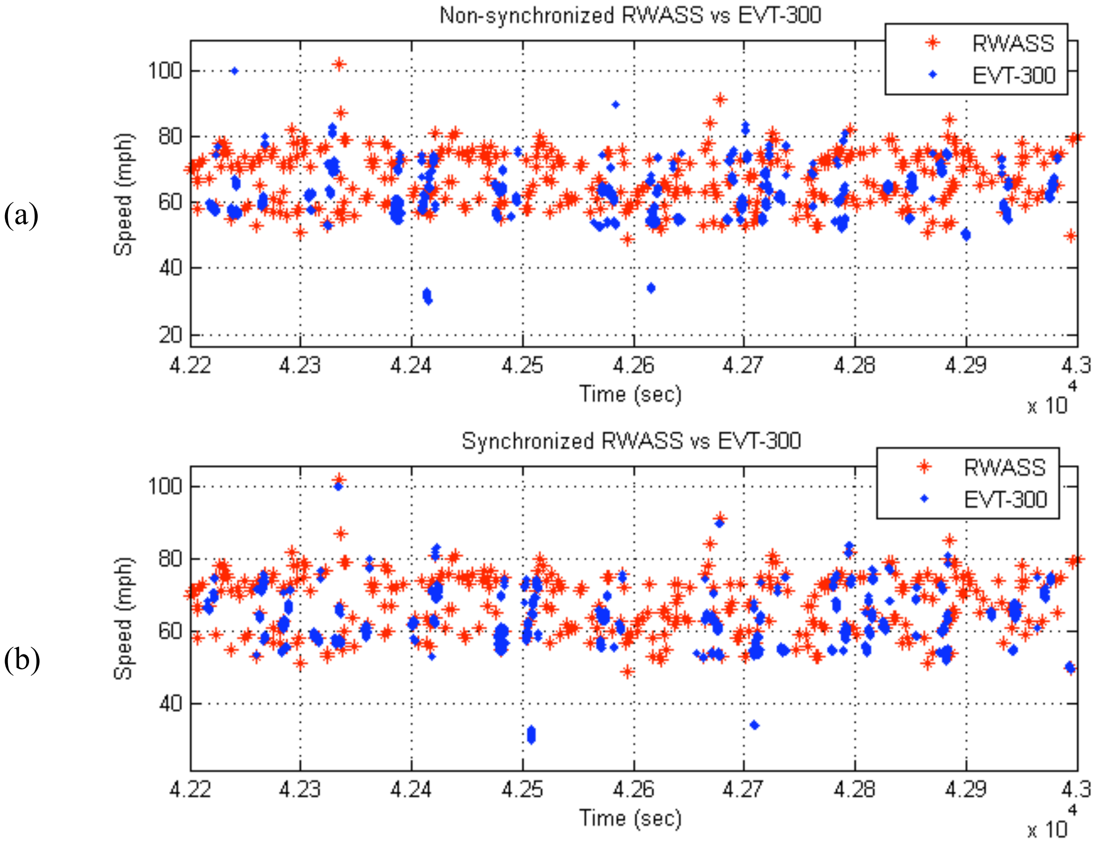


Figure 36 Synchronization of RWASS and EVT-300 Data Collected on I-5 (a) Non-synchronized and (b) Synchronized

Figure 37 shows an example of data association for RWASS and EVT-300. The data shown in this figure were the same as that in Figure 36. Since the EVT-300 was originally developed for the forward-looking collision warning system, the lateral detection range was desired to cover around one lane only to avoid possible signal reflection problems. Therefore, the internal signal processing algorithm of EVT-300 filters out the data of objects outside the desired detection range. Hence, the shape of EVT-300 signal coverage appears to be an incomplete cone as illustrated in Figure 31(b).

On the other hand, the RWASS has a wider detection range , which can cover more than one or two lanes. As a result, the number of vehicles detected by RWASS can actually be more than that by EVT-300. Due to this reason, the set of total vehicles detected by EVT-300 can be regarded as a subset of the total vehicles detected by RWASS in the data association algorithm. Also, note that for each passing vehicle that was detected both by RWASS and EVT-300, there was only one set of RWASS measurements, S_{RWASS} (time, distance, speed), but more than one set of EVT-300 measurements, $S^{i}_{EVT\text{-}300}$(time, distance, speed, azimuth), $i \geq 1$. Thus, the objective of data association is to pair one RWASS data set and one element of EVT-300 data sets of each vehicle, in which the time and distance data measured by two systems are closet to each other.

As illustrated in Figure 37, each pair of associated RWASS and EVT-300 speed data are quite close to each other, in particular, for speed values greater than 70 mph.

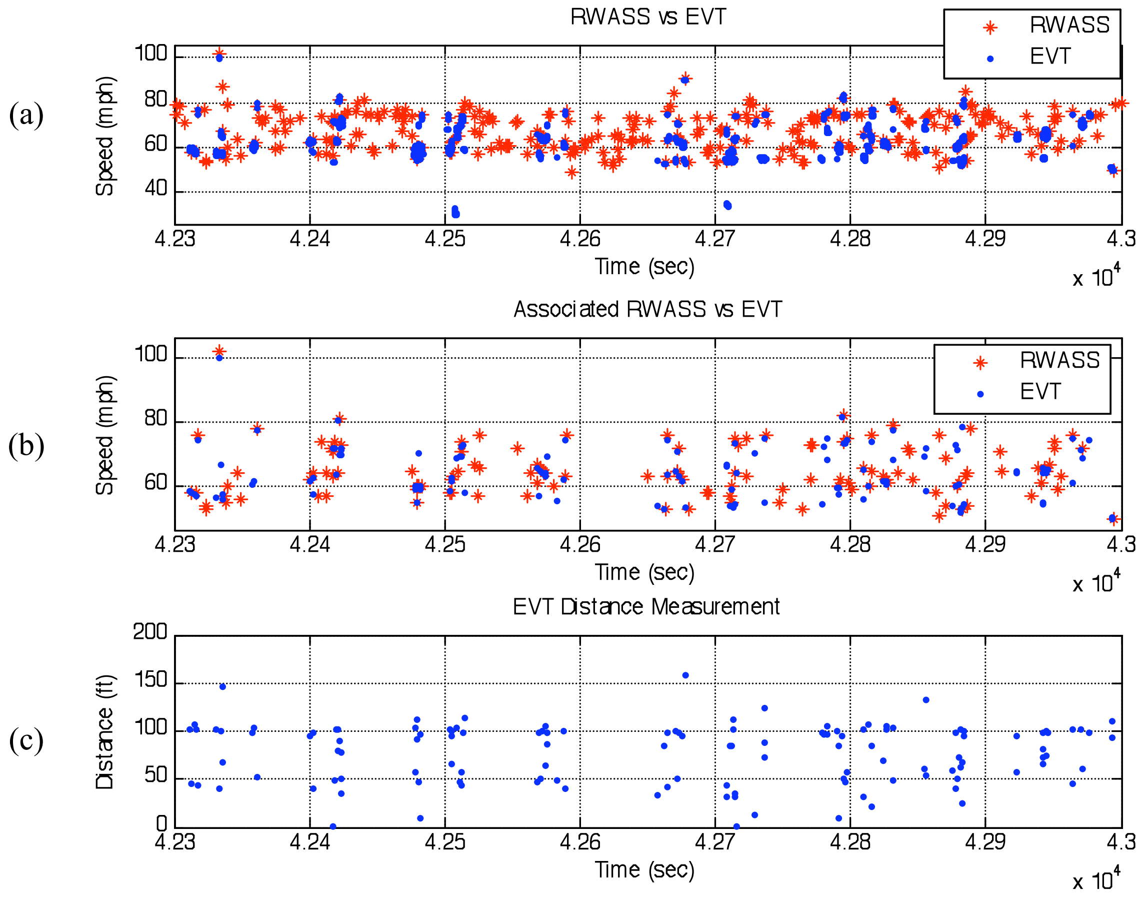


Figure 37 Data Association for RWASS and EVT-300 Data Collected on I-5

Figure 38 illustrates the data association result using the field data collected on SR-160. It can be seen that the associated RWASS and EVT-300 speed data match quite well although the associated distance data are not necessarily close to each other.

