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Title: Performance Requirements and Evaluation Procedures for Advance Wide Area Detectors

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ABSTRACT

Dilemma zone protection ideally requires the exact position and speed of all the vehicles approaching the intersection. However, point detectors, typically used to protect vehicle incursion into the dilemma zone, only provide binary information about the presence or absence of a vehicle at a fixed point in space. The information regarding position and speed of the vehicle in subsequent time steps is extrapolated. The extrapolation error increases with the increase in projection time. Wide area detector (WAD) overcomes this drawback by tracking each vehicle at all times until they move out of range. Such a detector has the potential to improve the efficiency and safety of performance of dilemma zone protection systems. This paper develops performance measures for evaluating WAD. The performance of a WAD was evaluated at a heavily instrumented intersection in Noblesville, IN.

BACKGROUND

Two classes of detectors are discussed in this paper: wide area detector (WAD) and point detector. WADs provide the ability to simultaneously monitor the passage of each vehicle within a wide area and selectively signal calls based upon operational objectives related to measurements like position, speed, and count. Point detectors are usually loop detectors that signal calls based upon the presence of a vehicle at a fixed location. Point detectors are ubiquitously deployed for volume density operations, detection of congested traffic, and dilemma zone protection (1). Both detector types are examined in relation to dilemma zone protection. Researchers define the dilemma zone in terms of speed-dependent distance boundaries (1,2,3,4), or stop line arrival time (4,5). For example, the dilemma zone for a vehicle traveling at 55 mph is in the range of 400 ft to 240 ft (1) upstream of stop bar whereas it is in the range from 212 ft to 105 ft for a 35 mph vehicle (1). The dynamic nature of dilemma zone distance boundaries presents challenges for safe and efficient dilemma zone protection using point detectors because they can only report the position of a vehicle at a specific point in space and time. A relatively safe but inefficient approach is often followed for providing protection using just one point detector. This method uses the 85th and 15th percentile velocities from a historical distribution to determine a fixed location for the point detector near the start of the expected danger zone, as well as a fixed time for green extension after the detection of a presence at the fixed location. This approach will not provide the anticipated level of safety when the historical 85 percentile speed underestimates actual vehicle speeds, and lowers operational efficiency by increasing the average headway required for gap out. Furthermore, due to the phase maxing out, dilemma zone protection often fails (6).

Researchers have used multiple point detector schemes like Beirele Method, Winston-Salem method (7), SSITE (8), and NDOR Detector spacing (4), along with advanced control algorithms (9,10,11,12), to improve the safety and efficiency of operations. Advanced dilemma zone algorithms like SOS (12) and D-CS (11) use probabilistic models to track the vehicle over time. These models generally assume that the vehicle speed (during green phase) measured by an advance speed trap remains constant until the vehicle crosses the stop bar. This assumption does not typically hold in reality. Bleyl (13) shows that the average speed and variance change as the vehicle approaches the stop bar during green. The impact of a traffic signal is different on different drivers. The effect is more pronounced as drivers move closer to the intersection. This phenomenon can be responsible for an increase in speed variance as the vehicle approaches the stop bar.

A WAD can significantly benefit dilemma zone protection algorithms by detecting the actual position and speed of every vehicle in the dilemma zone instead of using extrapolated values. This paper first illustrates the tracking advantages of a WAD over point detector and speed trap. It proposes a general-purpose evaluation methodology and tests the WAD at an intersection in Noblesville, Indiana. However, the paper does not directly evaluate the operational performance of proprietary dilemma zone protection algorithms embedded in the WAD (14).

STUDY SITE DESCRIPTION AND DATA COLLECTION METHODOLOGY

The data collection site is the signalized intersection of SR 37 and SR 38 in Noblesville, Indiana as shown in Figure 1a. This instrumented intersection logs detector actuations, signal states, and simultaneous video recording of the existing traffic condition. Figure 1b illustrates the data collection environment used for the evaluation.

The detectors used for data collection include:

- NA7, NB7, NA5, NB5, SA5 and SB5: Point detectors located 413 ft away from the stop bar. These detectors were used to estimate arrival volumes in both directions. The combination NA7 and NA5; NB7 and NB 5 were used as speed traps to determine the speed of arriving vehicles. A "speed trap" is pair of detectors separated by a fixed distance. The speed of a vehicle is calculated by measuring the elapsed travel time between the pair of detectors separated by a known distance.
- SB WAD and NB WAD: The southbound WAD was mounted on a mast arm 155 ft behind the stop bar at a height of 37 ft. The northbound WAD was mounted on the span wire pole adjacent to the stop bar at a height of 30 ft
- SB Video and NB Video: Video cameras mounted on SB and NB mast arms were used for visual validation.

The detector actuations and phase change data were recorded in a data file with a resolution of 1/1000 of a second and an approximate accuracy of 1/100 of a second. These data were used to estimate the speed and position of the vehicle entering the control area. WAD track files with the distance, speed, and identification number of reported detections were logged and displayed on a PC with video feed with hyper text showing change in detector status and signal phases. The displayed WAD and video data were simultaneously recorded using screen capture software as shown in Figure 1b. Test runs were made with probe vehicles having a hand held GPS device (15).

ILLUSTRATION OF ADVANTAGES OF WADS

A set of 100 vehicles in free flow state were tracked using the data collection scheme described above. The vehicle position and speed for 4 discrete time periods (t_0 , t_0+1 , t_0+2 , and t_0+3 separated by one second duration) given by the WAD were compared against those from the following technologies:

1. Point detector: This detector provides the time when the vehicle is at 413 ft from the stop bar. The position of the vehicle in subsequent time intervals is projected using the posted speed limit (55 mph).
2. Speed Trap: This detector provides the time and speed when the vehicle is 413 ft from the stop bar. The position of the vehicle in subsequent time intervals is projected using the measured point speed.

Figures 2a, 2b, 3a and 3b show the frequency distribution of the position of 100 vehicle at each time step t_0 , t_0+1 , t_0+2 , and t_0+3 as estimated by the three technologies, respectively. At time t_0 , both the point detector and speed trap report the vehicles to be

present at 413 ft from the stop bar. However, there is some variance in the distances reported by the WAD. This variation can be attributed to one of three factors: i) the WAD has an estimation distance accuracy of ± 5 ft, ii) erroneous distance is reported by the WAD iii) vehicles with varying magnetic properties are detected at different points in space but reported as 413 ft by the point detector and speed trap.

Figure 2b plots the vehicle distribution in space for time step 1 (one second after detection by point detector). All vehicles detected by the point detector are projected to a single point in space because of the constant speed assumption. Vehicles projected using the speed trap and the WAD occupy different positions over time due to speed variance. Figure 3a and Figure 3b present plots of spatial vehicle distribution for time steps 2 and 3, respectively. The point detector performed the worst at estimating the position of vehicle over time. The speed trap performed slightly better, but the performance deteriorated considerably with increased extrapolation time.

This simple case study illustrates the advantages of WAD over point detector and speed trap in tracking vehicles over time. The full benefits of a WAD are realized only if it performs as per the ideal requirements. The next few sections describe these requirements and evaluate their performance.

PERFORMANCE REQUIREMENTS AND EVALUATION PROCEDURES

Table 1 lists the performance requirements for the ideal operation of a WAD and compares WAD with point detector. WAD should be able to:

- Accurately detect vehicle entry: WAD should be able to accurately detect all the vehicles (with no false or missed detections) as they enter a certain location upstream of stop bar. The required performance yardstick for ideal operational range for a WAD depends on the dilemma zone boundaries for the given facility. Point detector performs accurately in detecting the presence of a vehicle at a predetermined position.
- Accurately track vehicle position: WAD should precisely measure the position of each vehicle within the danger zone. Point detector cannot track the vehicle position over time, but can estimate it using an assumed speed.
- Accurately track vehicle speed: WAD should be able to precisely measure the speed of each vehicle within the danger zone.
- Accurately detect vehicle exit: WAD should continuously sustain monitoring of detection until it crosses a certain location in the vicinity of the stop bar.

For dilemma zone applications, the performance criteria are best evaluated during the green phase of the cycle after the initial queue has cleared. The performance tests conducted are briefly described hereafter:

Start distance and end distance histogram

This test evaluates the WAD's functional range. The variation of the start and the end point of detection should be within acceptable limits. Figure 4a gives a conceptual figure of expected distribution and acceptable limits. Ideally, crisp boundaries for start and end distance are preferred, but some variation is acceptable if it is outside the dilemma zone

boundaries. After a vehicle has been registered it should be continuously tracked through the dilemma zone.

