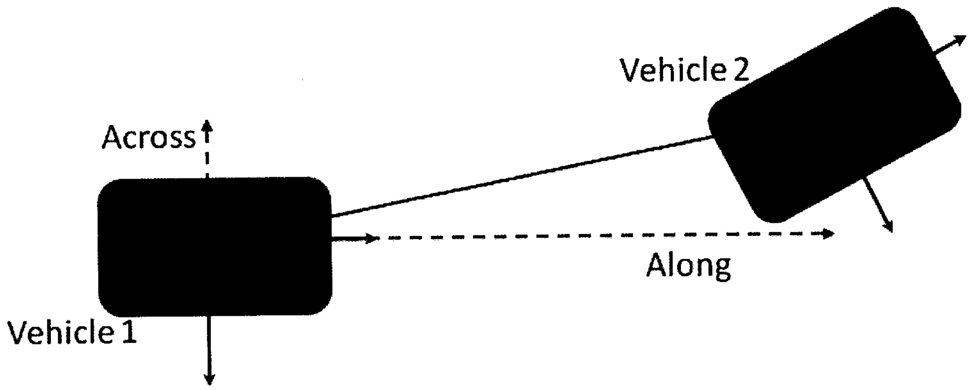


Figure 4-1: Definition of the Along Track (AT) and Across Track (XT) Components of the Inter Vehicle Vector (IVV)

A slight complication to the processing scheme just described arises because the resulting IVV depends upon the locations of the receiver antennas used in the calculations. As was mentioned in Section 3.1, the antennas used by the AW and B receivers on each vehicle were separated by 36 cm and placed on the centerline of the vehicle. Since the analysis requires the comparison of the IVV calculated using different receiver pairs, common reference points on each vehicle were required. Thus, in the calculations, the heading and pitch of each vehicle's GPS/INS reference system was used to effectively account for the location of the antenna for the B receivers, so that the reference points for the IVV could always be considered to be the phase centers of the antennas for the A receivers. The basic method by which this was achieved is shown schematically in Figure 4-2. In the figure, A_{Ant} and B_{Ant} are the locations of the phase centers of the antennas used by the A and B type receivers--the points at which the navigation solutions from the two receiver types are defined. The unit vector, **u**, in the vehicle's direction of travel is determined using the GPS/INS integrated system on the vehicle. As is shown, the navigation solutions from the B receivers can be translated back to A_{Ant} by subtracting 0.36**u**.

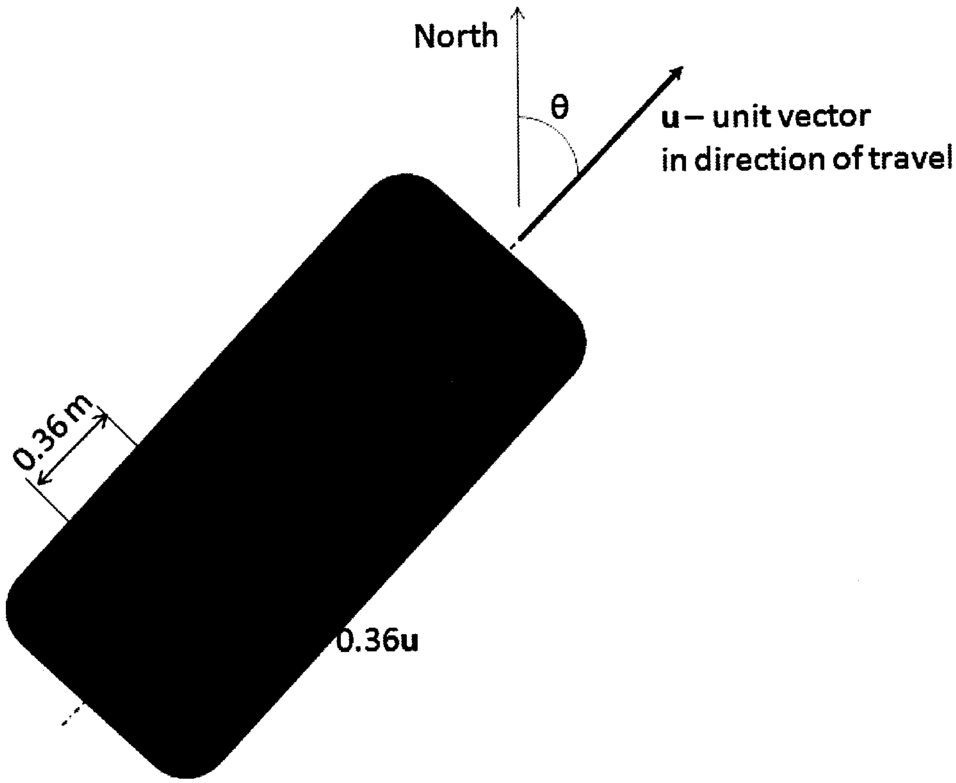


Figure 4-2: Schematic Showing the Antenna Geometry on One Vehicle

4.1 Reference Solutions

As mentioned in Section 3.1, dedicated Global Navigation Satellite System (GNSS) receivers and a GPS/INS system were included on each vehicle so that reference values of the IVV could be determined. For all environments except Deep Urban, multiple reference IVVs, at least three, were determined for redundancy. Once they were calculated, the solutions were compared visually for each data collection. Based on these comparisons, one of the references was chosen as the standard for that particular data collection, and a second was chosen for comparative purposes. The difference between the reference and comparison IVVs gives an indication of the confidence in the reference, particularly when different methods are used to calculate them. If the reference and comparison IVV differed by too much for a certain portion of a data set, that segment was marked as having an uncertain reference. The threshold for the difference was set at 1 m for all environments except Deep Urban; but as is shown in Section 8.1, this level was very rarely crossed. The root mean squared (RMS) difference between the chosen and comparison IVVs was usually much less than 20 cm.

As mentioned above, this multiple reference approach was not used for the Deep Urban environment. This was because the GNSS-based approaches could not be relied upon in the urban canyons--the GPS/INS derived IVV was used exclusively.

The methods by which the various reference solutions were calculated are now described. Commercially available GPS/INS SW was used to process the dual frequency GPS/INS data in a tightly coupled integration scheme using the base stations at CCIT. The geodetic positions of the two vehicles obtained from the SW were combined in the manner described above to obtain the AT, XT, and Up components of the reference IVV solutions.

Post-processing RTK estimates of the IVV in the local ENU frame were obtained using three SW packages. Two of the packages were developed within the PLAN group, one of which allowed either GPS only or GPS/GLONASS configurations. The third package was obtained from a commercial vendor.

The estimates of the IVV obtained were transformed into Along Track, Across Track, and Up components using the attitude of Vehicle 1 as determined by the GPS/INS system on that vehicle.

4.2 Vehicle to Vehicle (V2V) Processing Methods

Two methods of calculating the IVV solutions solely from the measurements of the test receivers were evaluated. These methods and their characteristics are described below.

4.2.1 Difference in Position (DPOS) Method

The SP navigation solution of each of the test receivers (AW, BW, BN, B24) on each vehicle was recorded. These navigation solutions were transformed using the method described with reference to Figure 4-1 to determine the AT, XT, and Up components of the IVV. This method is referred to as the Difference in Position Method (DPOS).

The major advantage of DPOS is its simplicity; it requires only that the receiver be able to calculate positions in real-time, and vehicles in the same area share their calculated positions. It may also be useful to transmit quality values along with this position estimate, including the number of satellites, the HDOP, or any other built-in quality indicators.

In DPOS, as long as measurement errors or biases affect both receivers in the same way, they will not affect the relative positions between the receivers. Although maximizing the number of satellites in view is the best strategy for calculating the best possible individual, SP position, it is not the best strategy for calculating the best possible relative position. For best results in terms of the relative position accuracy between two receivers, the use of common satellites is the most important condition.

4.2.2 Moving Base-Station RTK

As discussed in Section 3.3, RTK SW was used to calculate and log the six receiver baselines specified in Table 3-1. The solutions from this SW can be transformed to the desired components of the IVV using the method outlined at the beginning of Section 4. It should be mentioned that the solutions using the AW receiver on Vehicle 2 as base needed to have the direction of the IVV reversed.

With conventional RTK systems, one stationary receiver is used as the base station and is positioned at a known location. With a Moving Base-Station RTK, one receiver, the "host," is selected as the base station for each baseline; however, the location of the host is updated at every epoch using SP processing. Since the recommended operating range of the radios used in the V2V tests is 300 m (Bai & Krishnan 2006) [1] and the expected

SP position error is less than 10 m, the error that might be introduced in the IVV due to the above SP error is at the mm level (Luo & Lachapelle 2003) [3] and inconsequential in the present case.

Moving Base-Station RTK, generally referred to in the following simply as RTK unless clarification is required, has some significant advantages over the DPOS approach described previously. Only satellites that are visible to both receivers are utilized in RTK solutions, because a differencing method between measurements is used to reduce errors. This increases the likelihood that measurement errors that affect one receiver will affect both receivers similarly and will, therefore, not adversely affect the estimate of the IVV. RTK also makes full use of precise carrier phase measurements. The use of carrier phase measurements is described in the Literature Review document. It is important to reiterate that it may not always be possible to validate the estimated integer ambiguities, which would limit the precision of the position solution. Changes in the fixed or estimated integer carrier phase ambiguities also create changes in the estimated positions. Changes from float to fixed ambiguities or changes between fixed ambiguities can also cause discontinuities in the position solution.

4.3 Vehicle to Infrastructure (V2I) Processing Method

The implementation of position-assisted infrastructure is intended to improve positioning accuracy around key intersections or other critical locations. The Concept of Operation in the Cooperative Intersection Collision Avoidance System-Violations (CICAS-V) prototype system is an example of the use of this concept. In deployment, the infrastructure locations would broadcast reference station corrections in a zone surrounding a broadcasting point. When vehicles enter the infrastructure zone, they could switch their positioning methods from unassisted SP to kinematic mode relative to the reference point.

In this project, a broadcasting infrastructure point with a 300 m range was simulated using post-processing. The first part of the processing involved determining the location of the stationary tripod mounted antenna shown in Figure 3-5. This location was obtained by processing the measurements collected by the stationary receiver and base receivers at CCIT using commercial RTK-network SW. This SW estimated that the obtained RTK solution was accurate to 5 mm (1 sigma). Next, the GPS/INS position solution for each vehicle was used to identify the times at which the vehicle crossed the circle of 300 m centered on the infrastructure point. Using the stationary infrastructure receiver as base, commercial post-processing RTK SW was then used to determine RTK solutions for each of the test receivers (AW, BW, BN, B24W) on each vehicle for the times at which the vehicle was inside the circle. It is important to note that the processing for each time segment during which the vehicle passed through the circle was initiated at exactly the instant the vehicle crossed the circle, and the SW generally took a few epochs to converge or provide a solution. This was done because it emulates the conditions that will occur in future possible deployment (i.e., communication will only be possible within the specified range (here 300 m)), and this is when calculations could begin. The RTK solutions for each test receiver were transformed into geodetic positions using the previously determined location of the infrastructure point. Outside of the time segments during which a vehicle is within range of the infrastructure point, and for times during which no V2I solution is available, the derived geodetic position for each of the test receivers is replaced with that obtained from the receiver running in SP mode. Determination of the IVV from a pair of such padded V2I-aided solutions follows the same protocol as described for DPOS.