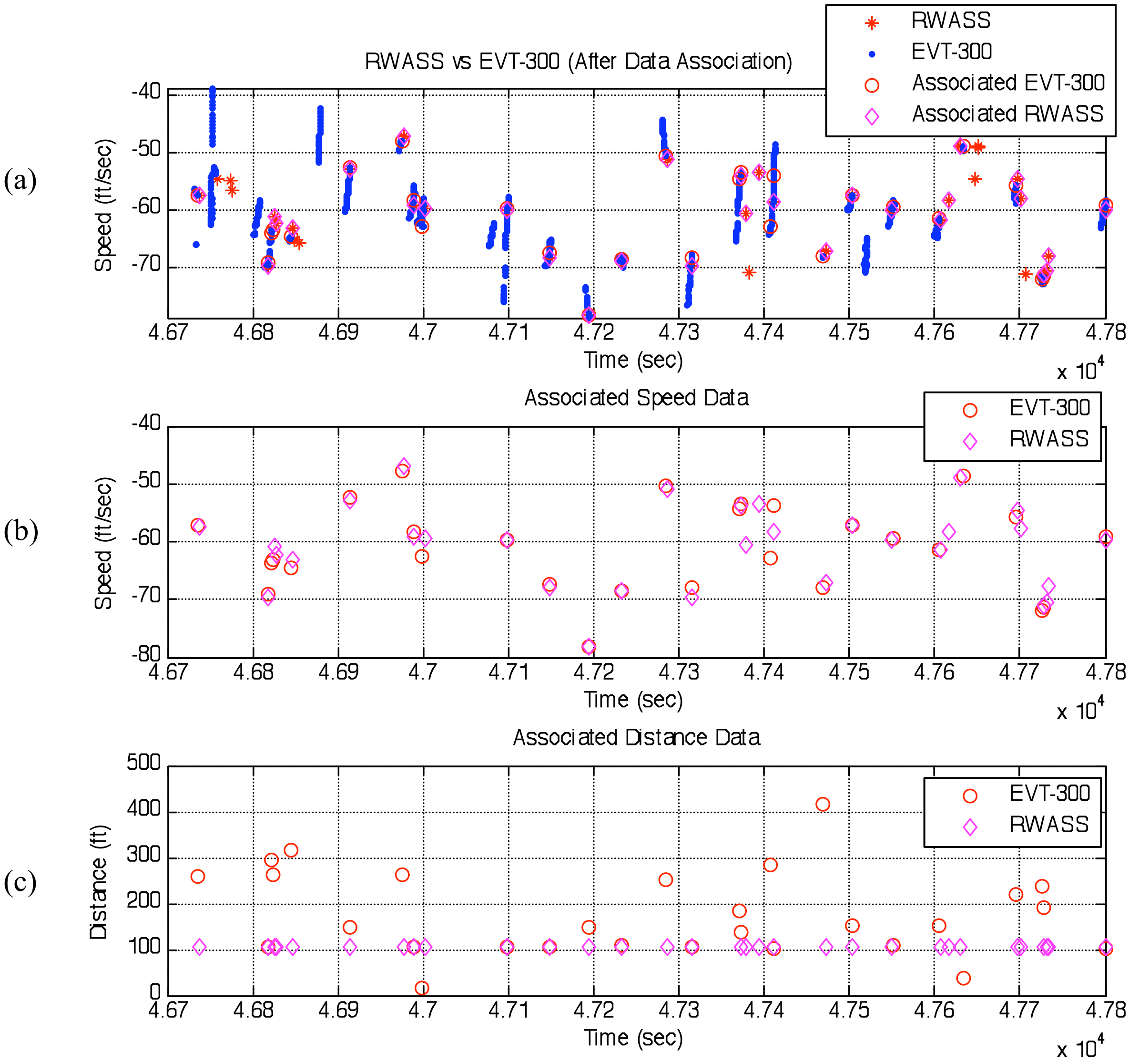


Figure 38 Data Association for RWASS and EVT-300 Data Collected on SR-160

4.3.2 Analysis of Field Data Collected on Interstate 5

Figures 39 and 40 show the comparison between RWASS and EVT-300 speed measurements using the data collected on I-5 on August 24th, 2008. From Figure 39(a), it can be seen that RWASS reported more vehicle counts than EVT-300 as expected. Figure 39(b) and 39(c) show the mean traffic speeds estimated based on all and associated speed data, respectively. Although the two radar systems have different signal coverage, the difference of the mean speed estimates is less than 3 mph.

.