Control Volume Test

This test evaluates sudden non-feasible change in the number of vehicles within a control range. Suppose XX and YY define the danger zone as shown in Figure 4b. The change in number of vehicles in the control range within an infinitesimal change in time (0.2 sec used for this study) cannot exceed 2. Either two vehicles (Veh1 and Veh2 in Figure 4) can simultaneously enter at specific time instances thereby increasing the number of vehicles in the control range, or two vehicles (Veh3 and Veh4 in Figure 4) can simultaneously exit reducing the control volume by 2 vehicles. Any other combination would lead to a smaller change in control volume. Any absolute change greater than 2 in control volume will signify false detections being generated or true detections being dropped before the vehicle passes the control range.

Ideally, only through vehicles should be detected. There is a possibility that vehicles in left or right turn bays are being continuously detected, but still the change in control volume is less than two. Such an error will be detected using the volume comparison test.

Volume comparison against the loop data

This test evaluates if there is an excess or shortage in the number of vehicles detected over a long-term aggregation period. This test can capture if extraneous detection of turning traffic is erroneously adding to through-movement detection. Five minute aggregate volume data as measured by point detector was compared against the five minute aggregate volume data obtained by multiplying space mean speed and density in the control range as shown in Figure 3b. Constant overestimation of traffic by the WAD can significantly reduce the number of gap out opportunities thus affecting the safety and efficiency of operations.

A short duration ground truthing experiment was performed to verify the accuracy of counts measured by loop detector. One hour of detector counts was collected for each direction and also visually counted. The volume was in the range of 500 vph ~ 600 vph for both directions. The Southbound direction overcounted by 3.2% and the Northbound direction overcounted by 7.2%. These results are consistent with previous 24 hour studies (17) that show slight over counting is common due to artifacts such as large vehicles and vehicles towing trailers.

Probe vehicle test for accurate speed and position

Probe vehicles of different vehicle classes (sedan, pickup truck, 8-passenger van) equipped with GPS handheld device are tracked using the WAD. The speed and position information given by the WAD are compared against the GPS track. The GPS device used has a position estimation accuracy of ± 6 ft.

The speed obtained using the GPS device was validated against an Onboard Diagnostic Device (OBD) (16) which logs the vehicle's built-in speed sensor. Figure 5 shows the speed profiles of the GPS and the OBD. It confirms that the GPS device can be accurately used for speed measurements.

INDIVIDUAL VEHICLE PERFORMANCE

Three vehicle types: sedan, pickup truck, and 8-passenger van, were used to collect data for the probe vehicle test. Ten runs were conducted in each direction for each vehicle type. Time was dynamically synchronized to a 0.01 second precision across the data collection computer and GPS device.

Figure 6 presents an example of the actual performance of a WAD in both directions. The speed and distance plots agree closely with GPS as desired. Figure 7 presents an example of undesired performance of WAD. It can be observed in Figure 7b that WAD stops updating the speed of the vehicle at time t_1 and registers a constant speed until time t_3 . The error in speed exists for the vehicle though its position is tracked accurately as shown in Figure 7c. Note that there is a clear change in speed at the point of inflection t_2 which is not reflected in Figure 7b. A visual verification of the run indicated that the error was due to a passing vehicle in the adjacent lane. In the southbound direction, the WAD speed curve shown in Figure 7e has a stair-step appearance because the reported speed is not continuously updated. Speed errors like these may lead to erroneous decisions on whether a vehicle is in its dilemma zone.

Regression analysis was performed on the distance and speed errors. The analysis results are presented in Tables 2 and 3 and summarized below:

Distance error analysis

- There is a systematic negative bias in the distance reported by the WAD in the SB direction. This can also be seen in the percentile errors. This bias can be easily corrected by providing a fixed correction to the estimated distances.
- The effect of distance, speed and acceleration on the precision accuracy is within 5 ft for the operating range. This is within the acceptable realm for practical applications.
- The vehicle type affects the estimation accuracy. The larger vehicles are reported to be further away than their actual locations. The location of the sensor seems to play a major role in this error, which appears to be twice as large for the southbound direction in comparison to the northbound one. The error may also be related to the vehicle's external geometry or lane position, and the cosine correction used by WAD.

Speed error analysis

- Speed error is low in both directions as can be observed from the percentile errors.
- None of the speed-error drivers had a significant impact on the accuracy. The speed error was within 2 mph for operating range, which is within the acceptable range for field application.

Analysis of the results, reported above, suggests that the WAD performs reasonably well in term of tracking individual vehicles. The WAD showed some fixed bias which can be removed by tweaking setup parameters during installation.

CALL ACTIVATION AND DEACTIVATION PERFORMANCE

Four hours of performance test data were collected on July 4, 2007, Wednesday, from 5:00 P.M. to 9:00 P.M. Video feeds were also recorded for the manual validation of errors.

The tests described earlier were conducted and associated results are summarized below.

Control volume test

Figures 8a and 8b present the control volume test results for the northbound and the southbound directions, respectively. The northbound direction exhibited 7 outliers with an absolute change in control volume exceeding 2. The southbound direction showed just one outlier.

The error of sudden surge or drop in detection is insignificant for the southbound direction. However, it may be of concern for the northbound WAD, with the observed rate of approximately 45 errors per day. These errors can reduce operational efficiency. It should be pointed out here that the points lying outside the thresholds are definitely errors, but that points lying inside the thresholds can also represent errors.

Volume comparison against the loop data

Figures 9a and 9b present the volume comparison test results for the northbound and the southbound directions, respectively. The WAD reports higher volumes than the point detector in both directions. The error is more prominent in the northbound direction. The mean error in northbound direction was 340 vph, and in southbound direction was 180 vph. Manual observation showed that the standing queue, simultaneous double detection of large vehicles, and the turning volumes, were responsible for these errors. The main difference in the errors between the northbound and the southbound direction can be attributed to two reasons:

1. The left turn and right turn volumes in the northbound direction are greater than those for southbound direction.
2. The northbound WAD is mounted roadside and oriented so as to envelop more of the turn bays in its sensing area.

Start distance and end distance histogram

Figures 10a and 10b present the results of the start distance and end distance test. There is considerable noise in the data in both the northbound and the southbound direction. These figures reconfirm the fact that the presence of the long turn bays and stop-and-go vehicle queues lead to undesired detection of turning movements and multiple identifications of the same vehicle. For example, in the northbound direction there are considerable amount of detections that start and end in the region of 300 ft to 150 ft away from stop bar. The performance of the WAD is better in southbound direction because of fewer left turning vehicles and smaller standing queues. Due to the small queue length in southbound direction, the region of queue noise shifts closer to the stop bar. The effect of this noise on the dilemma zone protection algorithm is reduced if region of noise falls outside the dilemma zone boundaries, as is the case in the southbound direction.

The starting distance at which the vehicle is first detected is closer to the stop bar in the southbound direction. The range of the WAD in both the northbound and the southbound

direction is fixed, but the installation on the mast arm in the southbound direction reduces the coverage of the WAD beyond the stop bar. This is an important element to be considered while installing a WAD. The location should be such that the range of the sensor covers the boundaries of the dilemma zone.

The WAD, as it is currently installed at Noblesville site, performs well in terms of accurately tracking the vehicle position and speed, but needs to be improved to accurately detect only vehicles that enter and then exit the approach in the through lanes.

DISCUSSION AND CONCLUSION

This paper lays out a structured approach to evaluate the performance a new technology in the field of wide area detector. Theoretically, a WAD is a superior technology than a point detector for implementing dilemma zone algorithms. However, after evaluation using the criteria laid out in Table 1, the results were mixed:

- Accurately detect vehicle entry: The performance of the WAD for this metric was sub-standard due to the excessive number of false detections generated on turning traffic and standing queues (Figure 9). Three to four occurrences of completely undetected vehicles by the WAD were also observed during an hour.
- Accurately track vehicle position: Overall, the WAD performed well on this metric. A fixed bias was observed in the southbound direction, but this can be removed by fine-tuning the sensor in the field. Some insights gained by the regression model can be used to further improve the accuracy of the WAD.
- Accurately track the vehicle speed: The WAD performance was satisfactory for this metric. There were a few cases where the speed was not updated after a certain point in time (Figure 7c). These errors were particularly noticeable when adjacent vehicles were moving closely together.
- Accurately detect vehicle exit: The performance of the WAD on this metric was seriously affected by the standing queues and turning volumes. The WAD needs to filter such noise from the data.