5 Performance Measures

The performance of the three methods of estimating the IVV, namely RTK, DPOS, and V2I, is analyzed for the multiple receiver combinations using two main measures of accuracy and availability. The precise meanings of these terms as used in this project are described below.

5.1 Accuracy

The accuracy of a particular method (RTK, DPOS, or V2I) and receiver combination for a particular data set is determined using the error in the determination of the IVV as a function of time relative to the reference chosen for that data set (refer to Section 4.1). The AT and XT components of the error time series are presented in plots, while their means and standard deviations are tabulated. Histograms and Cumulative Distribution (CD) plots of the error components and CD plots of the magnitude of the horizontal errors are also presented. Errors in the vertical component of the IVV are not shown in this study because they are not a concern for vehicles on the same roadway[7].

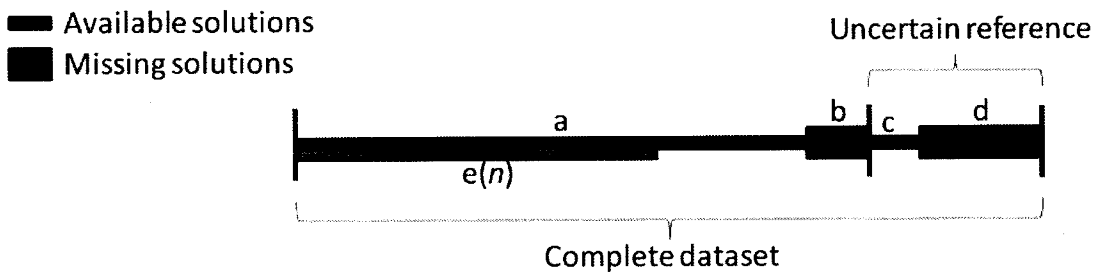
The mean of the AT or XT errors is an indication of possible biases relative to the reference IVV, while the standard deviation is an indication of the variability of the errors. These values are quoted based upon data that have less than 20 m error (relative to the reference IVV) in either component. The 20 m limit was chosen because errors of this magnitude should be able to be detected and eliminated using Receiver Autonomous Integrity Monitoring (RAIM), vehicle sensors such as inertial sensors or wheel speed sensors or possibly map-matching techniques. Removing data with large errors ensures that outliers, which may be in error by more than 1 km, do not bias the means and standard deviations, thereby allowing for better comparison and interpretation.

5.2 Availability

Availability used in this project is defined with reference to Figure 5-1. In this figure Missing Solutions," sections "b" and "d," occur at epochs when either a solution cannot be computed due to poor satellite geometry or when, for RTK calculations, there is a communications failure between the two vehicles. It was not possible to unambiguously determine the reason for the absence of solutions from inspection of the RTK logs because both radio failure and the inability to calculate a solution simply resulted in missing epochs in the log file. The section marked "uncertain reference" represents the epochs for which the either the reference or comparison IVVs (refer to Section 4.1) are missing or their difference between was beyond a threshold. As is discussed in Section 8.1, the RMS of the difference between the reference and comparison IVVs was

[7] For applications in which vehicles are on an interchange, the vertical component of the IVV may be useful to determine which vehicles are on the same road.

generally less than 20 cm, and less than 10 cm in environments permitting open sky views.



a	Epochs with available solutions and certain reference
b	Epochs with no solution and certain reference
c	Epochs with available solutions but uncertain reference
d	Epochs with no solution and uncertain reference
e(*n*)	Available with error less than *n* meters (and certain reference)

Figure 5-1: Availability Definitions

The three most important availability measures for a given method[8] (RTK or DPOS) and a given receiver combination are:

- Full Availability (FA): The percentage of the time a solution is available (with no regard to the quality of that solution).

$$FA = \frac{(a+c)}{(a+b+c+d)}$$

- Availability With Certain Reference (AWR): The percentage of the time a solution is available *and* the reference is of certain quality with respect to the time a reference of certain quality is available.

$$FA = \frac{a}{(a+b)}$$

This quantity specifies the availability of solutions of which it is possible to determine the accuracy.

[8] Availability calculations for the V2I method were not performed, because the intermittent nature of the solutions renders the results meaningless.

- Availability Without Certain Reference (AWOR): The percentage of the time a solution is available, but its accuracy cannot be quantified because the reference is of uncertain quality.

$$AWOR = \frac{c}{(a+b+c+d)}$$

Since the availability metrics just discussed do nothing to quantify the accuracy of the solutions, an additional measure was defined. Suppose "e(n)" in Figure 5-1 is the number of epochs for which the error (the AT or XT component) is less than n meters, then the following useful metric can be defined:

- Full Availability with Error Less than n m (FAWE(n)): The percentage of time a solution with error less than n meters is available.

$$FAWE(n) = \frac{e(n)}{(a+b+c+d)}$$

  This quantity is obviously bounded above by the FA. There is some uncertainty in the quantity due to the presence of the "c" portion of Figure 5-1, which represents epochs for which solutions exist; but their accuracy is not quantifiable, since the reference is of uncertain quality. For this reason, when FAWE(n) is quoted, it is increased by half of AWOR and has an uncertainty of the same amount (i.e., it is quoted as $FAWE(n) + \frac{1}{2}AWOR \pm \frac{1}{2}AWOR$).

FAWE(n) is quoted for $n = 1.5$ m and $n = 5$ m, since these distances are those considered sufficient to position (relatively) a vehicle at the lane and road level, respectively.

6 Predictive Measures

Under actual operation, no reference solution is available, and the accuracy of the IVV estimate cannot be known. For this reason it is of interest to determine if there are quantities, easily derivable from the measurements of a GNSS receiver, which can be correlated with the accuracy. If such quantities existed, they could be shared between vehicles to provide an estimate of the accuracy of the instantaneous IVV solutions.

6.1 Dilution of Precision

The DOP is an indicator of the satellite geometry. This is directly linked with the position accuracy, because an improvement in satellite geometry (represented by a lower value of DOP) for a constant level of measurement error results in improved position accuracy. The HDOP at each receiver in a pair is used for DPOS, while a single GDOP value is presented for the RTK method.

6.2 Number of Satellites

The number of satellites used in the calculation of position is also an indicator of the expected positioning accuracy and reliability. The more satellites used in the calculation of a position solution, the more position errors can be averaged, resulting in an overall improvement in accuracy. While this is true of SP solutions for DPOS as mentioned previously, it is important that common satellites be used. Thus, a direct correlation between number of satellites used in the position solution at each vehicle (i.e., a pair of numbers) and IVV accuracy is not likely for DPOS. For RTK, since common satellites are used in the solution, such a correlation could be expected.

7 Data Collection Summary

V2V data was collected in and around Calgary, Canada, between August 4, 2009 and August 25, 2009. In the majority of the tests, Vehicle 1 followed Vehicle 2 with a distance of less than 300 m, and generally between 30 and 150 m. Some driving environments forced modifications of the default behavior (e.g., on highways vehicles moved in between the two test vehicles necessitating lane changes). Approximately 52 hours of data was collected, but reduced to just over 45 hours of usable data.

The data was collected in the seven test environments listed below, which were selected in accordance with Federal Highway Administration (FHWA) descriptions [2]. Photos in each of the environments are shown in Section 13. The amount of data collected in each of these environments is summarized in Table 7-1.

Deep Urban Canyons: Streets deep within the city surrounded by many tall buildings are an example of the Deep Urban Canyon environment. These roads are characterized by high mask angles. Driving in this environment is at low speeds, typically 25 mph, with frequent starts and stops. For this study, streets in downtown Calgary were used. The mask angles were typically 20 to 40 degrees but occasionally reached 80 degrees.

Major Urban Thruway: This environment contains roads with 40 to 50 mph speed limits. The roads are surrounded by 3- to 4-storey buildings on both sides with approximately 20 degree elevation masks. Examples of this environment are Telegraph Road in Michigan or parts of Crowchild Trail in Calgary.

Major Rural Thruway: This environment also contains roads with 40 to 50 mph speed limits; but in distinction to the Major Urban Thruway area environment, the sides of the roads have only occasional 3- to 4-storey buildings and have an otherwise open view of the sky. Examples of this environment are US12 around Irish Hills in Michigan and parts of Sarcee Trail in Calgary.

Major Roads: Routes in this environment have speed limits of 30 to 40 mph and mask angles ranging from 5 degrees in rural sections to 20 degrees in urban sections. Examples of these types of roads include Mound Road in Warren, Michigan, or Shaganappi Trail in Calgary.

Local Roads: Local Roads are typical neighborhood roads with speed limits of approximately 25 mph. These roads are typically narrower than those in the Major Road environment and often have substantial numbers of trees that will limit the sky-view. Driving on Local Roads is generally characterized by frequent stops and cornering.

Interstate/Freeway: This environment comprises divided highways with at least 2 lanes in each direction with speed limits of 55 to 70 mph. Examples of this environment include Highway 1 outside of 16th Avenue between Shaganappi and Deerfoot Trails in Calgary. The environment is mostly open sky with 5 degree elevation masks with a few overpasses.

Mountains: The final environment type is on roads that would otherwise be described as Major Roads or Interstate/Freeway, that pass through tree covered and mountainous areas. The speed limit on these roads is similar to the interstate/freeway environment; however, the mask angle is significantly higher due to the trees and mountains.

Table 7-1: Data Collection Summary

Category	Time Collected	%
Deep Urban	1:39:54	3.7%
Major Urban Thruway	9:50:03	21.8%
Major Rural Thruway	8:40:09	19.2%
Major Road	8:10:40	18.1%
Local Road	6:30:48	14.4%
Interstate/Freeway	9:04:51	20.1%
Mountains	1:08:32	2.5%
Total	45:04:57	

V2I data was collected on August 26, 2009, and August 27, 2009. Collections were performed in five environments–those that were used for V2V tests with the exception of Deep Urban and Mountains. These two environments were excluded for reasons of safety. Three types of "coordinated pass" were performed in each environment:

- **Following**: Vehicle 1 followed Vehicle 2 past the infrastructure point.
- **Approaching**: The vehicles approached the infrastructure point from opposite directions attempting to pass it at approximately the same time.
- **Intersection**: The vehicles approached the infrastructure point from roadways separated by approximately 90 degrees. In the Freeway tests, an overpass was used; Vehicle 1 drove on the overpass, while Vehicle 2 drove on the Freeway underneath.

At least two passes of each type were collected in each environment.

8 Vehicle-to-Vehicle Test Results

This section contains presentation and discussion of the results of the field tests described in Section 7. It focuses on comparing data that isolates factors that may impact V2V performance, namely the effect of receiver type and quality, the effects of WAAS, the effect of a limited constellation size, and the IVV calculation method (RTK versus

DPOS). For each of these comparisons, tabulated data and figures obtained using specific receiver combinations are chosen to support arguments.

Each comparison contains the same subsections:

- A discussion of availability using the measures presented in Section 5.2 (FA and FAWE) and/or data gap statistics.
- Comments regarding the number of satellites and DOP using each method/receiver combination with a view as to whether these are effective accuracy predictors.
- Analysis of the accuracy allowed for each method/receiver combination.
- Comments regarding the performance of all method/receiver combinations in different environments.