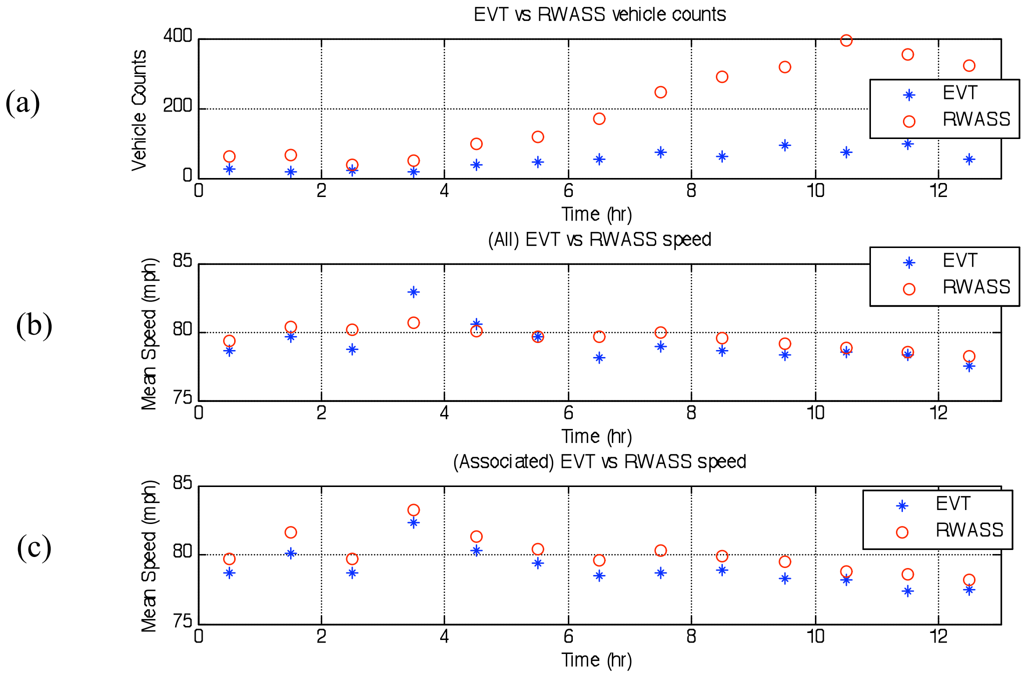


Figure 39 Vehicle Counts and Speed Measurements by RWASS and EVT-300

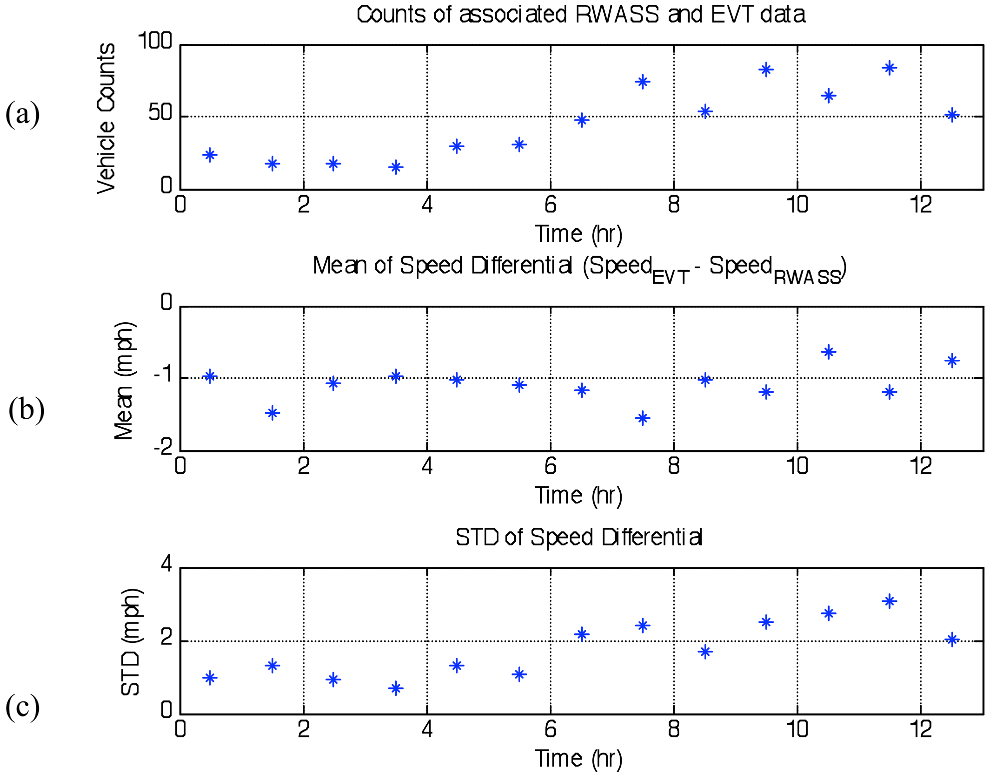


Figure 40 Analyses of Associated Speed Data

Figure 40 shows the analysis of associated speed measurements of two systems. The Speed Differential is defined as (EVT-300 speed ─ RWASS speed) and is calculated for every hour. The means of Speed Differentials are between -1.5 and -0.5 mph, and the standard deviations (STD) are between 0.5 and 3.25 mph

Table 12 lists the data association and analysis results for three complete days of field experiments. A speed threshold was used in this data analysis. Speed data of each data set lower than a pre-defined speed threshold are discarded. It should be noted that the speed threshold used on August 21 is 0 mph, which is lower than the threshold (75 mph) used in the other two days.

The range, mean and standard deviation of (RWASS versus EVT-300) speed and speed differential data are given in this table. The association rate is defined as the number of associated EVT-300 data divided by the number of total EVT-300 data. It appears that the data association rate is higher if the higher speed threshold is used. Also, the range and standard deviation of speed differential is smaller if the higher speed threshold is applied. With the 75 mph speed threshold, the mean of speed differential is around -1.09~-1.20 mph, and the standard deviation is around 2.2~2.3 mph.

From the associated speed data, it can be observed that the measurements of two radar systems are fairly consistent although the values of EVT-300 speed measurements are slightly lower than that of the RWASS speed data. In summary, the field data comparative analysis shows that the tracking radar EVT-300 can provide a sequence of speed measurements that are consistent with the speed data of selected ASE equipment, RWASS. Therefore, it has the potential to provide secondary speed measurement for an ASE system.

Table 12 Summary of Comparison between RWASS and EVT-300 Data Sets

Highway: I-5			
Date (August 2008)	21st (Thur)	23rd (Sat)	24th (Sun)
Speed Threshold (mph)	0.0	75.0	75.0
# of vehicles detected by RWASS	4,276	3,353	2,580
# of vehicles detected by EVT	2,318	782	687
Associated RWASS & EVT data	1,859	692	594
Association rate (%)	80.2	88.5	86.5
Maximum RWASS speed (mph)	102.0	108.0	110.0
Minimum RWASS speed (mph)	45.0	76.0	76.0
Mean of RWASS speed (mph)	66.5	78.8	79.2
STD of RWASS speed (mph)	8.0	3.0	3.4
Maximum EVT speed (mph)	100.1	96.0	97.8
Minimum EVT speed (mph)	10.2	75.0	75.0
Mean of EVT speed (mph)	61.7	78.3	78.8
STD of EVT speed (mph)	7.7	3.5	3.5

Maximum speed differential (mph)	24.2	9.2	10.0
Minimum speed differential (mph)	-23.0	-9.9	-10.0
Mean of speed differential (mph)	0.01	-1.20	-1.10
STD of speed differential (mph)	6.1	2.3	2.2
Mean of associated RWASS speed (mph)	65.2	78.9	79.6
STD of associated RWASS speed (mph)	7.3	3.3	3.6
Mean of associated EVT speed (mph)	65.2	77.7	78.5
STD of associated EVT speed (mph)	6.9	3.2	3.6

4.3.3 Analysis of Field Data Collected on State Route 160

Figure 41 shows the relationship between speed differential and speed, where the speed differential is defined as (EVT-300 speed – RWASS speed). As can be observed from the two plots in this figure, the speed differential is between -5 ~ + 15 ft/sec. Regardless of the two large speed differential values greater than 10 ft/sec, all speed differentials are within the ±6 ft/sec bounds. The two large speed differentials can be due to several possible reasons, such as data association errors or measurement errors of radar systems.

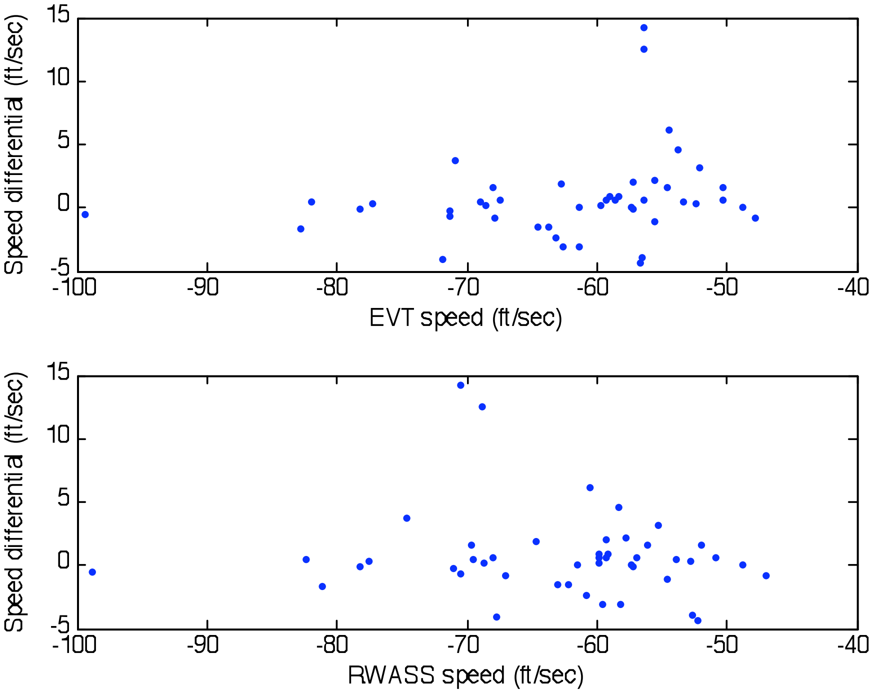


Figure 41 Speed Differential versus Speed Data

Table 13 lists the analysis results of speed measurements of RWASS and EVT-300. The number of vehicles detected by EVT-300 is larger than that by RWASS in that RWASS only reported speeding vehicles (speed >44 ft/sec) but EVT-300 reported all passing vehicles. Also, it was found that EVT-300 may give multiple ID numbers for the same target, which resulted in overcounting passing vehicles based on vehicle IDs. However, the speed measurements of two systems appear to be fairly consistent. The mean of speed differential is 0.71 ft/sec, and the standard deviation is 3.43 ft/sec. In addition, the associated speed data of two systems match quite well. Thus, from the viewpoint of sensor redundancy, the tracking radar, EVT-300, has the potential to provide secondary speed measurements for supporting enhancement of ASE equipment.