In summary, the WAD shows a considerable potential for improving the safety and efficiency of dilemma zone protection algorithm. But the detection and tracking accuracy of the WAD need to be further improved, particularly when used on approaches with significant turning traffic.

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LIST OF TABLES AND FIGURES

TABLE 1 Comparison of point detection versus wide area detection.....	13
TABLE 2 Regression model for error in distance	14
TABLE 3 Regression model for error in speed	15
FIGURE 1 Data collection setup used in Noblesville, IN.	16
FIGURE 2 Frequency distribution of vehicle location as seen by the controller using three different detection systems (initial and 1 second after).	17
FIGURE 3 Frequency distribution of vehicle location as seen by the controller using three different detection systems (2 seconds and 3 seconds after).	18
FIGURE 4 Concept figures for explaining evaluation tests.	19
FIGURE 5 Speed comparison between the GPS and onboard diagnostic device.	20
FIGURE 6 An example of desired performance of WAD for tracking probe vehicle (Dodge Ram Van) on July 4, 2007.	21
FIGURE 7 An example of undesired performance of WAD for tracking probe vehicle (Dodge Dakota) on June 29, 2007.	22
FIGURE 8 Dilemma zone control volume test.....	23
FIGURE 9 Dilemma zone volume comparison test.	24
FIGURE 10 Histogram of vehicles arriving and departing the WADS detector zone during green (using WADS data with no manual filtering).	25

TABLE 1 Comparison of point detection versus wide area detection

Performance Requirements	Expected Capability		Test Conducted
	POINT DETECTOR	WAD	
Accurately detect vehicles entering	✓ (Advance Detector)	✓	• Start distance histogram • Control volume test • Volume comparison against loop data
Accurately track vehicle position	NO	✓	• Probe vehicle test for accurate position
Accurately track vehicle speed	NO	✓	• Probe vehicle test for accurate speed
Accurately drop calls when vehicles crosses stop bar	✓ (Stopbar Detector)	✓	• End distance histogram • Control volume test • Volume comparison against loop data

TABLE 2 Regression model for error in distance

a) NB direction:

Regression Statistics				Percentile Errors		
R^2 : 0.13	Adj R^2 : 0.13	Std Err: 7.03	Obs: 1511	15%: -4.1	50%:3.1	85%:8.4

Variables	Coeff	t-Stat	Comments
Intercept	-11.15	-7.00	Negative bias of 11 ft was observed for NB direction.
Speed	0.23	8.41	WAD predicted higher distances for the vehicles traveling faster. So, WAD will have an approximate error of 11.5 ft for vehicles traveling at 50 mph.
Distance from WAD (per 100ft)	0.48	2.74	WAD predicted higher distances for the vehicles further away from stop bar. It adds 0.5 ft with every 100 ft. This error is insignificant for all practical purposes.
Acceleration	-0.83	-5.89	WAD predicted lower distances for accelerating vehicles and higher distances for decelerating vehicles. Typically dilemma zone protection algorithm works during free flows, when the level of acceleration or deceleration is low.
Truck	1.73	3.76	WAD predicted higher distance for pickup truck as compared to normal sedan.
Van	6.57	13.16	WAD predicted higher distance for van as compared to normal sedan.

a) SB direction:

Regression Statistics				Percentile Errors		
R^2 : 0.51	Adj R^2 : 0.51	Std Err: 5.07	Obs: 1433	15%:-28.6	50%:-20.9	85%:-13.2

Variables	Coeff	t-Stat	Comments
Intercept	-20.14	-40.46	Negative bias of 20 ft was observed for SB direction.
Distance from WAD (per 100ft)	-1.38*	-13.99	WAD predicted lower distances for the vehicles further away from WAD. It adds 1.4 ft with every 100 ft. This error is insignificant for all practical purposes.
Acceleration	0.22*	4.19	WAD predicted higher distances for accelerating vehicles and higher distances for decelerating vehicle. Typically, dilemma zone protection algorithms work during free flows where the level of acceleration and deceleration is low.
Truck	4.22	13.06	WAD predicted higher distance for pickup truck as compared to normal sedan.
Van	11.56	35.58	WAD predicted higher distance for van as compared to normal sedan.

(* the sign of these factors reversed from NB to SB)

TABLE 3 Regression model for error in speed

a) NB direction:

Regression Statistics				Percentile Errors		
R^2 : 0.4	Adj R^2 : 0.4	Std Err: 3.57	Obs: 1511	15%: -5.2	50%: -2.1	85%:0.96

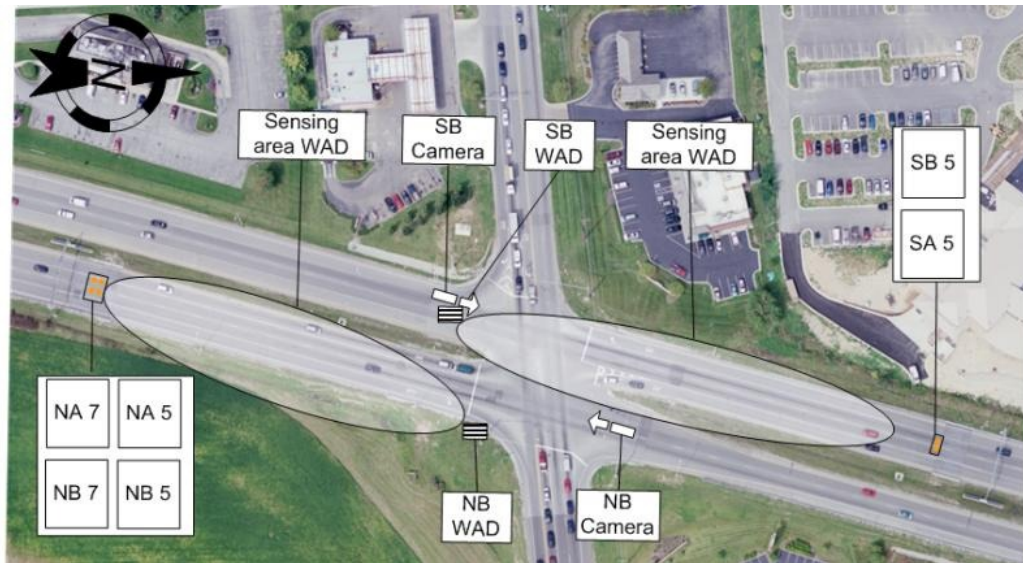
Variables	Coeff	t-Stat	Comments
Speed	-0.09	-17.97	WAD predicted lower speeds for the vehicles traveling faster. Everything else remaining constant the WAD will have an approximately error of -4.5 mph for vehicles traveling at 50 mph.
Dist from WAD (per 100ft)	0.54	9.44	WAD predicted higher speeds for the vehicles further away from stop bar. It adds approximately 2 mph at a distance of 400 ft.
Acceleration	-0.60	-18.06	WAD predicted lower speeds for accelerating vehicles and higher speeds for decelerating vehicle. Typically dilemma zone protection algorithm work during free flows where the level of acceleration and deceleration is low.
Truck	0.42	2.17	WAD predicted higher speeds for pickup truck as compared to normal sedan. The error of 0.4 mph is negligible for all practical purposes.

a) SB direction:

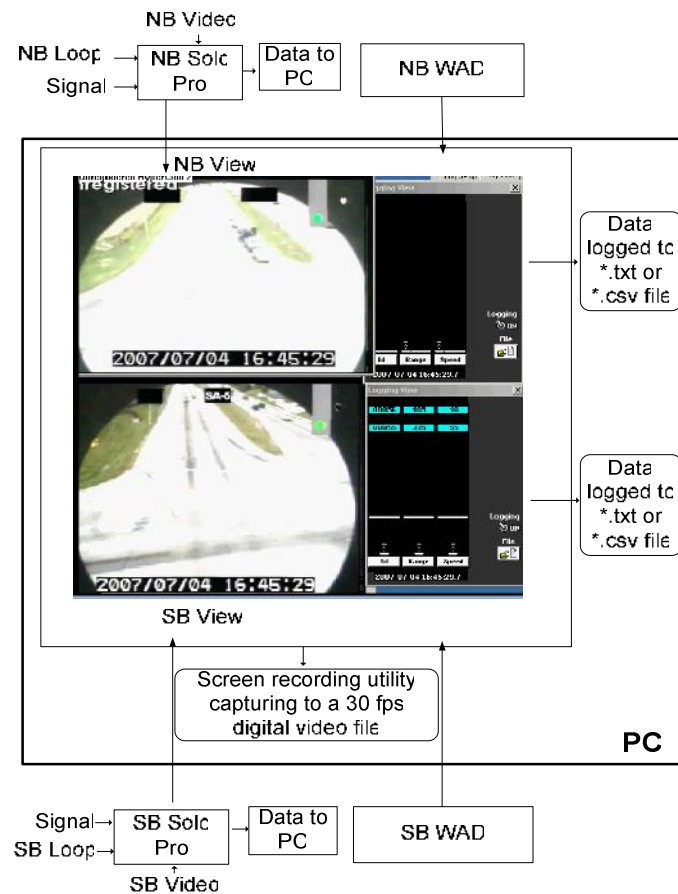
Regression Statistics				Percentile Errors		
R^2 : 0.24	Adj R^2 : 0.24	Std Err: 2.64	Obs: 1469	15%: -2.5	50%:0.0	85%:2.8

Variables	Coeff	t-Stat	Comments
Speed	-0.04	-7.58	WAD predicted lower speeds for the vehicles traveling faster. Everything remaining constant WAD will have an approx error of -2.0 mph for vehicles traveling at 50 mph.
Dist from WAD (per 100ft)	0.15	2.90	WAD predicted lower speeds for the vehicles further away from stop bar. It adds 0.6 mph at a distance of 400ft.
Acceleration	-0.46	-18.19	WAD predicted lower speeds for accelerating vehicles and higher speeds for decelerating vehicle. Typically dilemma zone protection algorithm work during free flows where the level of acceleration and deceleration is low.
Truck	-0.23*	-1.57	WAD predicted lower speeds for van as compared to normal sedan. The error of 0.2 mph is negligible for all practical purposes.

(* the sign of these factors reversed from NB to SB)

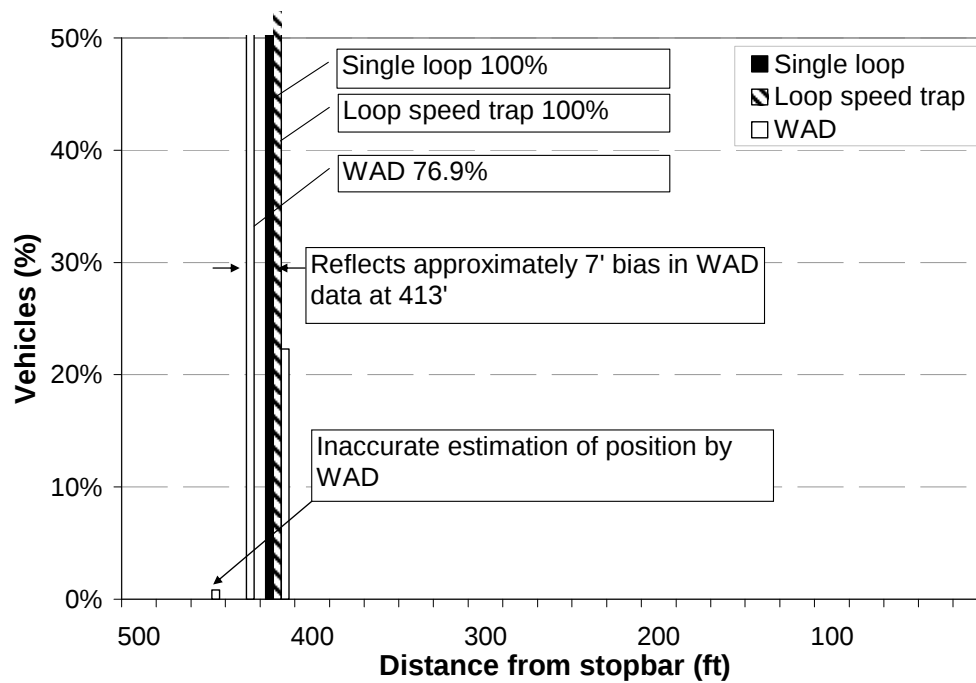


a) Intersection layout

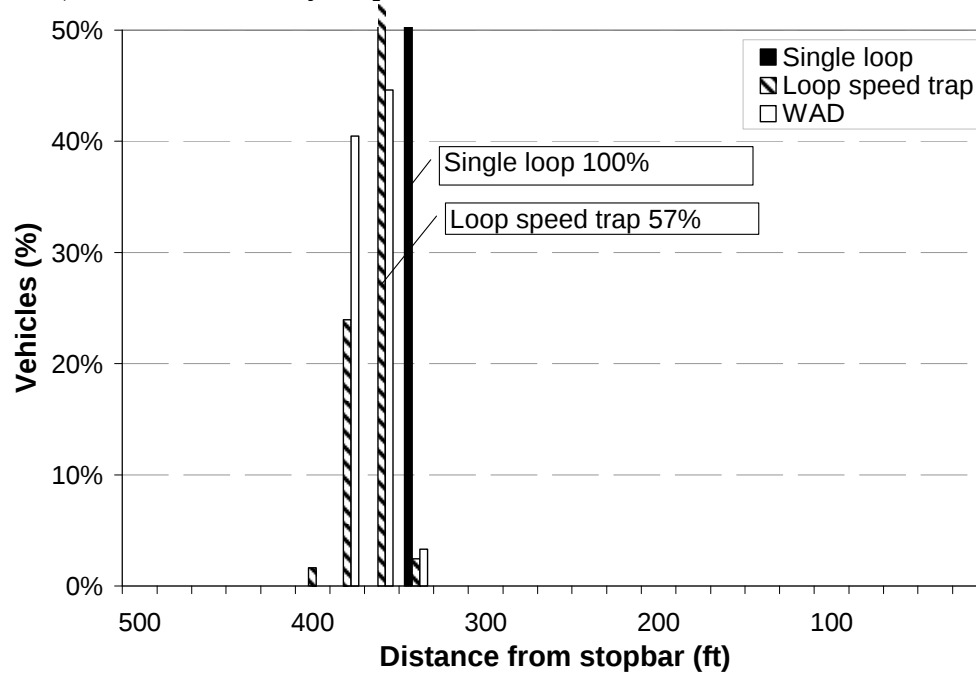


b) Data collection environment

FIGURE 1 Data collection setup used in Noblesville, IN.