8.1 Reference IVV Statistics

Before making comparisons between various methods of determining the IVV, it is essential that one has confidence in the reference values used to determine the vector. As was discussed in Section 4.1, the reference IVV was calculated using a variety of different methods, HW, and SW. Visual comparisons of plots of the magnitudes of the differences between the various reference IVV solutions were then used to select the reference IVV and the second best solution to assess the agreement between the two solutions. Table 8-1 summarizes the important statistics for the selected reference and comparison IVVs for each of the V2V data collections. The columns of this table have the following interpretation.

- **Total RMS**: The RMS of the differences between the reference and IVVs selected over the entire duration of the test.
- **Post-Reject RMS**: The RMS of the difference between the reference and comparison IVVs after the data has been rejected (see below).
- **Missing**: The percentage of the duration of the test during which the reference or comparison IVV is absent.
- **Rejected**: The percentage of the duration of the test during which the difference between the reference and comparison IVVs is greater than 1 m, so the reference is of uncertain quality.

As was discussed in Section 5.2, portions of data where there are rejected or missing reference IVVs add slightly to the uncertainty in the specification of availability measures.

When interpreting the data in Table 8-1, it is important to note that there was no data rejection in the Urban Canyon environments, despite the fact that the RMS values are on the order of 10 m. This is because GNSS-only techniques cannot be used reliably in this particular environment. The IVV obtained using the integrated GPS/INS system on each vehicle was used as the reference IVV. The only other number standing out in the table is the high level of missing data for the August 12, 2009 data collection. The local roads environment, and this test run in particular, involves frequent heavy tree cover, making it a challenging environment for GNSS.

Aside from the aforementioned Urban Canyon results, the RMS of the differences between the reference and comparison IVVs is generally less than 20 cm, with the largest differences occurring on the local roads, for the reason discussed above. For the environments involving mainly open sky, the RMS of the differences is generally below 10 cm, indicating excellent agreement.

Table 8-1: Reference IVV Statistics for each of the V2V Data Collections

Date	Test	Environment	Total RMS (m)	Post- Reject RMS (m)	Missing (%)	Rejected (%)
04Aug	A	Interstate	0.08	0.08	0.2	0.0
	C	Mountain	0.16	0.16	1.4	0.0
	D	Interstate	0.02	0.02	0.0	0.0
05Aug	A	Urban Canyon	9.47	9.47	0.0	0.0
	B	Urban Canyon	12.24	12.24	0.0	0.0
06Aug	A	Interstate	1.52	0.07	2.3	0.3
12Aug	A	Local Roads	0.28	0.22	20.9	1.5
13Aug	A	Interstate	0.04	0.04	1.5	0.0
	B	Local Roads	0.03	0.03	1.1	0.0
14Aug	A	Major Roads	0.09	0.05	3.2	0.1
	C	Interstate	0.70	0.22	5.1	3.5
17Aug	A	Local Roads	0.20	0.17	0.0	0.4
	B	Local Roads	0.36	0.27	1.5	2.9
19Aug	A	Major Roads	1.04	0.04	4.0	0.2
	B	Major Roads	6.93	0.19	4.1	3.1
	C	Major Roads	0.19	0.12	5.4	0.4
20Aug	A	Urban Thruway	0.15	0.15	1.2	0.1
	B	Major Roads	0.05	0.05	0.0	0.0
21Aug	A	Urban Thruway	0.20	0.08	0.9	0.3
	B	Urban Thruway	0.05	0.04	2.1	0.0
	C	Urban Thruway	0.07	0.06	2.8	0.1
24Aug	A	Urban Thruway	0.06	0.06	3.9	0.0
	B	Urban Thruway	0.09	0.05	0.4	0.2
	C	Rural Thruway	0.02	0.02	1.8	0.0
	D	Rural Thruway	0.29	0.06	0.6	0.6
25Aug	A	Rural Thruway	0.05	0.05	1.2	0.0
	B	Rural Thruway	0.09	0.06	3.7	0.2
	C	Rural Thruway	0.04	0.04	0.5	0.0
	D	Rural Thruway	0.06	0.06	0.5	0.0

8.2 Effects of Positioning Method

The DPOS and RTK positioning methods are compared in this section. Two homogeneous receiver pairs (AW-AW) and (BW-BW) and two mixed pairs (AW-BW) and (BW-AW) were chosen for comparison.

8.2.1 Availability

As shown in Table 8-2, the FA (see Section 5.2) of the RTK positioning method, ranging from 82 percent to 92 percent is significantly lower than the DPOS method, which ranges from 97 percent to 100 percent. A very small percentage of missing RTK solutions are due to failure of the real-time radio link, which does not affect the DPOS methods for this analysis (as discussed in Section 4.2.1, DPOS was calculated in post-mission). It should be noted that it was not possible to unambiguously determine the cause of a data gap in the RTK solutions; but out of the 45 hours of data, there were only 6 minutes during which there was a communication failure, as was determined through comparison of locally and remotely logged data.

Table 8-2: Availability Statistics for Selected Receiver Pairs Comparing the RTK and DPOS Positioning Methods

Receivers		Proc. (D)POS/(R)TK	FA (%)	FAWE (1.5 m)		FAWE (5 m)		UNC. (%)
Host	Remote			AT (%)	XT (%)	AT (%)	XT (%)	
AW	AW	R	92	91	91	91	91	<1
		D	97	93	92	96	95	1
	BW	R	84	68	69	83	83	<1
		D	98	62	66	95	95	1
BW	AW	R	84	81	80	84	83	<1
		D	98	59	68	94	95	1
	BW	R	82	74	71	81	81	<1
		D	100	89	88	97	97	2

While the FA of DPOS is considerably higher than that of RTK for all considered receiver pairs, the same cannot be said for the FAWE values. The DPOS and RTK FAWE (1.5 m) values for (AW-AW) are almost identical. Indeed, the fact that FAWE (1.5 m) for the (AW-AW) pair is only 1 percent less than the FA for RTK means that when a RTK solution is available from the pair, it is almost certain to have an error less than 1.5 m. The FAWE (1.5 m) values for both mixed pairs are higher for RTK than they are for DPOS.

The low FA for (BW-BW) in RTK is likely because the RTK SW rejects more BW measurements than AW measurements. This would be caused by the increased noise and multipath errors present in the measurements of the B receivers that is a consequence of their high-sensitivity signal tracking. The Type A receiver phase lock loops are also expected to be of a higher quality, resulting in better carrier phase measurements that contain a lower number of cycle slips.

Table 8-2 and the availability and accuracy tables that follow show there is usually very little difference between the magnitude of the errors in AT and XT components of the IVVs. There is indeed little theoretical reason to support a difference in accuracy of these components in the general case. Cases where one might expect a higher accuracy for one of the components include those where the environment (tall buildings/trees) reduces the observable satellite constellation to a strip parallel with the direction of travel. Assuming sufficient satellites are available to calculate the IVV, one would expect greater accuracy for the AT component in such a case.

Finally, Table 8-2 shows incongruous FAWE(1.5) values for the (AW-BW) and (BW-AW) pairs using RTK. Since the receivers involved are the same, one would expect similar performance. The discrepancy, which is no longer apparent at the 5 m level, is likely due to the RTK SW treating the two receiver types, or the host and remote, differently.

Table 8-3 shows that RTK has more and longer data gaps than DPOS. This is most pronounced in the (BW-BW) where there are approximately 1500 more data gaps for RTK than with the same receiver pairs using DPOS. While a small number of the data gaps are due to communications failures, the majority is because of the aforementioned rejection of measurements from the high-sensitivity receivers and because the number of satellites used in the RTK solution is bounded by the smaller of the two numbers of satellites observed by receiver pair. This bound exists because, as mentioned previously, RTK can only use observations common to both receivers.

When the vehicles enter environments that limit the number of satellites in view, the satellites rejected by the RTK processing software cause the RTK solution to have too few satellites to calculate and output a solution. It may be possible to tune the RTK processing software so that it does not reject as many measurements, which would increase availability but would also impact position accuracy.

Table 8-3: Data Gap Statistics for Selected Receiver Pairs Comparing the RTK and DPOS Positioning Methods

Receivers		Proc. (D)POS/(R)TK	# Gaps	Gaps < 15 s		15s < Gaps < 30 s		Gaps > 30 s	
Host	Remote			%	Ave (s)	%	Ave (s)	%	Ave (s)
AW	AW	R	1459	90	5	6	21	4	72
		D	1123	97	2	2	19	2	77
	BW	R	1375	56	7	31	20	13	67
		D	894	96	2	2	20	2	58
BW	AW	R	1377	56	6	31	20	13	9
		D	829	97	2	2	20	2	1
	BW	R	1455	53	6	33	20	14	71
		D	8	100	3	0	-	0	-

8.2.2 Number of Satellites

The number of satellites used in DPOS solutions[9] is significantly higher than that in RTK solutions for all receiver combinations, as is shown in Table 8-4. For (BW-BW), the 30 percent increase in the number of satellites used is, at least in part, why the DPOS positioning method performs better than the RTK method for this receiver combination.

Table 8-4: Mean Number of Satellites used by Selected Receiver Pairs Comparing the RTK and DPOS Positioning Methods

Receivers		Proc.	Mean #	
Host	Remote	(D)POS/(R)TK	Satellites	
AW	AW	R	7.7	
		D	9.0	
	BW	R	7.1	
		D	9.6	
BW	AW	R	7.1	
		D	9.6	
	BW	R	7.0	
		D	10.1	

8.2.3 Dilution of Precision

It is not possible to compare the DOP values for the RTK and DPOS methods because, as mentioned previously, the RTK SW only output GDOP, while DPOS yielded two HDOP values.

8.2.4 Accuracy

The accuracy of the various receiver and processing methods combinations can be determined with reference to Table 8-2, which shows the availability of solutions with specified levels of accuracy (1.5 m and 5 m), and Table 8-5, which tabulates the means and standard deviations of the AT and XT errors. As mentioned in Section 5.1, the means and standard deviations are presented for the data that has had errors (relative to the reference IVV) larger than 20 m in each of the components removed. The 20 m limit was chosen since errors of this magnitude should be detectable using RAIM and/or additional vehicle sensors or map-matching. The FAWE(20) values, which are shown in Table 8-6, indicate the percentage of the data with AT or XT component errors less than 20 m (i.e., the percentage of the data used in the calculation of the means and standard deviations). Note that the FA, FAWE(20 m) values, and the means and standard deviations are split in two tables (Table 8-5 and Table 8-6) for clarity.

As could have been expected from Table 8-2, Table 8-6 shows that when an RTK solution is available, it has, to the resolution of the table at least, an error less than 20 m. The DPOS method generally shows a presence of 1 percent - 2 percent of solutions with more than 20 m error in the AT or XT components. It should be remembered, however,

[9] In this and subsequent tables, the numbers of satellites for DPOS are found by averaging those used by the two receivers involved so that a single number is produced for each receiver pair.

that the DPOS combinations have a significantly higher FA than the RTK combinations, as was discussed above.

Table 8-5 shows that the standard deviations for the DPOS pairs are consistently higher than those for the corresponding receivers using RTK, indicating that the RTK method has greater precision than DPOS for the same receiver pairs. The absolute values of the means for the RTK pairs are also generally smaller than the corresponding DPOS pairs, the one exception being the (BW-BW) pair where the mean of the XT error is the same for both methods and that of the AT error is less for DPOS. The difference in the means of the errors, which corresponds to a difference in accuracy, is most pronounced for the mixed pairs (i.e., (BW-AW) and (AW-BW)). This is because the RTK method only uses satellites that are common to both receivers and, therefore, the common measurement errors cancel. The DPOS method uses whichever satellites are available at each individual receiver and does not ensure that only common satellites are used. The use of different satellites, particularly those at low elevation, will introduce biases that are not common between the vehicles and, thereby, degrade the relative position accuracy. This effect is more pronounced as the number of different satellites increases.