Table 13 Speed Data Analysis

16-Oct-2008	
Total vehicles detected by EVT-300 (lane 1 & 2)	243
Total vehicles detected by EVT-300 (lane 1)	190
Total vehicles detected by RWASS (lane 1)	67
Total associated vehicle data	46
Association rate (%)	68.7
Mean RWASS speed (ft/sec)	-61.72
STD of RWASS speed (ft/sec)	10.06
Max RWASS speed (ft/sec)	-46.93
Min RWASS speed (ft/sec)	-98.86
Mean EVT-300 speed (ft/sec)	-57.41
STD of EVT-300 speed (ft/sec)	15.07
Max EVT-300 speed (ft/sec)	-2.51
Min EVT-300 speed (ft/sec)	-116.92
Mean speed differential (EVT speed - RWASS speed) (ft/sec)	0.71
STD of speed differential (ft/sec)	3.43
Max speed differential (ft/sec)	14.22
Min speed differential (ft/sec)	-4.42
Mean of associated RWASS speed (ft/sec)	-62.95
STD of associated RWASS speed (ft/sec)	10.06
Max associated RWASS speed (ft/sec)	-46.93
Min associated RWASS speed (ft/sec)	-98.85
Mean of associated EVT-300 speed (ft/sec)	-62.24
STD of associated EVT-300 speed (ft/sec)	10.24
Max associated EVT-300 speed (ft/sec)	-47.82
Min associated EVT-300 speed (ft/sec)	-99.42

4.4 Field Evaluation of Tracking Radar System

In this section, the performance of adopted tracking radar system, EVT-300, is evaluated in two aspects. Firstly, the target tracking performance is assessed in different traffic conditions. Secondly, the accuracy of EVT-300 measurements (speed and vehicle count) is evaluated against the data of Caltrans Traffic Data Station.

4.4.1 Target Tracking Performance Assessment on Interstate 5

The target tracking performance of EVT-300 is evaluated based on the tracking range and the number of tracking data points for each vehicle. The target update frequency of EVT-300 is 65 ms. In reference [17], the tracking performance of EVT-300 was investigated in a simpler scenario, in which one target vehicle (truck or sedan) was used in each run. It was reported that an average of 47 data points were collected for the runs at 72 km/hr (44.7 mph) and 91 data points at 40 km/hr (24.9 mph); the maximum sensor range was 134 m (439.6 ft), and the sensor coverage was between 43~124 m (141.1~406.8 ft) depending on the vehicle type, speed, sensor distance to the lane center, and sensor orientation.

However, the traffic volume at this study site was much higher, where the vehicle count on three lanes was around 44,000-48,500 per day according to the data from Caltrans Traffic Data Station. Thus, notable performance degradation of the tracking radar system can possibly occur due to serious signal reflections and disturbances.

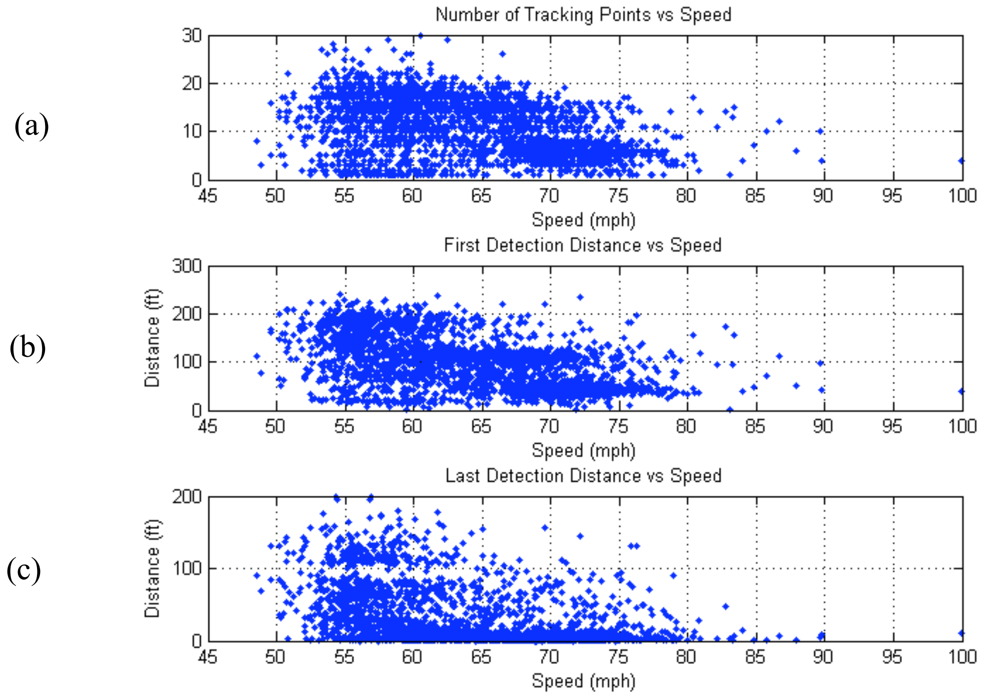


Figure 42 Analysis of Vehicle Tracking Performance (EVT-300) versus Speed

Figure 42 shows the relationship between target tracking performance versus speed. The illustrated data were collected on August 21, 2009. It can be observed that the traffic condition in terms of vehicle speed and traffic volume has a great impact on the tracking function of the radar system. For speeding vehicles (speed > 65 mph), the number of data points is mostly less than 20. As the vehicle speed is greater than 85 mph, less than 15 data points are recorded.

Figure 42 (b) and (c) show the first and last range measurements for each vehicle, respectively. The maximum sensor range is less than 250 feet, which is shorter than the sensor range (439.6 feet) reported in [17]. For the vehicles with speeds greater than 75 mph, the first range measurement is less than 200 feet, which implies that the sensor coverage is less than 200 feet. On the other hand, for the vehicles with speeds less than the speed limit, i.e., 65 mph, the first range measurement is also around or less than 200 feet.

Table 14 lists the results of tracking performance analysis for three complete days of field experiments, where traffic conditions can be assessed from Tables 13 and 15. The number of target tracking points has a mean value of around 10.5~10.7 and a standard deviation of around 5.4~5.6. As for the sensor coverage, the means of the first and last range measurements are around 95.7~100.6 feet and 28.6~29.3 feet, respectively. Therefore, the resulting sensor coverage is around 69.6 feet, which is shorter than the sensor coverage (141.1~406.8 feet) reported in [17].

Table 14 Summary of Vehicle Tracking Performance Analysis

Highway: I-5			
Date (August 2008)	21st (Thur)	23rd (Sat)	24th (Sun)
Maximum number of tracking points	30	31	29
Minimum number of tracking points	1	1	1
Mean of number of tracking points	10.5	10.7	10.7
STD of number of tracking points	5.6	5.4	5.5
Maximum first detection distance (ft)	239.2	248.5	249.6
Minimum first detection distance (ft)	1	0	1.4
Mean of first detection distance (ft)	95.7	99.6	100.6
STD of first detection distance (ft)	52.8	51.4	52.0
Maximum last detection distance (ft)	198.9	204.6	242.3
Minimum last detection distance (ft)	0	0	0
Mean of last detection distance (ft)	29.2	28.6	29.3
STD of last detection distance (ft)	38.8	38.7	39.3

4.4.2 Target Tracking Performance Assessment on State Route 160

In this section, the target tracking performance of EVT-300 is assessed under less traffic condition impacts. The field experiment was conducted on a normal two-lane rural roadway on SR-160, where the traffic volume and mean speed are relatively low. Thus, it is likely to reveal the upper bound of target tracking performance of EVT-300 on a normal highway while the evaluation presented in the last section may provide an estimate of the performance lower bound of EVT-300. By combining both evaluation results, the functional limits of select tracking radar system for supporting ASE system enhancement can be assessed.