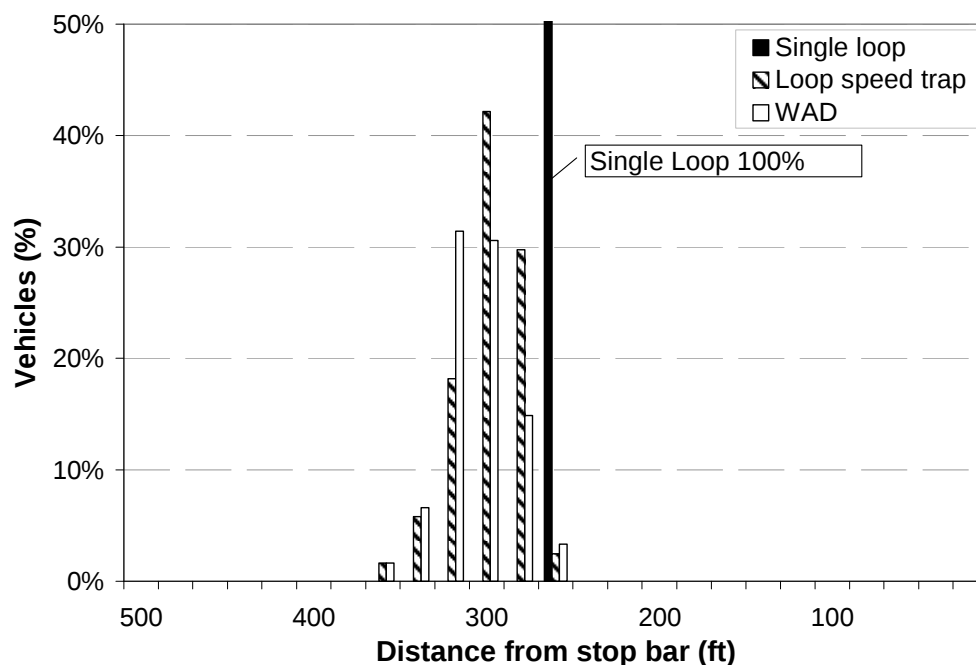


a) Initial detection by loop detector

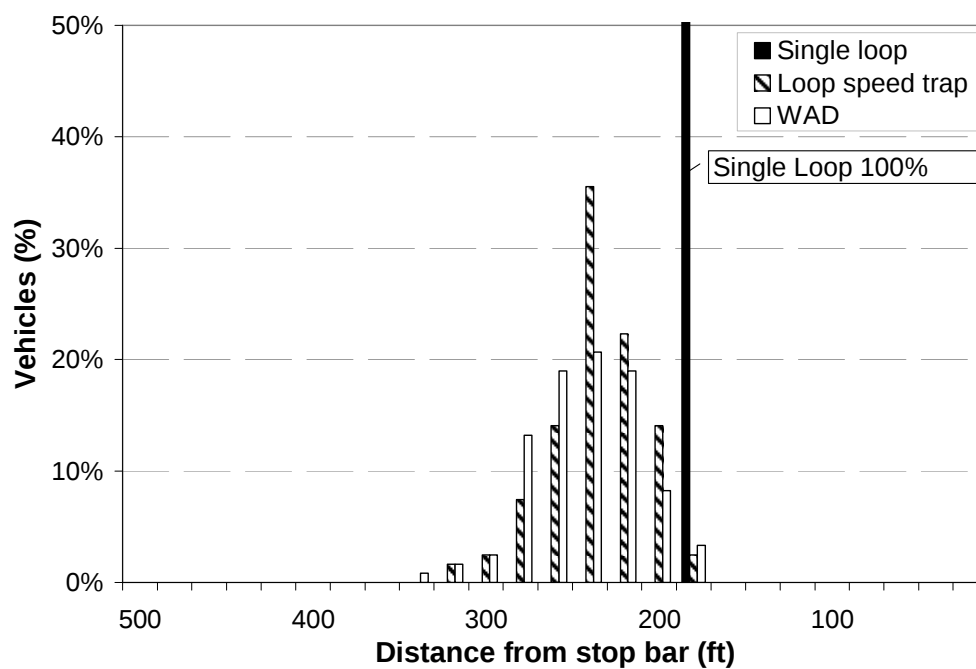


b) 1 Second after initial detection

FIGURE 2 Frequency distribution of vehicle location as seen by the controller using three different detection systems (initial and 1 second after).

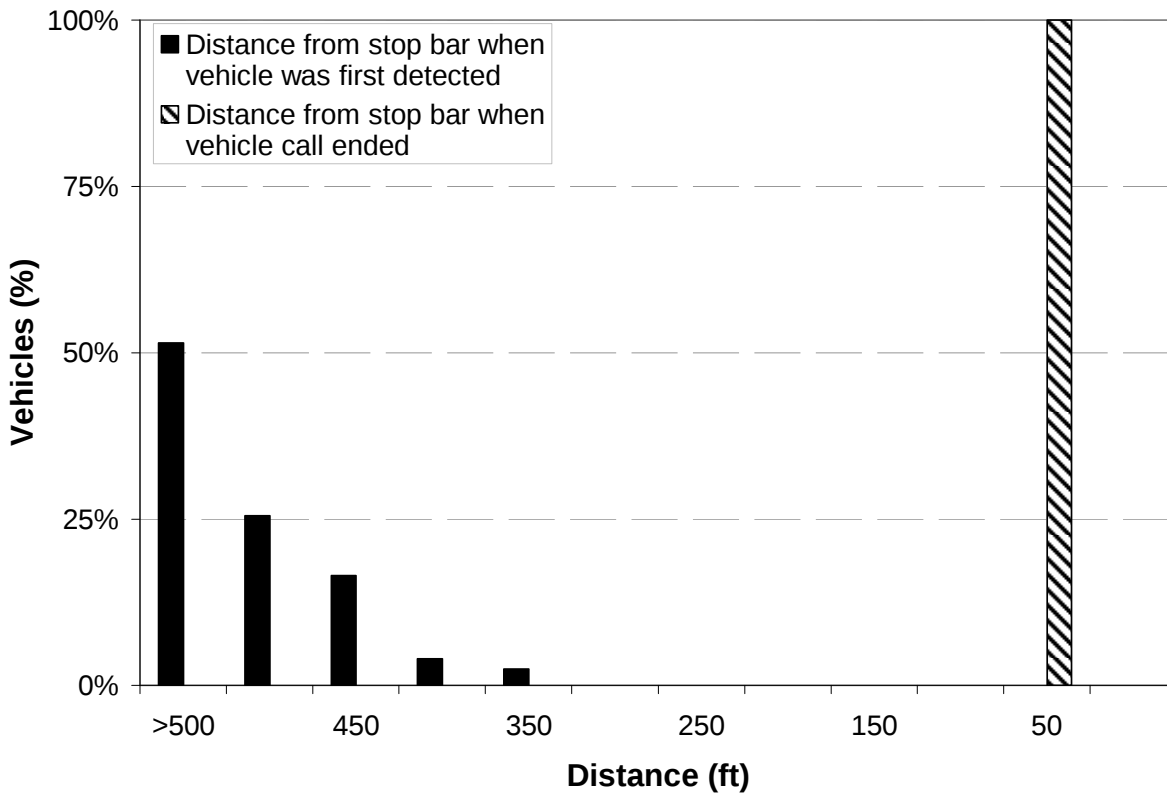


a) 2 Seconds after initial detection

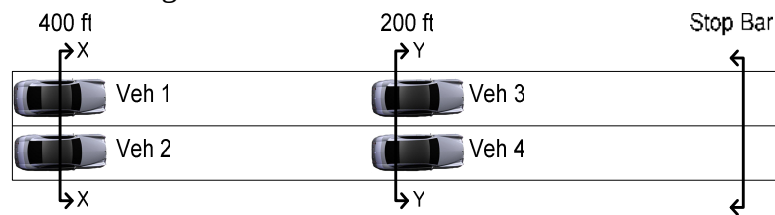


b) 3 Seconds after initial detection

FIGURE 3 Frequency distribution of vehicle location as seen by the controller using three different detection systems (2 seconds and 3 seconds after).

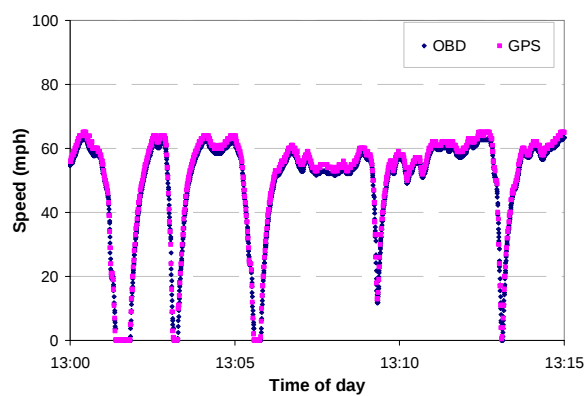


a) Hypothesized start and end distance histogram.

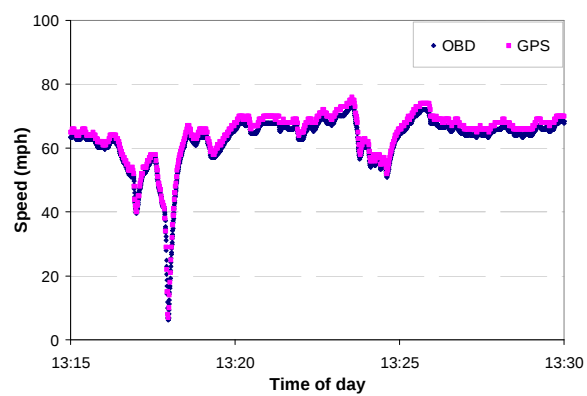


b) Dilemma Zone Control Volume Concept.