The fact that (BW-BW) DPOS shows slightly better accuracy (as judged by the magnitude of the mean of the error) than (BW-BW) RTK is not regarded as very significant; the DPOS method still results in a lower precision (large standard deviations). The reason that the performance of the pair using RTK is not substantially better than the pair using DPOS in terms of mean and standard deviation is likely linked to the low quality phase measurements from the B receivers, as compared to the AW receivers. This is supported by the fact that for all pairs involving an AW receiver, the means and standard deviations are less, often significantly so, for RTK compared to DPOS.

Table 8-5: Along and Across Accuracy for Selected Receiver Pairs with the RTK and DPOS Positioning Methods

Receivers		Proc	Along Errors			Across Errors	
Host	Remote	(D)POS/(R)TK	Mean (m)	S.D. (m)		Mean (m)	S.D. (m)
AW	AW	R	0.01	0.42		0.01	0.57
		D	-0.02	0.78		0.02	0.99
	BW	R	0.05	1.37		-0.02	1.45
		D	-0.17	1.97		0.09	1.92
BW	AW	R	-0.02	0.74		0.05	0.91
		D	0.22	1.96		-0.15	1.79
	BW	R	-0.06	1.10		0.15	1.35
		D	0.02	1.41		0.15	1.59

Table 8-6: Availability of Solutions with Less than 20 m for Selected Receiver Pairs with the RTK and DPOS Positioning Methods

Receivers		Proc.	FA (%)	FAWE (20 m)	
Host	Remote	(D)POS/(R)TK		AT (%)	XT (%)
AW	AW	R	92	92	92
		D	97	96	96
	BW	R	84	84	84
		D	98	96	96
BW	AW	R	84	84	84
		D	98	97	97
	BW	R	82	82	82
		D	100	98	98

Figure 8-1 and Figure 8-2 show two graphical representations of the difference in accuracy between the RTK and DPOS positioning methods for the AW-AW pair.

When interpreting these cumulative distribution function (CDF) plots and others in this report, it is important to note that the percentages on the vertical scale are defined relative to the times when the solution and the reference is available. The following hypothetical example highlights the problem that may arise through incorrect interpretation of this kind of plot. Suppose for a certain data set using a certain receiver pair that:

- The reference is available 100 percent of the time.
- RTK is available only 40 percent of the time; but when available, its solution has an error always less than 5 m.
- DPOS is available 90 percent of the time; but when available, the error is only less than 5 m 50 percent of the time.

In this case the CDF comparing RTK and DPOS will show RTK reaching 100 percent within 5 m while DPOS will only reach 50 percent at the same point, making the performance of RTK look much better than that of DPOS. A different style of CDF might show the total percentage of solutions on the vertical axis, in which case RTK would reach only 40 percent and DPOS 45 percent by the 5 m mark, making their performance appear much closer. The CDFs adopted herein give a good indication of the distribution of errors for the *available solutions* for each method.

In the case of Figure 8-1 and Figure 8-2 the situation is not as extreme as in the hypothetical situation just discussed, because the full availability of the RTK and DPOS solutions for the (AW-AW) pair are reasonably close, 92 percent and 97 percent respectively. Even with these FA values, incorrect interpretation of the CDFs is possible. Figure 8-2 would seem to indicate that the (AW-AW) pair using RTK has a higher availability of solutions with component-wise errors smaller than 1.5 m than for DPOS, whereas Table 8-2 shows that the opposite is true. What the figures do show is that the quantifiable *available solutions* from (AW-AW) RTK almost all have a horizontal error of less than 1 m; more than 90 percent have a horizontal error less than 0.5 m. As for (AW-AW) DPOS, Figure 8-1 indicates that of the available solutions, just under 90 percent have a horizontal error less than 1 m.

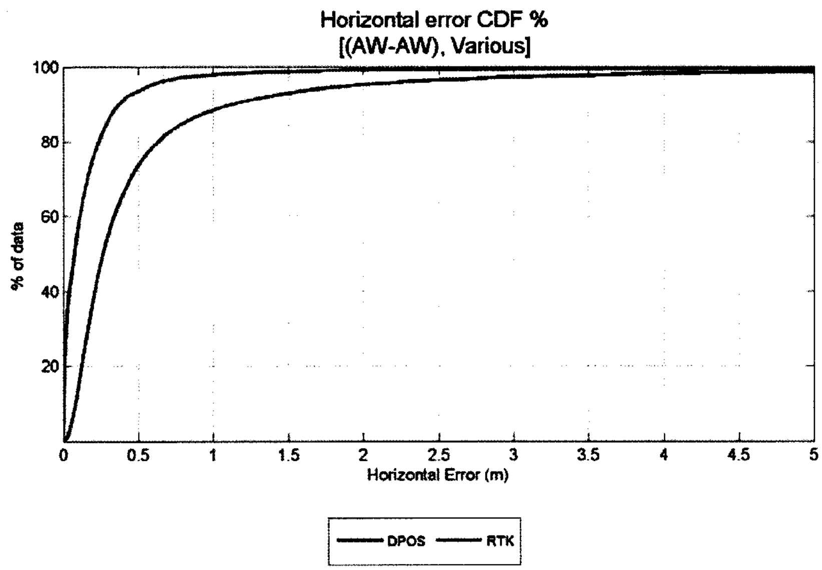


Figure 8-1: CDF for the Horizontal Error for RTK and DPOS Processing of all (AW-AW) Data

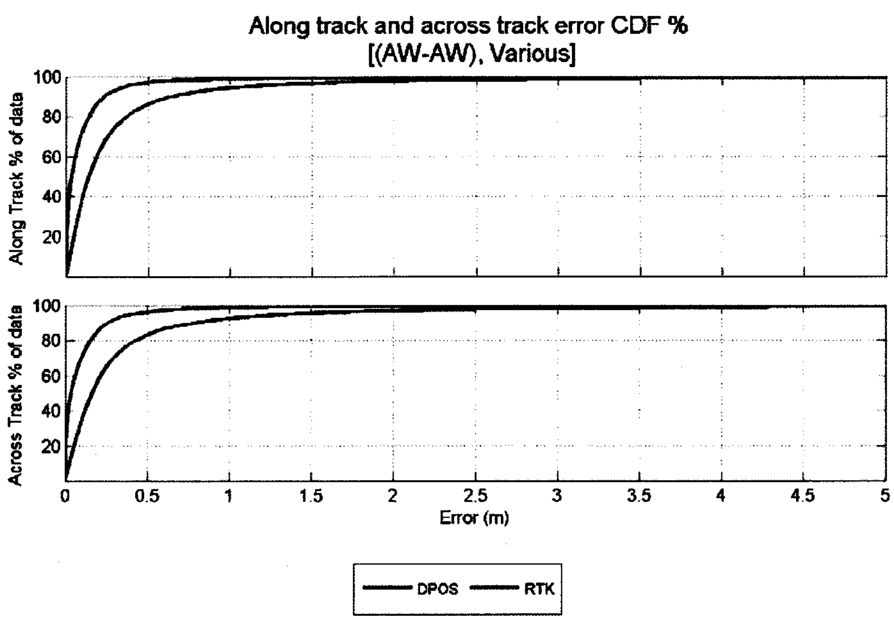


Figure 8-2: CDF for the AT and XT Errors for RTK and DPOS Processing of all (AW-AW) Data

8.2.5 Environment Types

Table 8-7 shows the availability of solutions with 1.5 m and 5 m accuracy from the (AW-AW) pair using both RTK and DPOS for each of the test environments. When using the DPOS, it shows that the FA is always greater than that for RTK (i.e., DPOS yields a solution more often than RTK). The difference in availability is greatest in the areas that are traditionally challenging for GNSS, Deep Urban, and Local Roads, the latter often being associated with heavy tree cover. With the exception of these environments, the availability of solutions using both DPOS and RTK is greater than 90 percent. The availability of solutions with less than 1.5 m error is almost the same for RTK and DPOS in each environment; the exception being Local Roads, where RTK yields solutions of this quality 8 percent less often. In all environments, FAWE(5 m) is essentially equal to FA for RTK, indicating that practically all available solutions have a component-wise error smaller than 5 m. This is also true for DPOS, with the exception of the Deep Urban environment where the approximate difference between FA and FAWE(5) is 11 percent.

Table 8-7: Availability Statistics for (AW-AW) using RTK and DPOS in each of the Environments

Environment	Proc. (D)POS/(R)TK	FA (%)	FAWE(1.5 m)		FAWE(5)		Unc.
			AT (%)	XT (%)	AT (%)	XT (%)	%
Deep Urban	R	47	39	37	45	42	0
	D	60	39	34	50	48	0
Interstate/ Freeway	R	95	95	95	95	95	<1
	D	99	96	95	95	95	<1
Local Roads	R	84	81	81	82	82	<1
	D	97	89	88	93	93	3
Major Roads	R	94	93	93	93	93	<1
	D	98	95	92	97	96	1
Mountain Roads	R	99	99	99	99	99	<1
	D	100	99	97	99	99	<1
Rural Thruways	R	97	97	96	97	97	<1
	D	99	98	98	99	99	<1
Urban Thruways	R	95	95	95	95	95	<1
	D	99	95	96	98	98	<1
Various	R	92	91	91	91	91	<1
	D	97	93	92	96	95	1

Table 8-8 shows the same information as Table 8-7 but for the (BW-BW) pair instead of the (AW-AW) pair. The availability for DPOS is considerably higher than that for RTK for all environments except Interstate and Mountain Roads where the differences are 5 percent and 8 percent, both in favor of DPOS. Solutions at the lane level (1.5 m) are always more available with DPOS than RTK, with the largest differences being in the Deep Urban and Local Roads environments. Perhaps the most surprising entries at the 1.5 m level are those for RTK in the Interstate environment. Here the difference between FA and FAWE(1.5 m) is 13 percent indicating that 13 percent of the solutions available from RTK in this environment have errors larger than 1.5 m. This is in contrast to the (AW-AW) pair using RTK in the same environment where all available solutions have errors less than 1.5 m, as was shown in Table 8-7. Given that this environment is characterized by open sky views, this relatively poor accuracy must be attributed to either the lower quality measurements from the B receivers or sub-optimal treatment of the measurements by the RTK SW. Not too much weight should be given to the fact that the FAWE(1.5 m) values are almost equal to the FA for the Mountain Roads environments when using RTK; this was a short data set comprising only 2.5 percent of the total data (refer to Table 7-1). As was the case for the (AW-AW) pair, the FAWE(5 m) values are almost equal to the corresponding FA values, indicating that regardless of environment and processing method, almost all available solutions have component-wise errors smaller than 5 m. The obvious exception is the Deep Urban environment, where the differences between FA and FAWE(5 m) are approximately 5 percent for RTK and more than 30 percent for DPOS.