Figure 43 shows all vehicle trajectories measured by EVT-300 in one day of field experiment. The radar antenna is located at the origin of coordinates. The two arrows indicate the traffic directions of two lanes. It should be noted that the coordinates of this plot have been rotated by 5 degrees in the clockwise direction, so that the directions are in parallel with the Y axis. As can be observed from this figure, the target tracking ranges on two lanes are different. For lane 1, which is closer to the radar antenna, the tracking range is around 0 ~ 437.5 feet. For lane 2, the tracking range is around 100 ~ 500 feet. The difference of target tracking range between two lanes is mainly due to the orientation of radar antenna with respect to the road heading and the internal data filtering process of the radar system. In addition, there exists a gap in the vehicle trajectories between the range of 330 ~ 355 feet. The measurement gap, which was also observed in all the other experimental data, was probably applied by the internal data filtering algorithm of EVT-300 for the collision warning application.

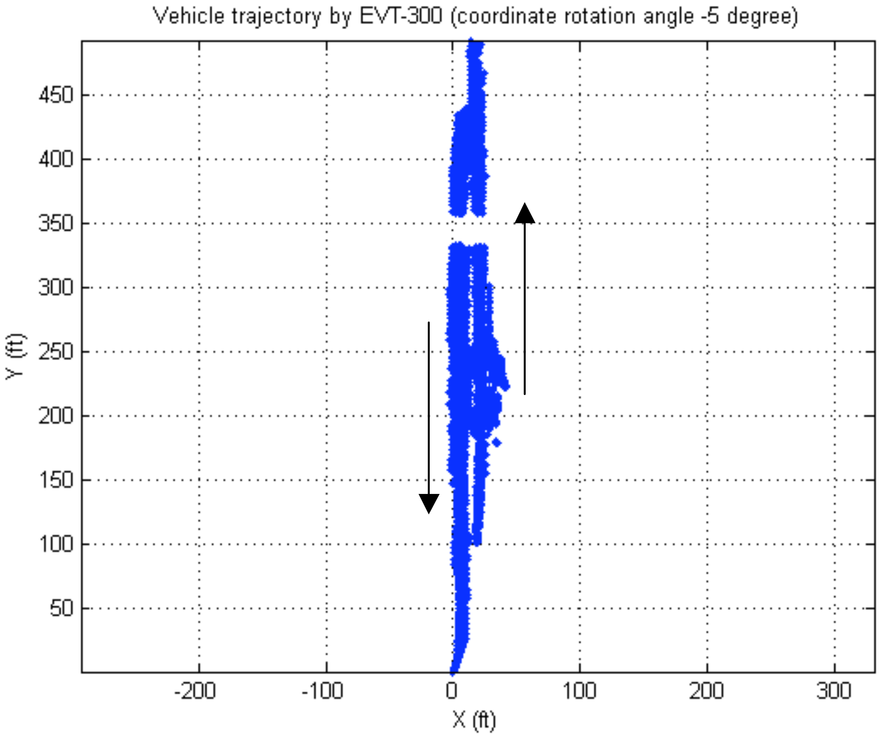


Figure 43 Vehicle Trajectory Measured by EVT-300

In principle, the target tracking range changes as the orientation of radar antenna changes. With the same radar signal beam width, a larger angle between the headings of antenna and road generally results in a shorter tracking range. Since the tracking radar EVT-300 is intended for the application of frontal collision warning, the target tracking function is restricted to targets within a certain virtual boundary in addition to the physical limitation of signal coverage. That is, the moving objects that are located outside the predefined tracking boundary will not be reported although they may be physically detectable. Therefore, it would be necessary to further examine and adjust the settings of target tracking functions of select tracking radar in order to optimize the functional support for ASE equipment enhancement.

Figure 44 shows the target tracking performance analysis for EVT-300. The target tracking range and reliability against target speed can be assessed from the plots in this figure. Figure 44(a) shows that the select tracking radar was capable of tracking moving targets starting at the distance greater than 400 feet at this study site. However, the tracking for some targets ended very early as indicated by the Last Detection data ranging from 0 to 400 feet. The discontinuous target tracking can be attributed to several reasons. As described in Section 4.4.1, radar signal reflection and blockage due to the dense traffic appeared to drastically degrade the tracking performance of select radar system. Also, it was found that the discontinuous target tracking was caused by the internal signal processing algorithm of the radar system as described below.

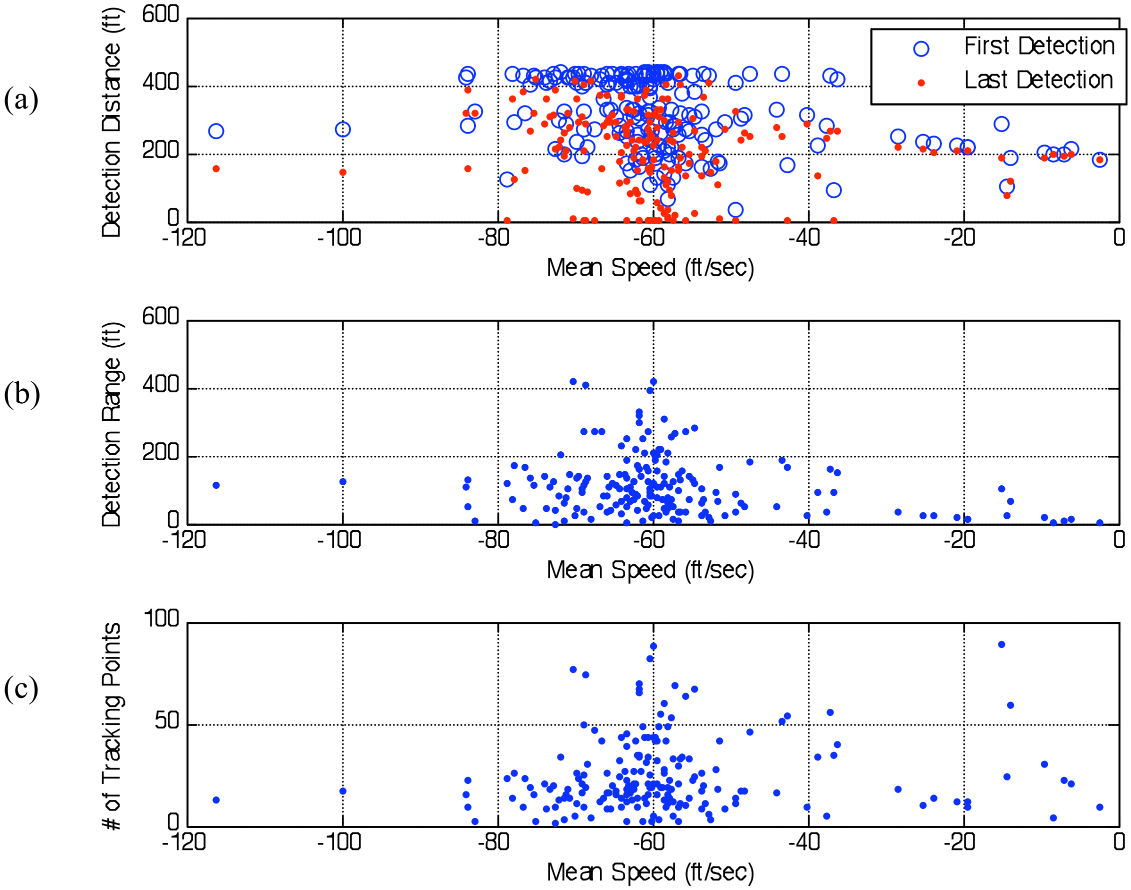


Figure 44 Evaluation of Target Tracking Performance of EVT-300

Figure 45 illustrate two examples of vehicle tracking by EVT-300. The series of rectangles along the road represent trajectories of tracked vehicles. A vehicle ID number is shown near the first detection location. Figure 45 (a) shows an example of complete vehicle tracking, which started at the distance of around 400 feet and ended at 0 feet. Figure 45 (b) shows the discontinuous tracking case. The vehicle with ID 4951 was first detected at the distance of around 430 feet and tracked until it was at the distance of 310 feet. Subsequently, the tracking of this vehicle resumed and stopped again two times as described by the trajectories of vehicles with IDs 4952 and 4953. In addition, the tracking was lost during the range of 0~75 feet.