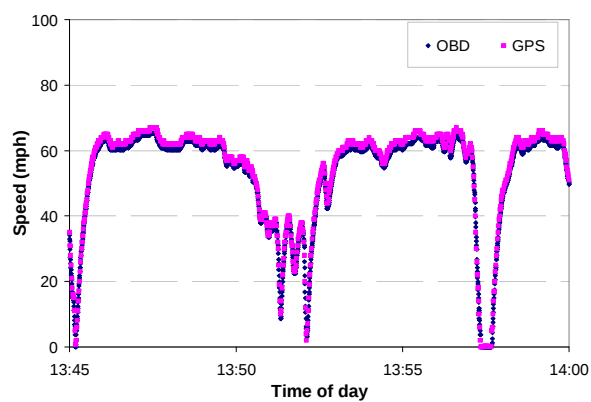
FIGURE 4 Concept figures for explaining evaluation tests.



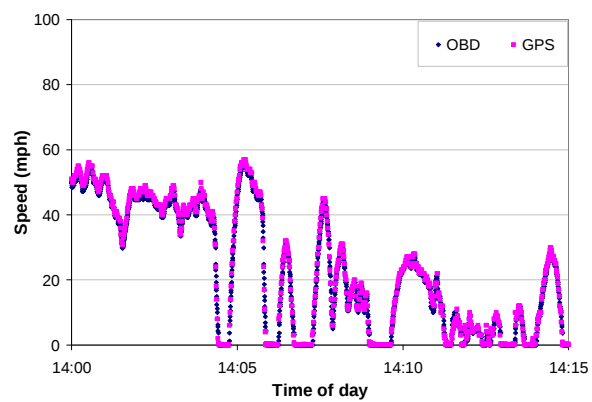
a) Speed versus time (1:00 PM-1:15PM)



b) Speed versus time (1:15 PM-1:30PM)

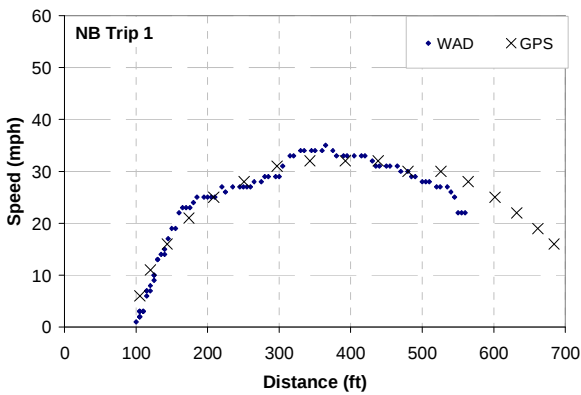


c) Speed versus time (1:30 PM-1:45PM)

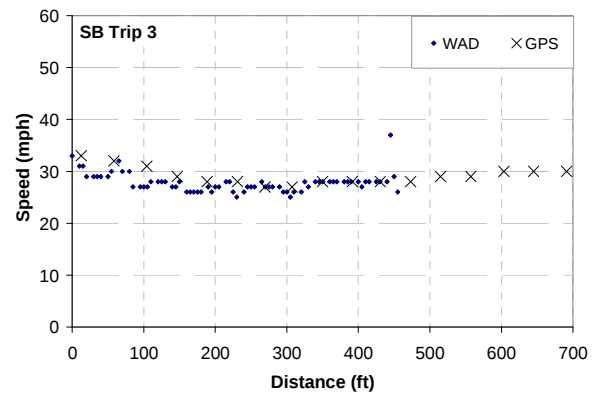


d) Speed versus time (1:45 PM-2:00PM)

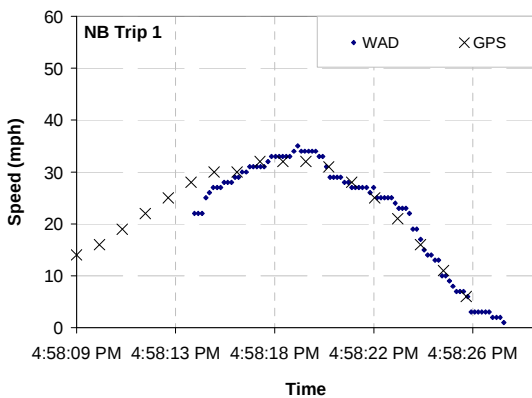
FIGURE 5 Speed comparison between the GPS and onboard diagnostic device.



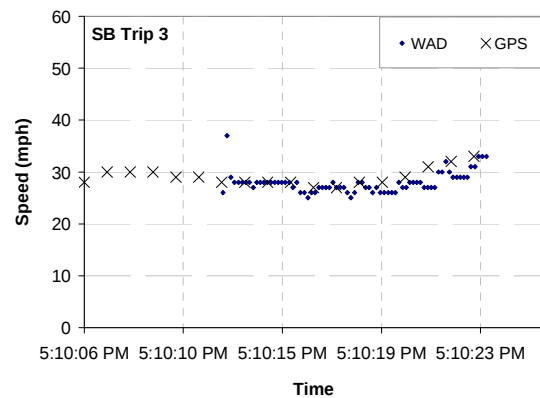
a) Speed versus distance (Northbound)



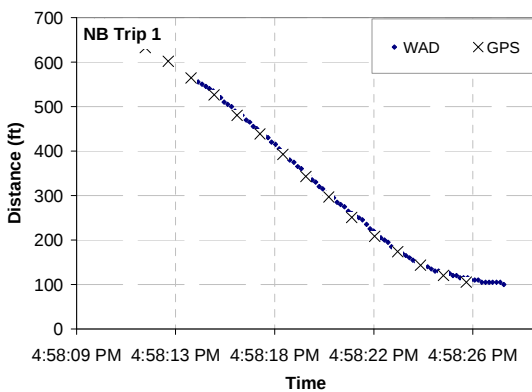
d) Speed versus distance (Southbound)



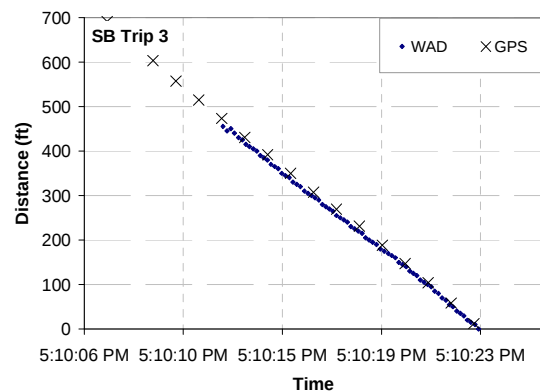
b) Speed versus time (Northbound)



e) Speed versus time (Southbound)

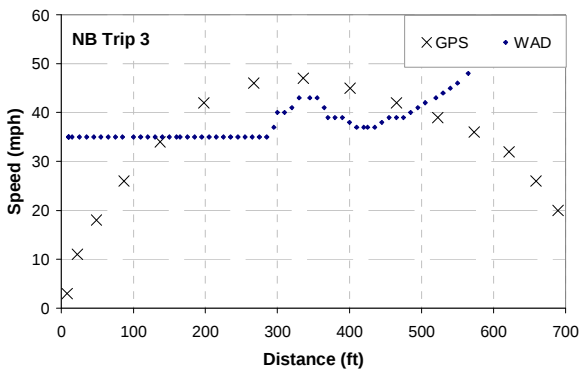


c) Distance versus time (Northbound)

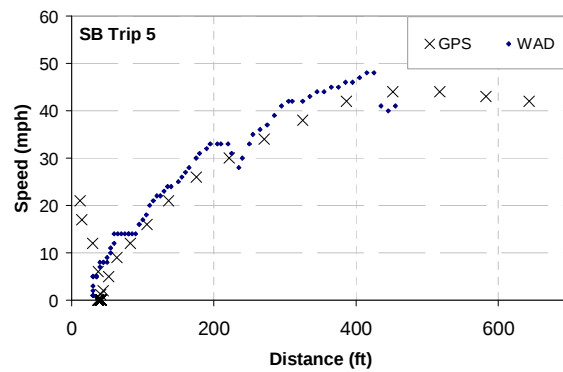


f) Distance versus time (Southbound)

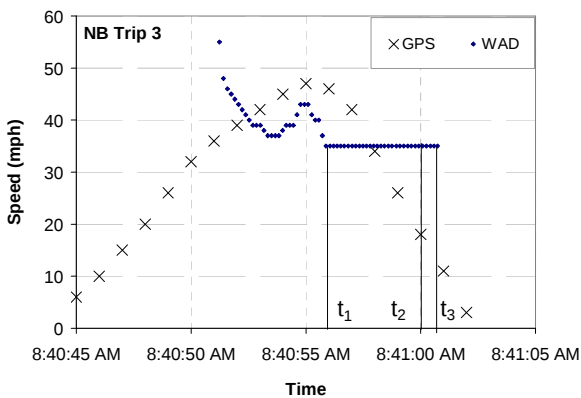
FIGURE 6 An example of desired performance of WAD for tracking probe vehicle (Dodge Ram Van) on July 4, 2007.