Table 8-8: Availability Statistics for (BW-BW) Using RTK and DPOS in each of the Environments

Environment	Proc. (D)POS/(R)TK	FA (%)	FAWE(1.5)			FAWE(5)		Unc.
			AT (%)	XT (%)		AT (%)	XT (%)	%
Deep Urban	R	34	21	21		29	28	0
	D	100	40	31		72	60	0
Interstate/ Freeway	R	95	82	82		95	95	<1
	D	100	97	98		99	99	1
Local Roads	R	64	54	47		63	62	<1
	D	100	80	79		96	96	3
Major Roads	R	81	78	74		81	80	<1
	D	100	88	86		98	97	2
Mountain Roads	R	92	91	91		91	91	<1
	D	100	94	94		99	99	<1
Rural Thruways	R	88	80	75		87	87	<1
	D	100	93	93		99	99	<1
Urban Thruways	R	84	78	76		84	83	<1
	D	100	82	86		99	99	<1
Various	R	82	74	71		81	81	<1
	D	100	89	88		97	97	1

8.3 Effects of Receiver Quality

The effect of receiver quality is evaluated by comparing the performance of homogeneous pairs of AW and BW receivers.

8.3.1 Availability

As shown in Table 8-9, the BW receivers have slightly higher availability than the AW receivers when using the DPOS positioning method. The difference in availability between these receiver combinations is more pronounced in the Deep Urban environment, as shown in Table 8-10. In this environment the high sensitivity B receivers using DPOS have much higher FA than the AW using DPOS, but the availability of solutions with an accuracy of 1.5 m is about the same.

The (AW-AW) receiver combination has a higher availability than the (BW-BW) combination when both pairs used RTK for all environments except for Interstate/Freeway. This is likely because the RTK SW rejects a significant number of measurements from the BW receivers.

Table 8-9: Availability Statistics for all Data for (AW-AW) and (BW-BW) Receiver Pairs

Receivers		Proc. (D)POS/(R)TK	FA (%)	FAWE (1.5 m)		FAWE (5 m)		UNC. (%)
Host	Remote			AT (%)	XT (%)	AT (%)	XT (%)	
AW	AW	R	92	91	91	91	91	<1
		D	97	93	92	96	95	1
BW	BW	R	82	74	71	81	81	<1
		D	100	89	88	97	97	1

Table 8-10: Availability Statistics for all Deep Urban Data for (AW-AW) and (BW-BW) Receiver Pairs

Receivers		Proc. (D)POS/(R)TK	FA (%)	FAWE (1.5 m)		FAWE (5 m)		UNC. (%)
Host	Remote			AT (%)	XT (%)	AT (%)	XT (%)	
AW	AW	R	47	39	37	45	42	0
		D	60	39	34	50	48	0
BW	BW	R	34	21	21	29	28	0
		D	100	40	31	72	60	0

The data gaps associated with the AW and BW receivers can be quantified in two ways. Table 8-11 shows statistics for the gaps in the receivers' solutions when running in SP mode. There are two orders of magnitude difference in the numbers of gaps between the AW and BW receivers. The majority of the gaps for the AW receivers have a duration of less than 15 seconds, but there are a non-negligible number, nearly 20, of gaps that are longer than 30 seconds. These occur in the Deep Urban environment.

Table 8-11: Data Gap Statistics for all Data of the AW and BW Receivers in SP Mode

Receivers		#Gaps		Gaps < 15 s			15 s < Gaps < 30 s			Gaps > 30 s	
Type	Vehicle			%	Ave (s)		%	Ave (s)		%	Ave (s)
AW	1	893		96.0	2.0		2.0	21.5		2.0	58.0
	2	825		96.5	2.2		1.8	20.1		1.7	57.6
BW	1	7		100.0	2.1		0.0	-		0.0	-
	2	3		100.0	2.3		0.0	-		0.0	-

The second way to quantify data gaps is shown in Table 8-12. As would be expected from the data in Table 8-11, (AW-AW) DPOS has significantly more data gaps than (BW-BW) DPOS. The new information that Table 8-12 adds is that the gaps for (BW-BW) RTK are longer (on average) than those for (AW-AW) RTK. While 97 percent of the gaps for (AW-AW) RTK are shorter than 15 seconds, only 53 percent of the gaps for (BW-BW) RTK fall in this range. This is, again, due to the rejection of poor quality measurements from the BW receivers by the RTK SW. The WAAS measurements have no effect on the above as they are not used in the RTK solutions.

Table 8-12: Data Gap Statistics for all Data of the AW and BW Homogeneous Receiver Pairs

Receivers		Proc. (D)POS/(R)TK	# Gaps		Gaps < 15s			15s < Gaps < 30s			Gaps > 30s		
Host	Remote				%	Ave (s)		%	Ave (s)		%	Ave (s)	
AW	AW	R	1459		90	5		6	21		4	72	
		D	1123		97	2		2	19		2	77	
BW	BW	R	1455		53	6		33	20		14	71	
		D	8		100	3		0	-		0	-	

8.3.2 Number of Satellites

Table 8-13 shows that, on average, the (BW-BW) combination uses one more satellite than the (AW-AW) combination in DPOS, but that the margin is effectively reversed for RTK. Again this can be explained by the fact that the BW receivers have a high sensitivity; and, therefore, track more satellites in SP mode. While the measurements they provide will be of lower quality than the AW receivers, a large number of them are consequently rejected by the RTK SW.

Table 8-13: Mean Number of Satellites for all Data of the AW and BW Homogeneous Receiver Pairs

Receivers		Proc. (D)POS/(R)TK	Mean # Satellites	
Host	Remote			
AW	AW	R	7.7	
		D	9.0	

Receivers		Proc. (D)POS/(R)TK	Mean # Satellites	
Host	Remote			
BW	BW	R	7.0	
		D	10.1	

8.3.3 Dilution of Precision

The average RTK DOPs for the (AW-AW) and (BW-BW) pairs are 2.0 and 2.8 respectively, implying that the IVV estimates calculated using the AW receivers should have higher accuracy. The average DOPs[10] of the receivers in SP mode (as used in DPOS) are approximately 1.3 for the AW receivers and 0.9 for BW receivers. This indicates that if the measurements from the two receivers were of the same quality, the BW receivers should have more accurate SP solutions.

8.3.4 Accuracy

Table 8-9 shows that (AW-AW) in RTK yields nearly 20 percent more solutions capable of positioning vehicles at the "lane level" (1.5 m) than (BW-BW) using the same processing method. At the 5 m accuracy level, the difference is approximately 10 percent still in favor of the AW pair. The superior accuracy of the AW pair is supported by a higher number of satellites, lower DOP values, and more accurate measurements. What the FAWE numbers do not show, but Figure 8-3 illustrates, is that the AW pair offers substantially more solutions that are accurate to the sub-meter level. When interpreting Figure 8-3, the discussion preceding Figure 8-1, the meaning of the percentages on the vertical axis should be considered.

The accuracy of the IVV estimates from the receiver pairs when using DPOS is nearly the same with AW at 92 percent versus BW at 89 percent, at least as far as the availability of solutions at the 1.5 m level is concerned. While the DOP is lower for the BW pair, this does not translate into noticeably more accurate IVV solutions for a number of reasons, including the fact that the measurements from the B receivers have larger errors than those from the A receivers. As discussed previously, the accuracy of the SP solution is a function of the satellite geometry (DOP) and the measurement errors. As was the case for RTK when using DPOS, (AW-AW) offers more solutions that are accurate to the sub-meter level than the (BW-BW) pair.

[10] These values are the averages of the DOP values at each of the two receivers.

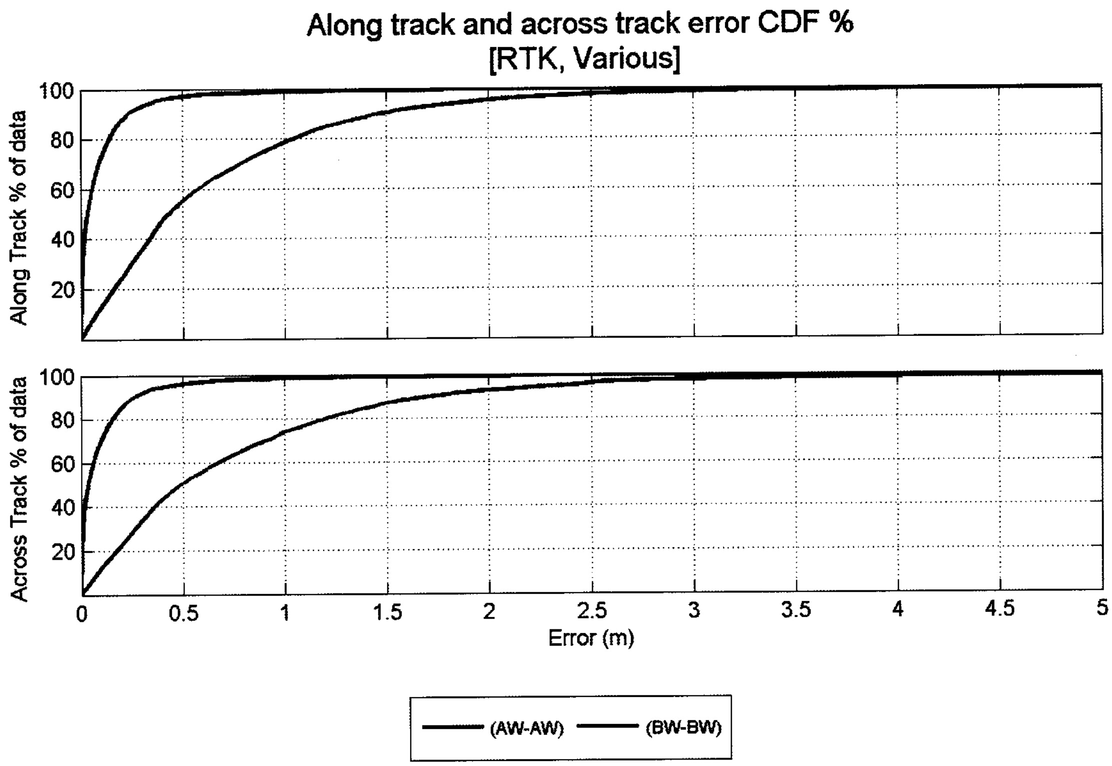


Figure 8-3: CDFs of the AT and XT Errors in the IVV Solutions Using (AW-AW) and (BW-BW), RTK

8.3.5 Environment Type

The points discussed in the previous section regarding the accuracy of receiver pairs and methods generally apply for all tested environments. The greatest difference in the performance of the receiver pairs when using RTK occurred in the Local Roads environment where the FAWE (1.5 m) for (BW-BW) was around 50 percent while it was 81 percent for (AW-AW).

8.4 Effects of WAAS

This section evaluates the effect of WAAS on the B receivers. The BW (like AW and B24W) receivers used both WAAS ranging and differential corrections, while BN used neither. Three receiver pairs are considered, namely two homogeneous pairs (BW-BW) and (BN-BN) and one mixed pair, (BW-BN). Since the RTK SW does not use WAAS measurements, only the performance of DPOS is discussed.

8.4.1 Availability

Table 8-14 shows the effect of WAAS on the FA is negligible. The most obvious difference in the table is that between the mixed pair (BW-BN) and the homogeneous pairs for FAWE (1.5 m), the reasons for which are discussed in Section 8.4.4.