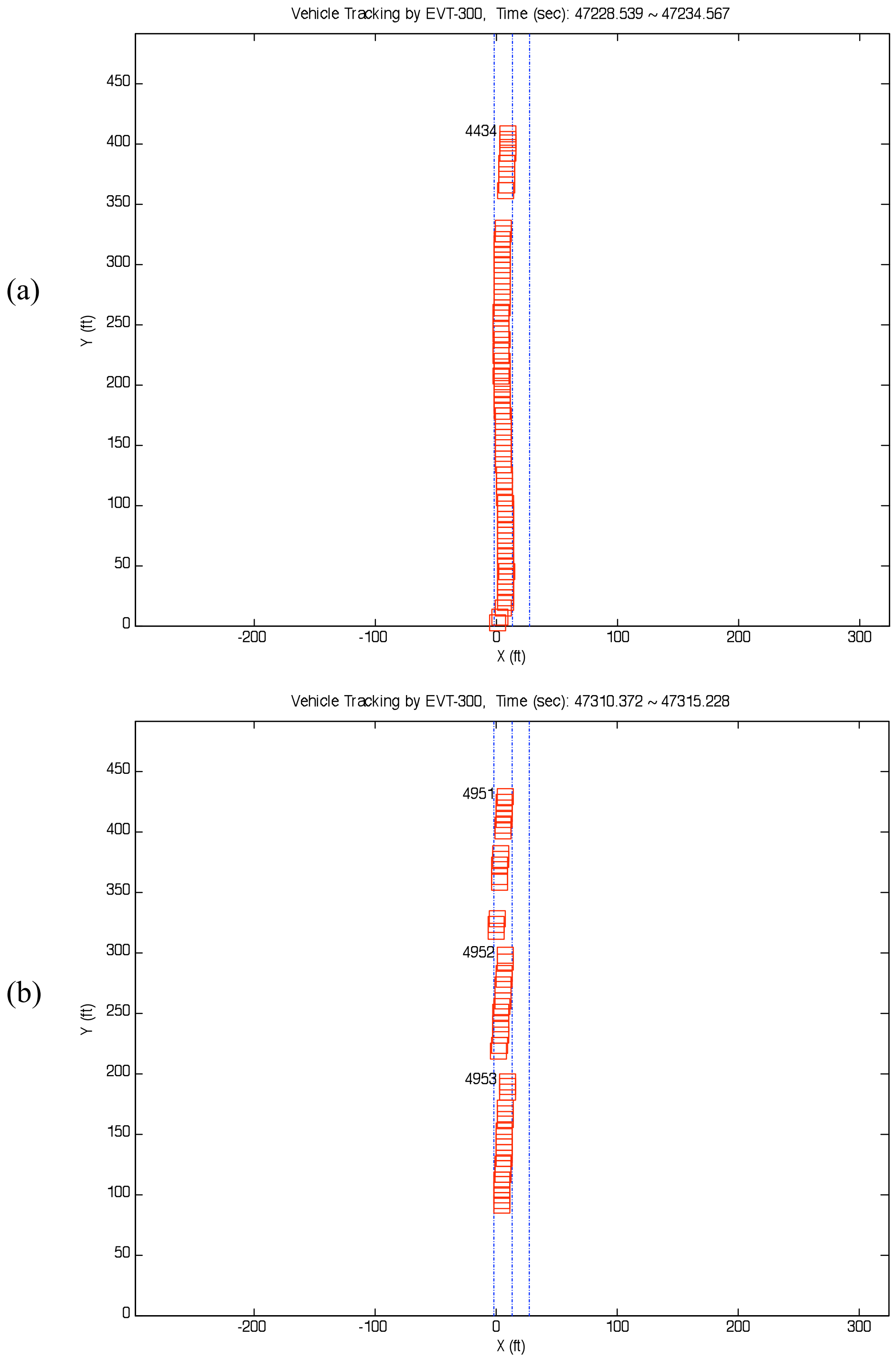


Figure 45 Examples of Vehicle Tracking by EVT-300

Table 15 lists the summary of tracking performance evaluation for EVT-300 at the study site on State Route 160. The tracking performance at this site appeared to be better than that at another site on Interstate 5 (I-5) in terms of tracking range and number of tracking points. The mean tracking range and average number of tracking points at this site are 111.05 feet and 24.6, respectively. At the site on I-5, the two values are relatively smaller, 69.6 feet and 10.6, respectively. In addition, the maximum detection distance at this site is also longer, which is 441.6 feet as opposed to 245.8 feet at the site on I-5.

Table 15 Vehicle Tracking Evaluation

Max first detection distance (ft)	441.6
Min first detection distance (ft)	36.3
Mean of first detection distance (ft)	316.22
STD of first detection distance (ft)	103.42
Max last detection distance (ft)	428.8
Min last detection distance (ft)	0.1
Mean of last detection distance (ft)	205.17
STD of last detection distance (ft)	118.39
Max # of tracking points	89
Min # of tracking points	1
Mean # of tracking points	24.6
STD of # of tracking points	18
Max tracking range (ft)	417.6
Min tracking range (ft)	0
Mean tracking range (ft)	111.05
STD of tracking range (ft)	86.09

4.4.3 Data Analysis and Comparison between EVT-300 and Ground-Based Double Loop on I-5

In this section, the field experimental data (vehicle count and speed) of EVT-300 and Caltrans Traffic Data Station are compared. As explained earlier, the Caltrans Traffic Data Station is considered a reliable data source, and at least the vehicle count measurement should be fairly accurate. Therefore, the Caltrans loop sensor data were used as the baseline in the evaluation.

Due to data recording system's problem, some sensor data were not recorded properly and were discarded. Table 16-17 lists the data comparison for three complete days of field experiments. From Table 16, it can be observed that most EVT-300 vehicle counts are less than the counts by loop sensors. This observation was also made in another field evaluation for the RWASS system on SR-12 as presented in section 3 of this report. Both EVT-300 and RWASS tend to underestimate the count of passing vehicles probably due to its relatively low mounting position at approximately one meter above the ground, which can cause some oncoming traffic obscured by leading vehicles.

Table 17 shows the mean speeds estimated by EVT-300 and loop sensors. It can be seen that EVT-300 underestimates the mean speed by around 12~16 mph compared with the loop sensor speed data. However, it should be noted that a speed threshold of 75 mph is applied to two data sets in Table 12, and the resulting mean speed estimates of EVT-300 (78.3 and 78.8 mph) are fairly close to the mean speed estimates of loop sensors. The underestimation of mean speed can be attributed to several factors, for example, the compound effects of radar signal reflections and occlusions and false detection of surrounding targets. As long as speed measurements for high-speed moving targets are fairly accurate, the determination of mean speed is not an important issue for the ASE system.