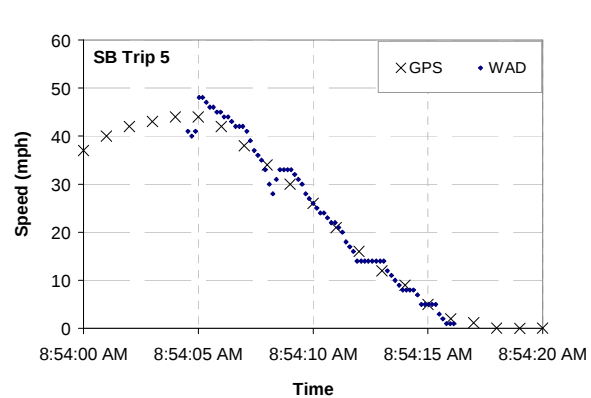
a) Speed versus distance (Northbound)



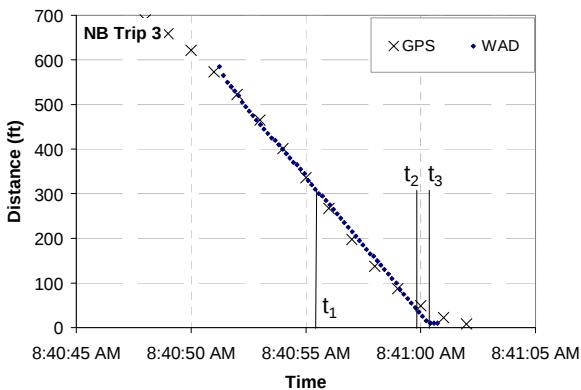
d) Speed versus distance (Southbound)



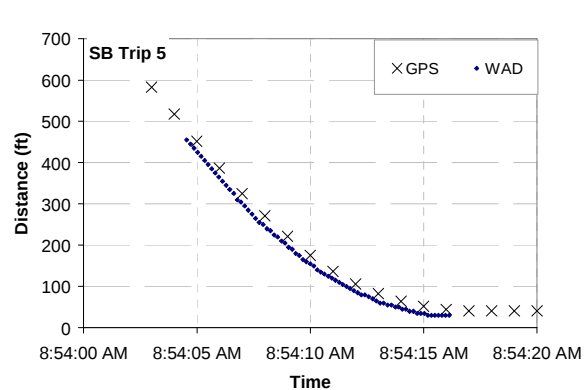
b) Speed versus time (Northbound)



e) Speed versus time (Southbound)

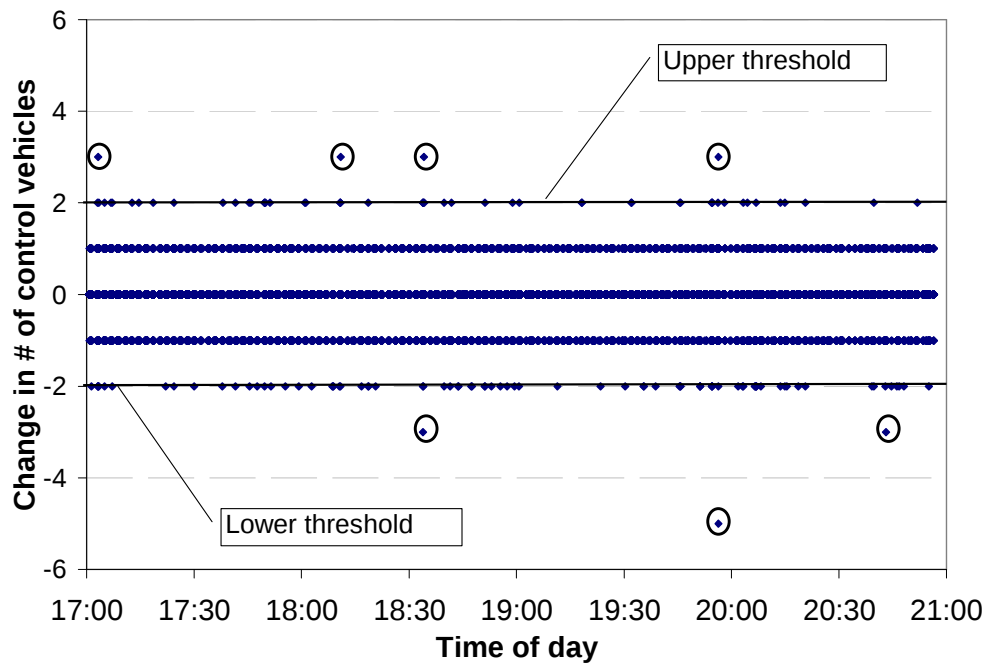


c) Distance versus time (Northbound)

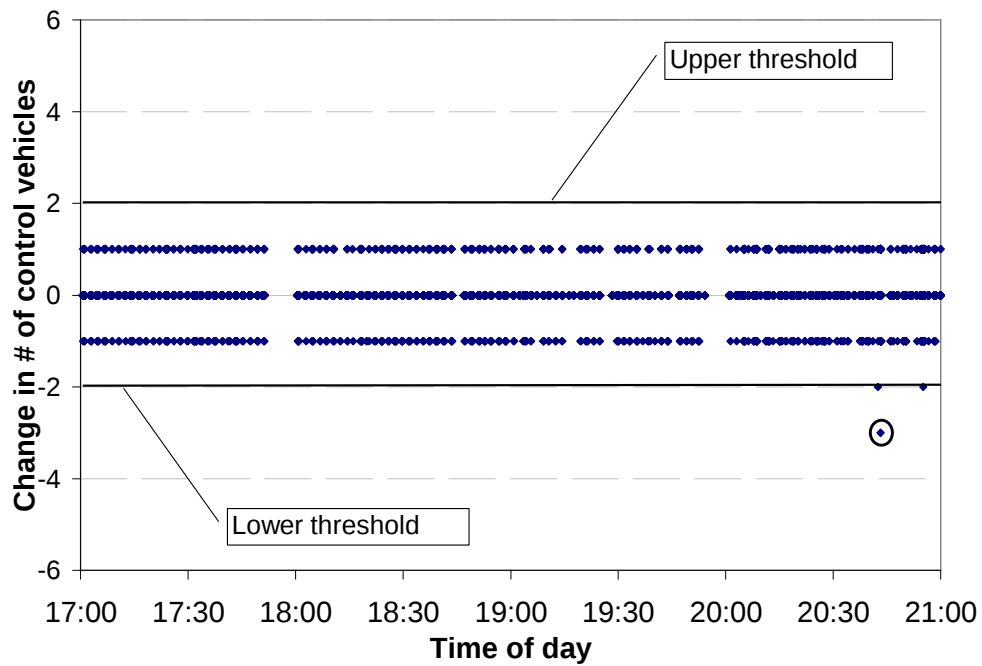


f) Distance versus time (Southbound)

FIGURE 7 An example of undesired performance of WAD for tracking probe vehicle (Dodge Dakota) on June 29, 2007.