Table 8-14: Availability Statistics for all Data for Selected Receiver Pairs Showing the Effect of WAAS

Receivers		Proc.	FA	FAWE (1.5 m)		FAWE (5 m)		UNC.
Host	Remote	(D)POS/(R)TK	(%)	AT (%)	XT (%)	AT (%)	XT (%)	(%)
BN	BN	D	100	90	89	97	97	1
BW	BN	D	100	82	84	97	97	1
	BW	D	100	89	88	97	97	1

8.4.2 Number of Satellites

As illustrated in Figure 8-4, on average, the BW receivers track approximately 1.4 satellites more than the BN receivers. This is due to the two WAAS satellites. On average, both receiver types use over 8 satellites in their navigation solutions, hence the addition of 1.4 satellites is not very significant.

8.4.3 Dilution of Precision

Figure 8-4 also shows the DOP for each of the receivers used in the pairs under consideration. As would be expected, since the BW receivers use a larger number of satellites, their DOP value is lower than that of the BN receivers. The difference, however, is small at approximately 0.1 on average.

8.4.4 Position Accuracy

As was shown in Table 8-14, the effect of WAAS satellites on position accuracy is negligible when the receiver pair is homogeneous. While the WAAS satellites and differential corrections make a SP solution more accurate, there is no visible benefit for the estimation of the IVV. The likely reason is that the position errors for each of the BN receivers will be similar and, therefore, cancelled when the IVV is calculated. For the (BW-BN) pair, such canceling does not occur. The BW receiver will have a more accurate SP solution, principally due to the available differential corrections. Since the BN receiver solution does not use these, the accuracy of the corresponding IVV solution decreases. Table 8-14 shows that these effects are confined to the sub 5-meter level. Figure 8-5 shows that the errors in the IVV solutions incurred by having only one WAAS-enabled receiver are generally below 3 m in the horizontal plane. When ionospheric activity increases, this error will increase.

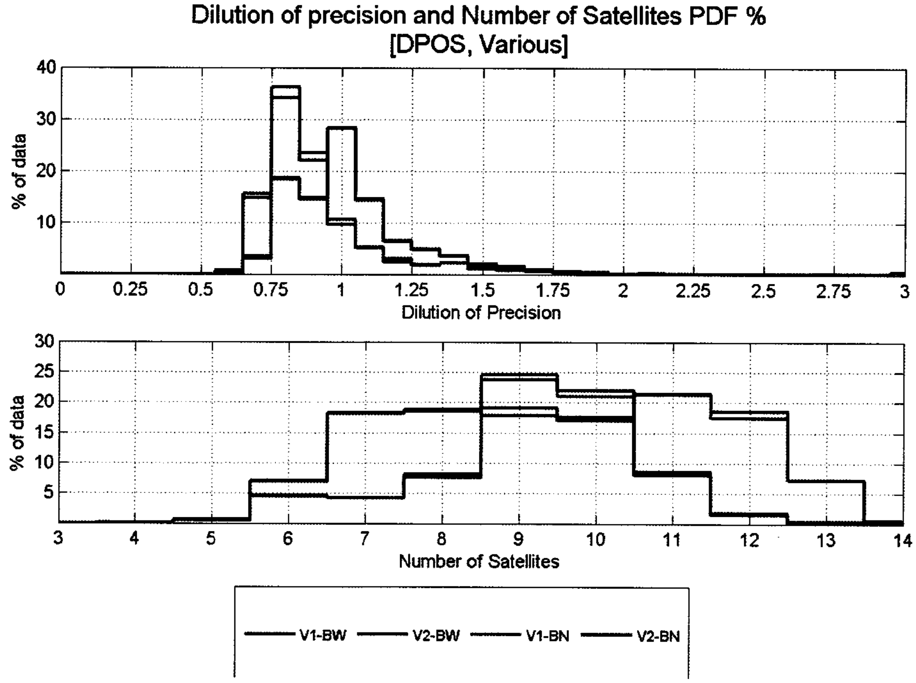


Figure 8-4: Effects of WAAS on the Number of Satellites and DOP

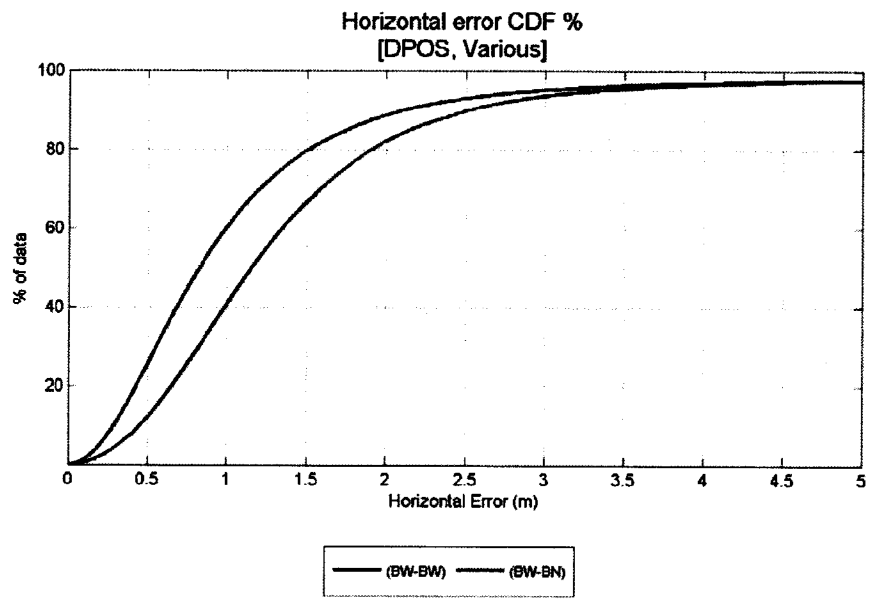


Figure 8-5: CDF of the Horizontal Error for (BW-BW) and (BW-BN) Combinations Over All Environments

8.4.5 Environment Types

The points discussed above, namely that two homogeneous pairs are more accurate than the mixed pair and the homogeneous pairs have similar accuracy, apply almost regardless of the environment. The exceptions to this are the Local and Mountain environments where (BN-BN) is more accurate than (BW-BW). The case for the Local Environment is shown in Figure 8-6. The reason is that in these two environments, which are both characterized by frequent turns and signal blockage due to trees and topography, one of the receivers in the pair (BW-BW) is intermittently denied access to the WAAS corrections, essentially rendering it the same as (BW-BN). In the other environments involving more open sky views and less frequent turns, with the exception of Deep Urban, the receivers will normally have access to the same satellites and corrections. In the Deep Urban case, there is little difference in the performance of (BW-BW), (BN-BN), and (BW-BN), as shown in Table 8-15. What is interesting to note in this table is the pronounced difference in the availability of solutions in the along and across track directions. This is likely due to the previously mentioned reduction of the visible GPS constellation caused by the presence of tall buildings.

Table 8-15: Availability Statistics for Deep Urban Data for Selected Receiver Pairs Showing the Effect of WAAS

Receivers		Proc. (D)POS/(R)TK	FA (%)		FAWE (1.5 m)			FAWE (5 m)				UNC. (%)
Host	Remote				AT (%)	XT (%)		AT (%)	XT (%)			
BN	BN	D	100		39	33		69	63			0
BW	BN	D	100		37	30		69	63			0
	BW	D	100		40	31		72	60			0

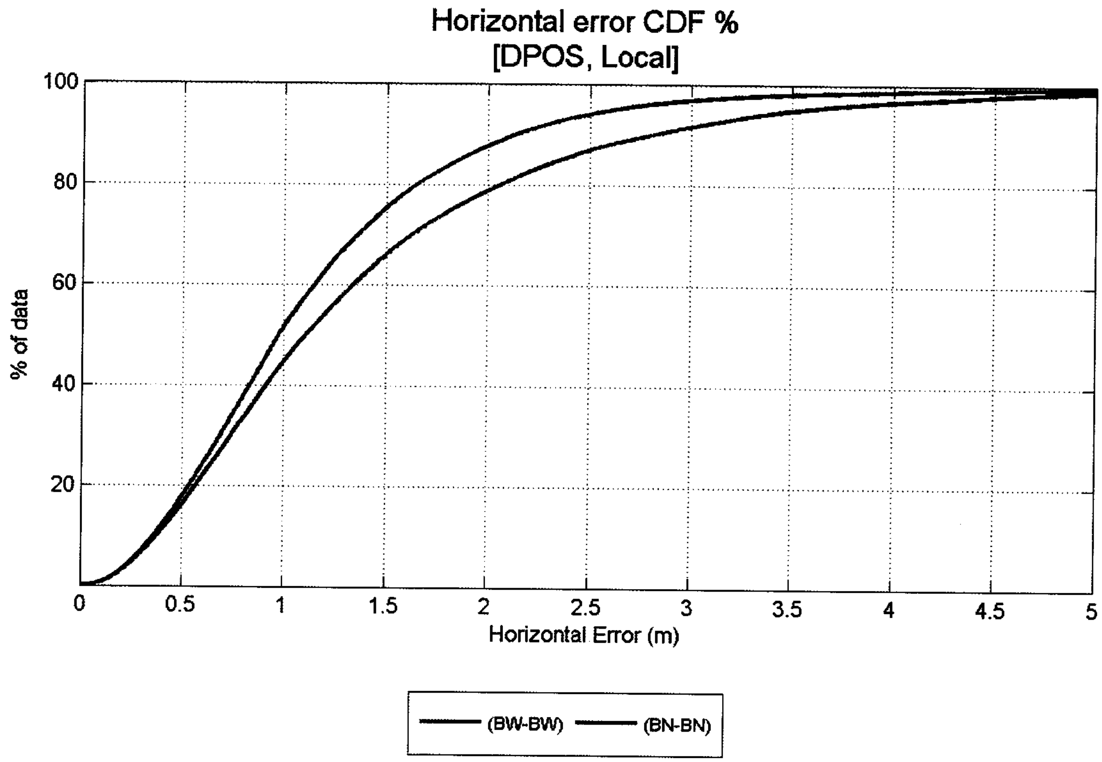


Figure 8-6: CDF of Horizontal Errors in the Local Road Environment for (BW-BW) and (BW-BN), DPOS

8.5 Effects of Constellation Limitations

The effects of a limited constellation, as would result if the US Government allowed the GPS constellation to drop to the minimum guaranteed, are shown by comparing the performance of the (BW-BW) and (B24W-B24W) pairs. This choice of pairs is logical since the receivers are of the same type (i.e., high sensitivity), and both have WAAS satellites and corrections enabled. The difference in their performance should be entirely due to the smaller constellation of satellites that the B24W receivers can use in their navigation solutions. Since the measurements of the B24W receivers were not processed using RTK, the comparison is limited to performance using the DPOS method.

It is noted that while the comparison used here isolates the effect of the limited constellation, more dramatic results may be obtained through the comparison of the high-sensitivity (BW-BW) pair with a standard receiver pair using a limited constellation in the navigation solution. This was not part of the objectives of this project.

8.5.1 Availability

As shown in Table 8-16, there is negligible difference in the availability of solutions between (BW-BW) and (B24W-B24W). Both yield solutions 100 percent of the time, and these are accurate to the lane level approximately 90 percent of the time.