Table 16 Vehicle Count Comparison between EVT-300 and Loop Sensors

Vehicle Counts in Lane 1 on I-5														
Date	Sensor	Time	12~1	1~2	2~3	3~4	4~5	5~6	6~7	7~8	8~9	9~10	10~11	11~12
8/21/2008	Loop Sensor	AM	49	57	71	168	671	1267	1326	1512	1335	1079	1039	1075
		PM	1124	1216	1338	1466	1449	1405	969	680	559	463	305	163
	EVT-300	AM	0	0	0	0	0	0	0	0	0	0	138	913
		PM	916	663	0	0	0	0	0	0	0	0	0	0
8/23/2008	Loop Sensor	AM	148	89	83	99	156	374	440	570	790	1030	1193	1180
		PM	1124	1244	1140	1149	1116	957	795	647	569	577	501	275
	EVT-300	AM	0	0	0	0	0	0	0	530	659	808	844	799
		PM	885	436	0	0	0	0	0	508	631	629	505	267
8/24/2008	Loop Sensor	AM	174	115	92	70	115	216	204	288	419	677	981	1140
		PM	1247	1290	1351	1358	1268	1109	1091	890	852	648	409	216
	EVT-300	AM	156	107	71	59	151	224	253	381	477	651	679	944
		PM	552	22	0	0	0	0	0	410	718	536	352	130

Table 17 Mean Speed Comparison between EVT-300 and Loop Sensors

Mean Speed (mph) of Vehicles in Lane 1 on I-5														
Date	Sensor	Time	12~1	1~2	2~3	3~4	4~5	5~6	6~7	7~8	8~9	9~10	10~11	11~12
8/21/2008	Loop Sensor	AM	79.3	79.8	79.5	79.6	81.7	79.2	79.7	80.1	74.2	78.7	77.1	78.6
		PM	77.3	78.2	77.4	78.1	77.6	77.8	79.7	70.7	78.2	78.1	77.8	77.8
	EVT-300	AM	0	0	0	0	0	0	0	0	0	0	63.2	64.2
		PM	64.5	64.9	0	0	0	0	0	0	0	0	0	0
8/23/2008	Loop Sensor	AM	78.5	79.2	79.8	80.2	80.8	81.3	83	83.4	82	81.2	80.6	80.4
		PM	79.9	80.3	80.8	80.1	81.2	82	82.4	81.9	80	80	79.5	80
	EVT-300	AM	0	0	0	0	0	0	0	67.2	66.5	66.9	67.0	66.9
		PM	66.5	66.1	0	0	0	0	0	67.2	66.5	66.1	66.9	67.3
8/24/2008	Loop Sensor	AM	80.7	79.9	79.4	81.5	81.8	80.8	82.6	84.7	83.5	82.2	81.6	81
		PM	79.2	79.4	78.7	79.9	79.7	80.5	81.7	80.6	77.5	78.4	79.5	77.5
	EVT-300	AM	67.8	67.9	69.9	71.1	68.3	67.4	68.3	68.1	67.6	67.2	67.4	67.0
		PM	67.1	70.0	0	0	0	0	0	66.2	65.9	65.6	65.7	65.6

4.5 Concluding Remarks

Assessing Automated Speed Enforcement in California

This chapter describes the functional assessment of two Doppler radar-based speed monitoring devices for the development of enhanced ASE equipment. The commercially-off-the-shelf tracking radar system, EVT-300, along with a selected ASE system, RWASS, were field tested on I-5 and SR-160 in northern California.

Data processing techniques were adopted to investigate in depth the speed measurement discrepancies between the selected ASE equipment and the tracking radar system EVT-300. Although two radar systems have different signal ranges and coverage and functional features, the performance of speed measurements are comparable, in particular, for the high-speed moving target.

It was found that EVT-300 tended to report a smaller speed value than the RWASS speed measurement. However, the speed data of two systems are fairly consistent. At the study site on I-5, the mean of speed differential is around -1.09~-1.20 mph, and the standard deviation is between 2.2~2.3 mph. At another site on SR-160, the mean of speed differential is 0.71 ft/sec and the standard deviation is 3.96 ft/sec. Since the tracking radar EVT-300 can provide a sequence of range, speed, and heading measurements of the tracked targets, it has the potential to provide secondary measurements for an enhanced ASE system.

The functional performances of the selected tracking radar, EVT-300, were further assessed in two aspects in this study. Firstly, the target tracking performance analysis was conducted. The field evaluation results revealed notable impacts of traffic conditions to the tracking performance of the radar system. The target tracking range and sensor coverage drastically decreased possibly as a result of radar signal reflections and occlusions. Secondly, vehicle count and speed measurement data of EVT-300 were compared with the data provided by Caltrans Traffic Data Station. The results show that EVT-300 tends to underestimate both vehicle counts and speeds under complex traffic condition effects. Since the detection and tracking of high-speed vehicles are the major functional requirements for an ASE system, the underestimation of vehicle counts and mean speeds of traffic flows are not considered an important issue.

The evaluation presented in this section can provide valuable information for future ASE implementation in the California highway network as well as for the ASE system enhancement through integration with a tracking radar system. Further research into the parameter design of the tracking radar system for optimal ASE performance is also recommended for future research.

5 CONCLUSION

This report provides an overview of a recent project undertaken in California to assess various issues associated with Automated Speed Enforcement (ASE) systems. An earlier phase of the project was carried out and concluded with an extensive literature review and an examination of various institutional and legal issues involved in the implementation of ASE [11]. In the current second phase of the project, the focus is placed on the technological evaluation of ASE equipment. An ASE system designed for use in work zones was acquired and tested in several field experimental sites, along with several other commercially-off-the-shelf traffic monitoring devices. The objective of the study is to examine the field performance of the equipment in a real-world setting, when evaluated against other comparable traffic devices.

The results from the field experiments revealed that traffic speed measurements are likely to yield discrepancies. Since speed measurement consistency and accuracy are major concerns in the implementation of speed enforcement systems, it is critical that the operation of enforcement take into account the characteristics of field performance of such devices and set speeding thresholds accordingly. For a more robust and reliable system, it will also be desirable to utilize technical approaches to offer supplementary speed measurements.

For considerations of future deployment of ASE, the technologies can be expected to be advanced further. Since all types of sensing devices are susceptible to certain levels of interference and noises in the field, a consistent and robust method of verification and calibration for sensors used for ASE will be essential. From the design point of view, extra measures or techniques can be taken to ensure the robustness and accuracy of ASE systems.

The assessment of technical performance of ASE as carried out in this project can provide insights in the process of validating functional characteristics and seeking performance enhancements. The outcome of this study, in conjunction with the experience and knowledge gained by other agencies in their development and implementation of work-zone and general ASE systems will offer valuable support for future ASE implementation.

5.1 The Use of Sensing Devices in ASE

One critical aspect in the consideration of ASE field implementation will be to ensure accuracy and consistency of speed measurements that are qualified and verified thoroughly to sustain the challenges in the court of laws.

A large number of ASE relies on the speed measurements by radar or laser devices. Some suppliers are beginning to adopt video or image processing for target detection, but it is still in the minority. Radar is susceptible to more measurement noises and misidentification due to the natures of its operating principles. For example, one major supplier of red-light running and ASE equipment has steered away from using radar alone and resort to using double measurements for their products.

From a technical point of view, the consistency or robustness of speed measurements for ASE can be improved by implementing redundancy, which can be pursued in several manners:

(1) Using alternate measurement devices that are based on different physical principles, such as a combination of
   - in-ground electrical loops and radar,
   - radar and laser

(2) Using tracking radar
   - Conventional radar for ASE only captures and issues a triggering signal when the target vehicle passes its detection with one single instant of speed measurement.
   - Tracking radar captures the speed history of a target and records its trajectory data over a time window

For cost-conscious systems, where the use of double or multiple sensing devices are prohibitive or unavailable, there are ways to utilize multiple photo captures to track the trajectory of detected targets and to verify the accuracy of speed measurements by the sensor alone.