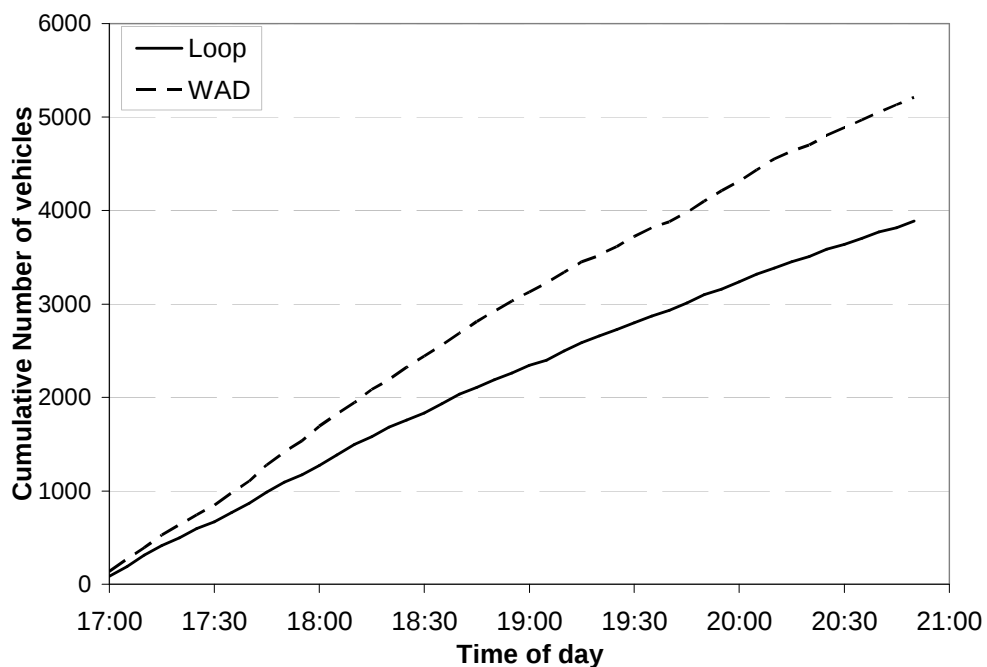


a) Northbound

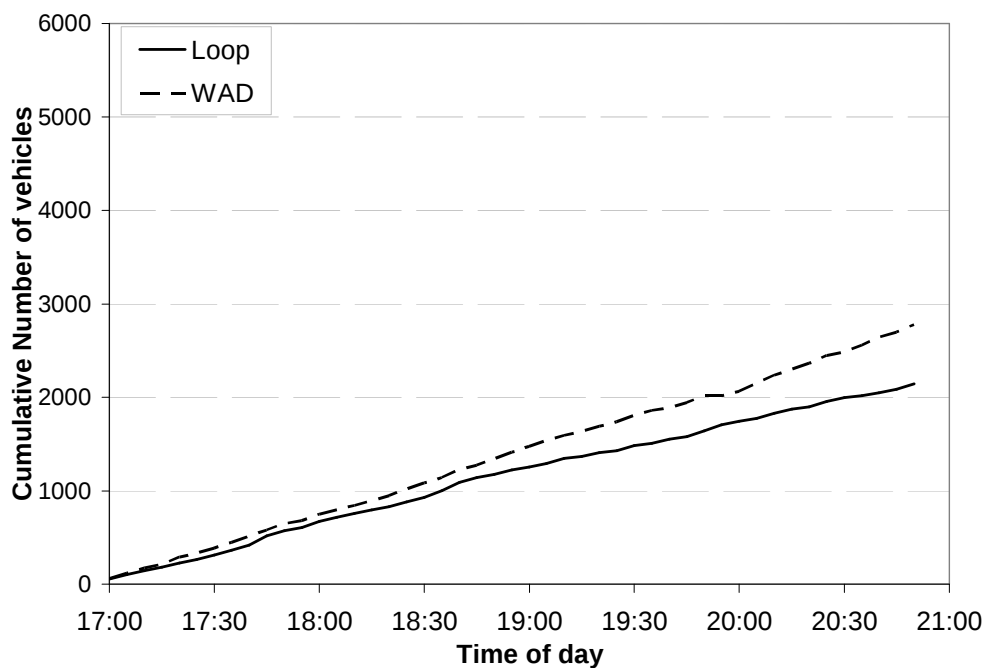


b) Southbound

FIGURE 8 Dilemma zone control volume test.

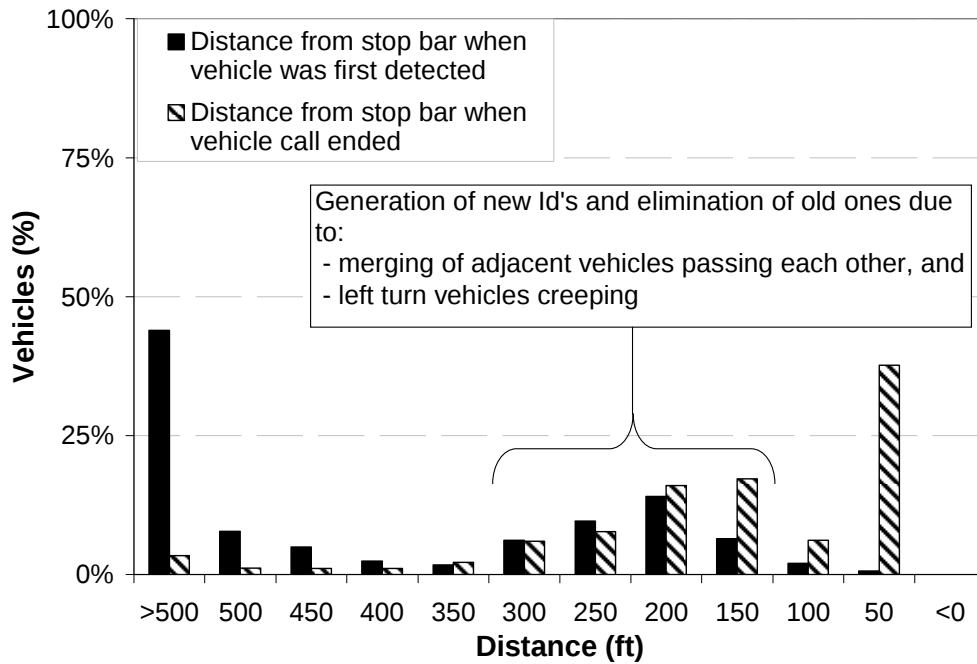


a) Northbound

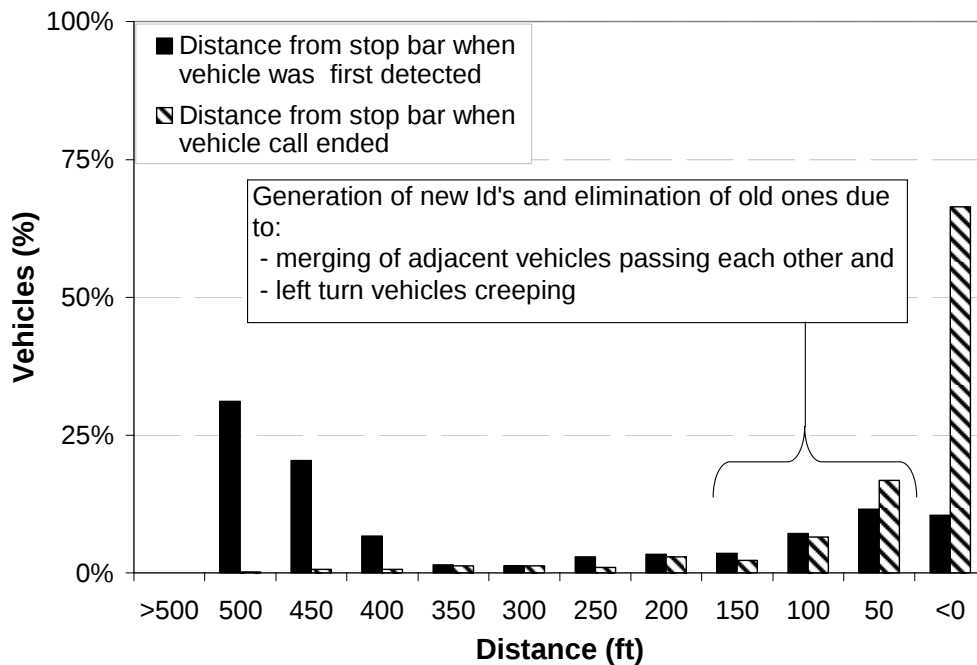


b) Southbound

FIGURE 9 Dilemma zone volume comparison test.



a) Observed histogram for the northbound approach (2581 vehicles).



b) Observed histogram for the southbound approach (476 vehicles).

FIGURE 10 Histogram of vehicles arriving and departing the WADS detector zone during green (using WADS data with no manual filtering).