Table 8-16: Availability Statistics for all Data for (BW-BW) and (B24W-B24) - Effect of Limited Constellation

Receivers		Proc. (D)POS/(R)TK	FA		FAWE (1.5 m)			FAWE (5 m)				UNC.
Host	Remote				AT	XT		AT	XT			
BW	BW	D	100		90	89		97	97			1
B24W	B24W	D	100		89	89		97	96			1

The B24W pair has 21 data gaps compared to 8 for the BW pair. In both cases, all gaps are less than 15 seconds. The increased number of gaps of the B24W pair is not very significant when it is considered that the (AW-AW) pair has in excess of 1000 data gaps over the same data, when using DPOS, and that 19 of 21 data gaps for the B24W pair occur in the Deep Urban environment.

8.5.2 Number of Satellites

As shown in Figure 8-7, the BW pair, as would be expected, uses more satellites in their calculation of the IVV solutions than the B24W pair. The difference is, on average, approximately 1.3. The difference is larger in open sky environments (e.g., 2.0 for the Interstate/Freeway environment). This being the case, the difference of 2 satellites is unlikely to correspond to a noticeable degradation in performance, since in these environments the B24W receivers typically use nearly 10 satellites in the computation of the navigation solutions.

8.5.3 Dilution of Precision

Figure 8-7 also shows the DOPs of the receivers involved in the calculation of the IVV solutions using the DPOS method for the BW and B24W pairs. On average, the DOPs of the limited constellation pair are within 0.05 of those for the BW pair.

8.5.4 Accuracy

As would be expected from an examination of the DOPs, the accuracy of the (BW-BW) and (B24W-B24W) pairs are very similar. The FAWE values in Table 8-16 and the CDF of horizontal errors in Figure 8-8 show that the performance is almost identical. The largest difference in accuracy occurs in the Deep Urban environment, where both perform poorly.

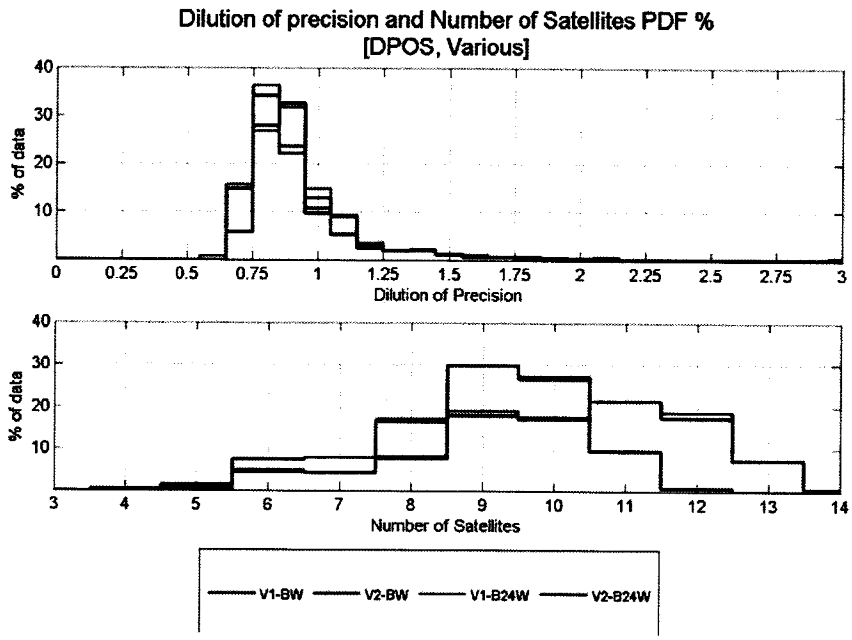


Figure 8-7: Dilution of Precision and Satellite Number Histograms for (BW-BW) and (B24W-B24W)

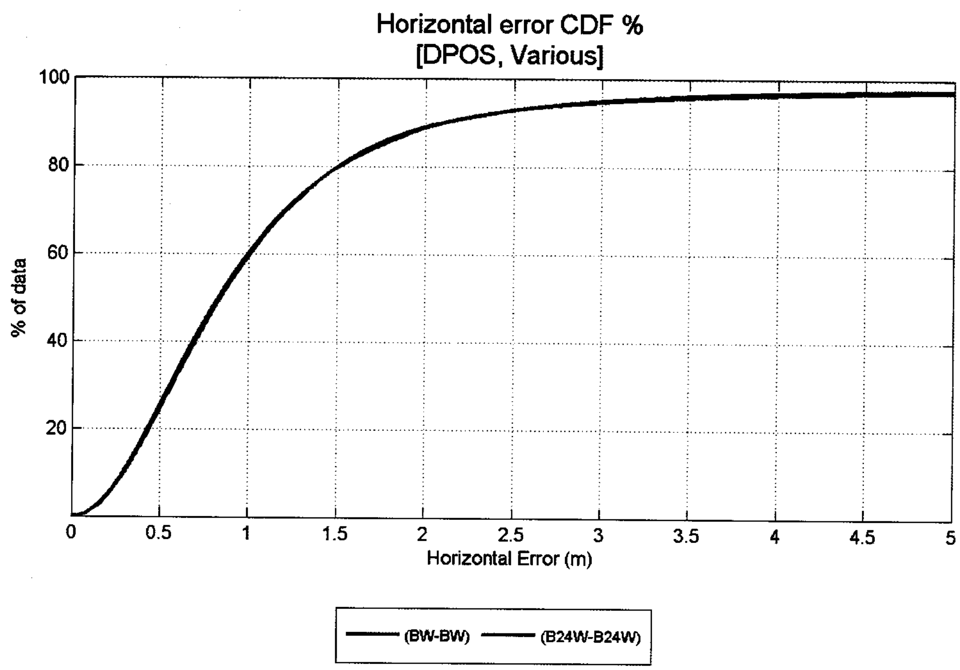


Figure 8-8: CDF of Horizontal Errors for (BW-BW) and (B24W-B24W) - Effect of Limited Constellation

8.5.5 Environment Types

It was noted above that the accuracy of the BW pair was noticeably better than the B24W pair in the Deep Urban environment. This observation is reversed in the Mountain environment, as is shown in Figure 8-9. It should be noted that the portion of data in the mountain environment was just over an hour, so the results shown in Figure 8-9 should not be taken to suggest that B24W will always perform better than BW in the mountains.

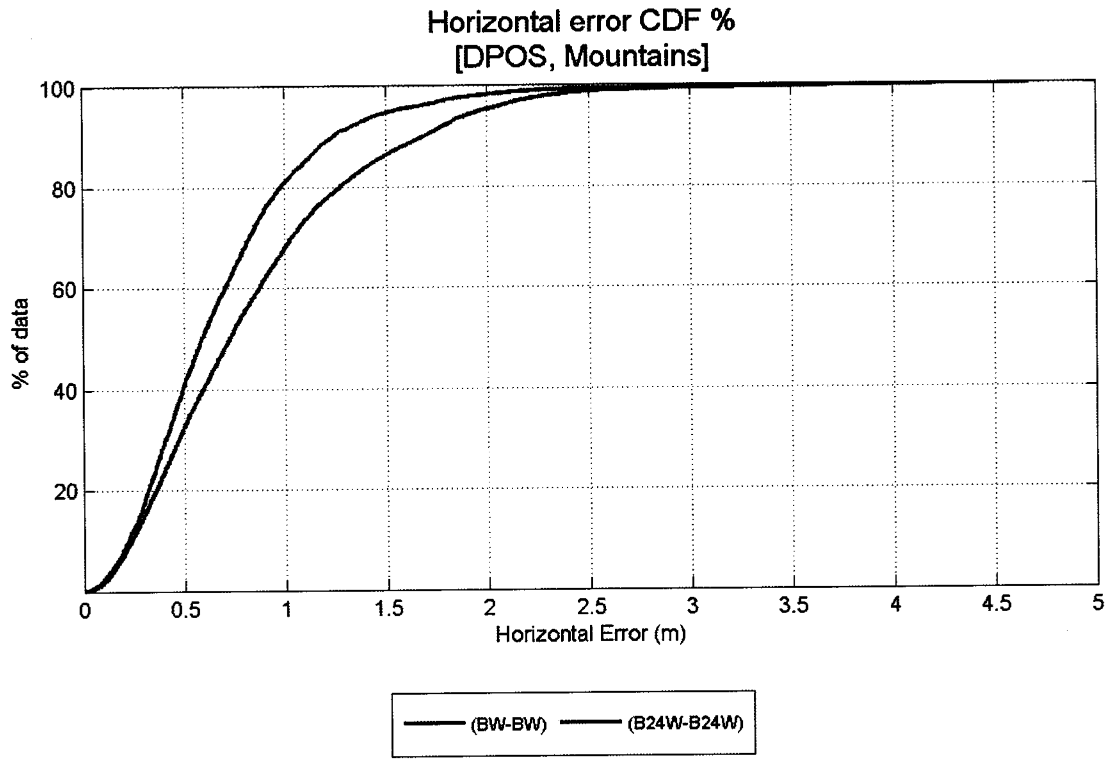


Figure 8-9: CDF of Horizontal Errors for (BW-BW) and (B24W-B24W) in Mountain Environment

9 Characterization of Errors

As mentioned in Section 6 where DOP and the number of satellites were introduced as potential predictive measures of the accuracy of the estimate of the IVV, it is desirable that the expected accuracy of the IVV be able to be determined in real-time. In this section, the efficacy of the two aforementioned predictive measures are discussed for (AW-AW) and (BW-BW) pairs. In addition to these predictive metrics, possible dependence of the accuracy of the IVV estimate on vehicle kinematics is explored. In particular, potential correlation between the errors in the IVV estimate and both inter-vehicle distance and vehicle speed were investigated. The potential dependence of the error on vehicle heading was also explored, but the figures are not included in this document as no conclusive results were obtained.

It should be noted that data from the Deep Urban environment was not used for this analysis for the following reasons. Firstly, the magnitudes of the errors in this environment are substantially larger than those in the other environments, meaning that the characterization of the errors in the other environments might be masked. Secondly, the Deep Urban environment was not the major focus of the present study; only 2 percent of the data collected was in this environment. To more fully characterize the environment may require a dedicated study.

9.1 Number of Satellites

It is well known that SP position accuracy is a function of the number of satellites in view. In general, the more satellites used in the navigation solution, the better the position accuracy.

The correlation between position accuracy and the number of satellites is very consistent for the (AW-AW) pairs (i.e., an increase in the number of satellites is accompanied by an increase in accuracy, and the accuracy is similar for each environment). Figure 9-1 and Figure 9-2 indicate that, on average, when using (AW-AW) in DPOS or RTK, if 7 satellites are used in the navigation solution, a horizontal RMS accuracy of 1.5 m or better can be expected in the estimate of the IVV. The figures also show that the RTK accuracy continues to improve as the number of satellites is increased while the DPOS positioning method appears to remain at the 1 m level.

Figure 9-3 and Figure 9-4 show that the correlation between accuracy and number of satellites used in the navigation solution is weaker for the (BW-BW) combination, particularly for the DPOS method. For example, the RMS error in the Local Roads environment is similar for 5 and 12 satellites. For the majority of the environments, the (BW-BW) receiver combination requires 8 or more satellites to achieve a horizontal position RMS of 1.5 m. The RTK position accuracy for the Interstate environment does not improve beyond 1.5 m even with a further increase in the number of satellites.