- radar and consecutive photographs
- laser and consecutive photographs

5.2 Performance Metrics for ASE Equipment

While ASE was not implemented during this study, it is still strongly desirable to establish a framework of evaluating ASE systems, especially from the design, installation, and maintenance perspectives. A preliminary set of performance measures for the evaluation of automated enforcement functions is outlined in Table 18. The performance measures are designed to serve as an evaluation tool for the selection of automated enforcement systems. Detailed specifications and criteria can be refined according to the configurations of a particular device or the setting of field experiments.

Table 18 Performance Measures of Automated Speed Enforcement Equipment

Category of Measures	**Specific Measures**	**Exemplar Criteria Description**
Long-term service contract requirements		
Ease of Operation (Assuming independent operation)	Setup Required	Procedures, requirements, and accessories for field setup
		Pre- and in-the-field calibration
		Parameter-changing procedures
		Remote-connection tuning or adjustment
	Diagnostic and Verification Tools	Tools for setup, calibration, and verification
	Level of Training Required, and Learning Curve	Operational handbook and manual availability
		Required training for equipment upgrade or update
Operational Capability and Robustness	Speed and Distance Accuracy	Threshold speed and tolerance range

	Field of View	Maximum distance and angular coverage
	Environmental Sensitivity	Temperature, humidity, rain, snow, wind, etc.
	Photography	Resolution
		Frequency
		File size
		Storage capacity
	License Plate Recognition	Error Rate
		Range of recognized symbols and characters
	Availability and Reliability	Average time between malfunctioning
		Indicators for equipment status
		Degraded mode operation
		Restoration procedures
		Ease of repair
		Availability of service
	Integration with other devices	Output message format and contents
		Output message protocol
		Output message file size
		Interface types
		Indicator of missed transmission
Flexibility in Operation	Equipment options	Choice of options
		System architecture flexibility and openness
		Remote access by networked connection
		Procedures in temporary shutdown and rebooting

APPENDIX Summary of Collisions on Highway 12 by Districts

Table 19 Eastbound summary of collisions by districts

		District			
Severity	**# of vehicles involved**	**3**	**4**	**10**	**Grand Total**
F	**M**	1	15	7	23
	S		8	2	10
I	**M**	24	505	148	677
	S	4	123	48	175
PDO	**M**	41	800	243	1084
	S	5	179	50	234
Grand Total		75	1630	498	2203

Table 20 Westbound summary of collisions by districts

		District			
Severity	**# of vehicles involved**	**3**	**4**	**10**	**Grand Total**
F	**M**	1	10	7	18
	S		5	2	7
I	**M**	25	441	158	624
	S	5	89	47	141
PDO	**M**	39	694	302	1035
	S	4	152	42	198
Grand Total		74	1391	558	2023

REFERENCES

(1) Oesch, Stephen L., Statement before the Maryland Senate Committee on Judicial Proceedings on Senate Bill 277, Research on Automated Speed Enforcement, February 24, 2009.
(2) Elvik, R. 2005. Speed and road safety: synthesis of evidence from evaluation studies. *Transportation Research Record* 1908:59-69. Washington, DC: Transportation Research Board.
(3) Insurance Institute for Highway Safety. 2009. [Unpublished analysis of data from the Fatality Analysis Reporting System]. Arlington, VA.
(4) Retting, R.A.; Farmer, C.M.; and McCartt, A.T. 2008. Evaluation of automated speed enforcement in Montgomery County, Maryland. *Traffic Injury Prevention* 9:440-45.
(5) Retting, R.A.; Kyrychenko, S.Y.; and McCartt, A.T. 2008. Evaluation of automated speed enforcement on Loop 101 freeway in Scottsdale, Arizona. *Accident Analysis and Prevention* 40:1506-12.
(6) Chen, G.; Wilson, J.; Wu, J.; Mehle, W.; and Cooper, P. 1998. Interim evaluation report: photo radar program one year after introduction of the violation ticket phase. Victoria, British Columbia: Insurance Corporation of British Columbia.
(7) Transportation Research Board. 1998. Special report 254; Managing speed: review of current practice for setting and enforcing speed limits. Washington, DC: National Academy of Sciences.
(8) Mountain, L.J.; Hirst, W.M.; and Maher, M.J. 2004. Costing lives or saving lives? A detailed evaluation of the impact of speed cameras on safety. *Traffic Engineering and Control* 45:280-87.
(9) Pilkington, P. and Kinra, S. 2005. Effectiveness of speed cameras in preventing road traffic collisions and related casualties: systematic review. *British Medical Journal* 330:331-34.
(10) Wilson, C.; Willis, C.; Hendrikz, J.K.; and Bellamy, N. 2006. Speed enforcement detection devices for preventing road traffic injuries. *Cochrane Database of Systematic Reviews* 2006, Issue 2, Article no.: CD004607. Oxfordshire, United Kingdom: The Cochrane Colaboration.
(11) C. J. Rodier, S. A. Shaheen, E. Cavanagh, "Automated Speed Enforcement for California: A Review of Legal and Institutional Issues," *California PATH Research Report, UCB-ITS-PRR-2007-14,* September 2007.
(12) A. Sharafsaleh, C-Y Chan, "Experimental Evaluation of Commercially-off-the-shelf Sensors for Intersection Decision Support Systems," Technical Paper, *Proceedings of the 2005 Intelligent Transportation System World Congress* in San Francisco, November 2005.
(13) C-Y. Chan, et al., "California Intersection Decision Support: A Systems Approach to Achieve Nationally Interoperable Solutions," *California PATH Research Report, UCB-ITS-PRR-2005-11,* April 2005.
(14) J. A. Misener, et al., "California Intersection Decision Support: A Systems Approach to Achieve Nationally Interoperable Solutions II," *California PATH Research Report, UCB-ITS-PRR-2007-1,* January 2007.
(15) Chen, C., Petty, K., Skabardonis, A., Varaiya, P., Jia, Z. Freeway Performance Measurement System: Mining Loop Detector Data, Annual Meeting of the Transportation Research Board, Washington, D.C., Jan 2001.
(16) Choe, T., Skabardonis A., and Varaiya. P. Freeway Performance Measurement system (PeMS): An operational analysis tool TRB 81st Annual Meeting, January 2002.

(17) Menon, A., A. Gorjestani, C. Shankwitz, and M. Donath. Roadside Range Sensors for Intersection Decision Support. Proceedings of the 2004 IEEE Intelligent Transportation Systems Conference, Washington, D. C., October 3-5, 2004.
(18)
(19)

Chan, C-Y., and K. Li. Comparative Analysis of Speed Measurements of Work Zone Speed Enforcement Equipment and Ground-Based Traffic Data Station. Presented at ITS America's 2009 Annual Meeting and Exposition, National Harbor, Maryland, June 1-3, 2009.

(1) Menon, A., A. Gorjestani, C. Shankwitz, and M. Donath. Roadside Range Sensors for Intersection Decision Support. Proceedings of the 2004 IEEE Intelligent Transportation Systems Conference, Washington, D. C., October 3-5, 2004.
(2) Shin, K., S. P. Washington, and I. van Schalkwyk. Evaluation of the Scottsdale Loop 101 Automated Speed Enforcement Demonstration Program. *Accident Analysis and Prevention*, Vol. 41, 2009, pp. 393-403.
(3) Kang, Jeong-Gyu. Changes of Speed and Safety by Automated Speed Enforcement Systems. *IATSS Research*, Vol. 26, No. 2, 2002, pp. 38-44.
(4) Carnis, L. The Automated Speed Enforcement System in Great Britain: between a Technical Revolution and Administrative Continuity, *International Review of Administrative Sciences*, Vol. 73(4), 2007, pp. 597-610.