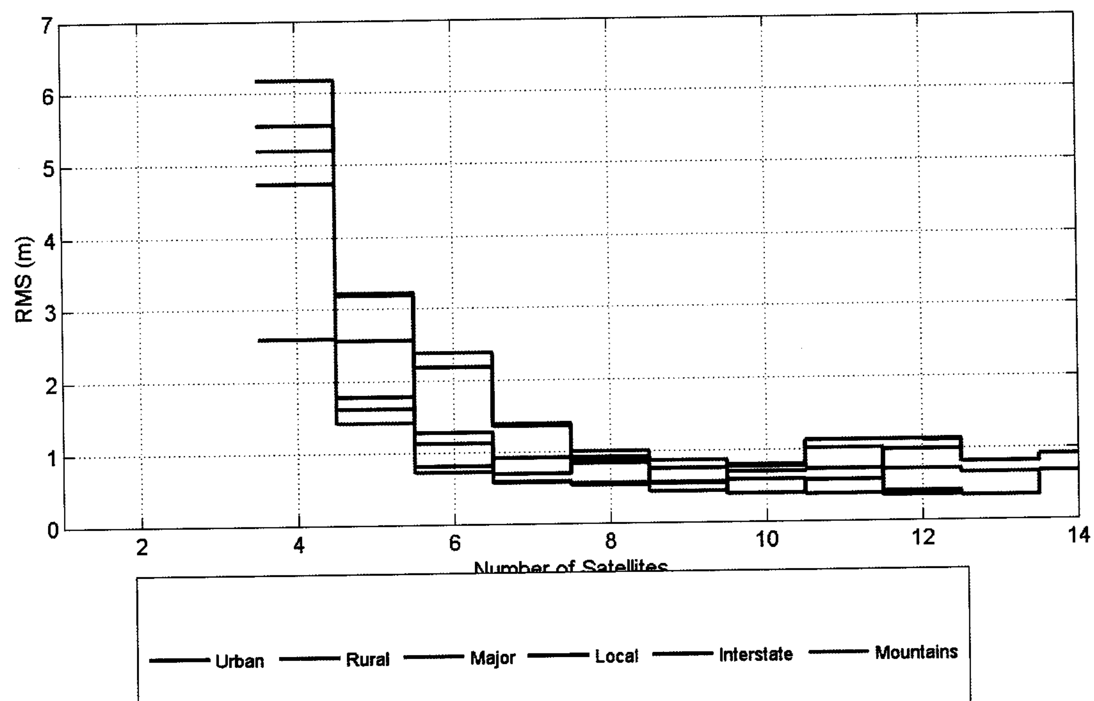


Figure 9-1: Horizontal RMS Error in IVV versus the Number of Satellites for (AW-AW), DPOS, for each Environment

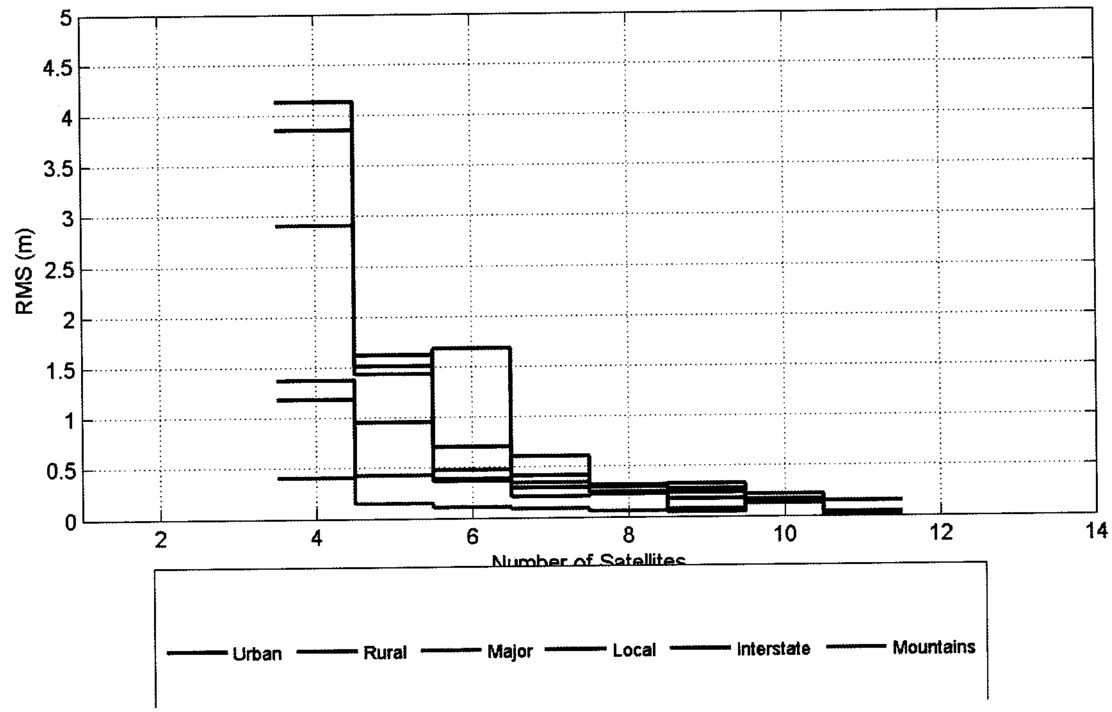


Figure 9-2: Horizontal RMS Error in IVV versus the Number of Satellites for (AW-AW), RTK, for each Environment

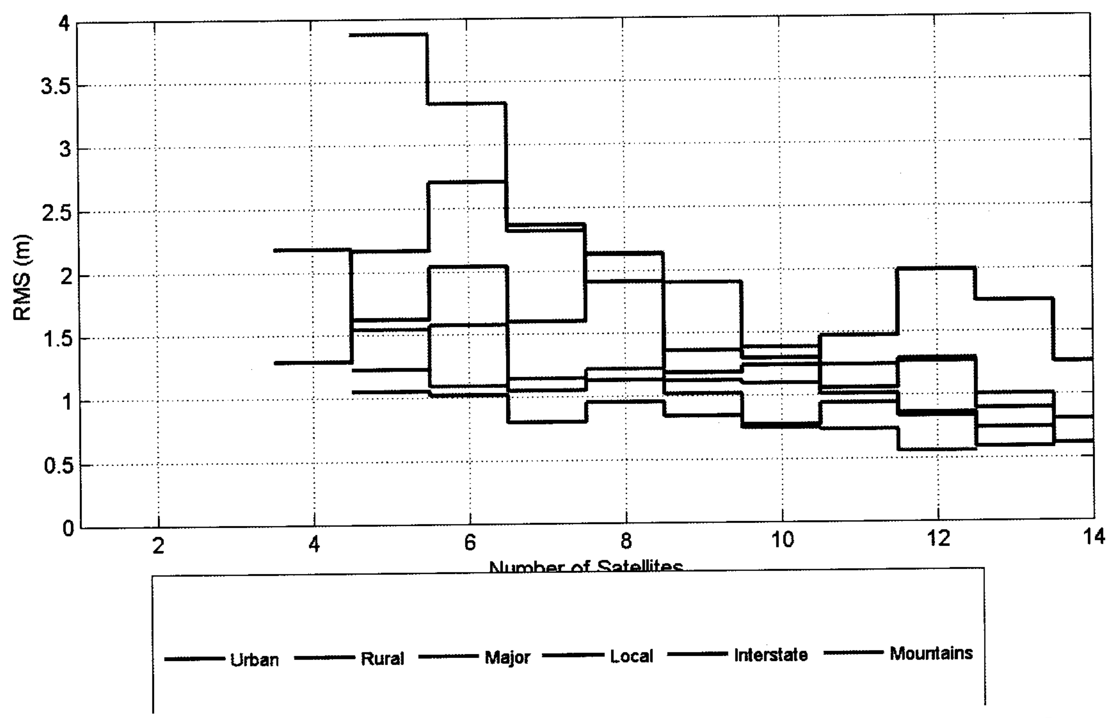


Figure 9-3: Horizontal RMS Error in IVV versus the Number of Satellites for (BW-BW), DPOS, for each Environment

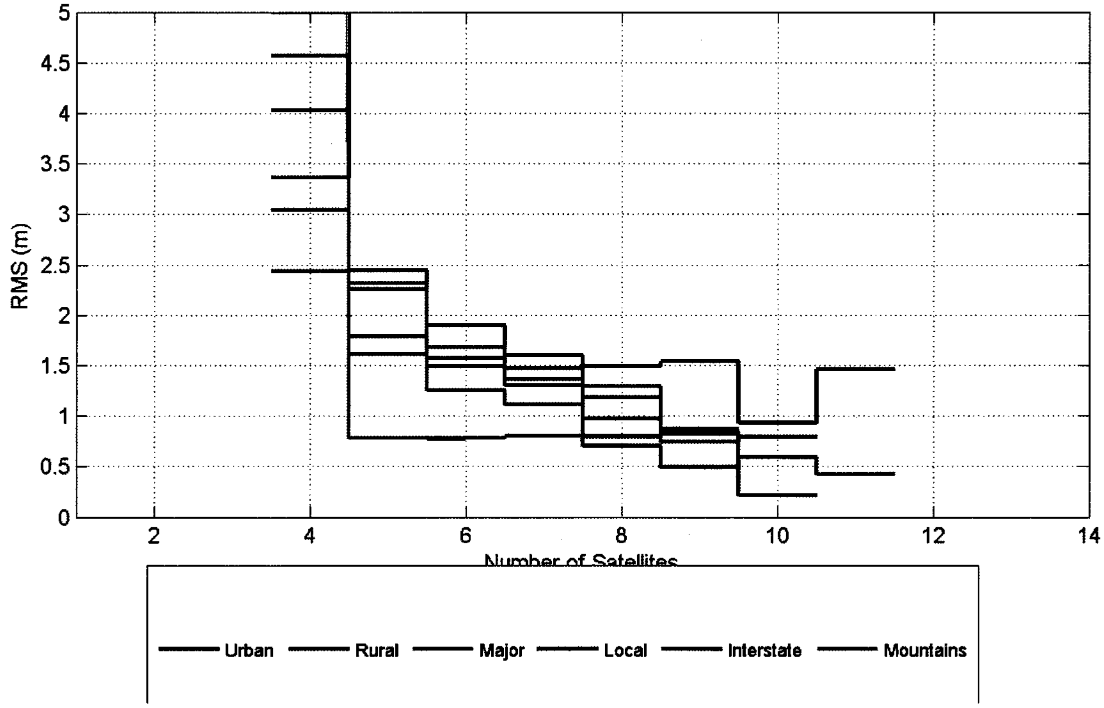


Figure 9-4: Horizontal RMS Error in IVV versus the Number of Satellites for (BW-BW), RTK, for each Environment

9.2 Dilution of Precision

As discussed in Section 5.1 of Alves, et al. (2009), the DOP is a measure of the geometry of satellites used in the navigation solution that can be related to the accuracy of the obtained solution. In general, the greater the geometrical dispersion of the satellites, the lower the DOP and the better the position accuracy. The HDOP for the RTK is not available. Therefore, only the DPOS positioning method is analyzed in this section.

Figure 9-5 shows that a horizontal RMS position error of 1.5 m or less was achieved for all considered environments for HDOP less than approximately 1.1 for the (AW-AW) receiver combination. With the exception of the Local Roads environment, a generally monotonic relationship exists between the HDOP and the error.

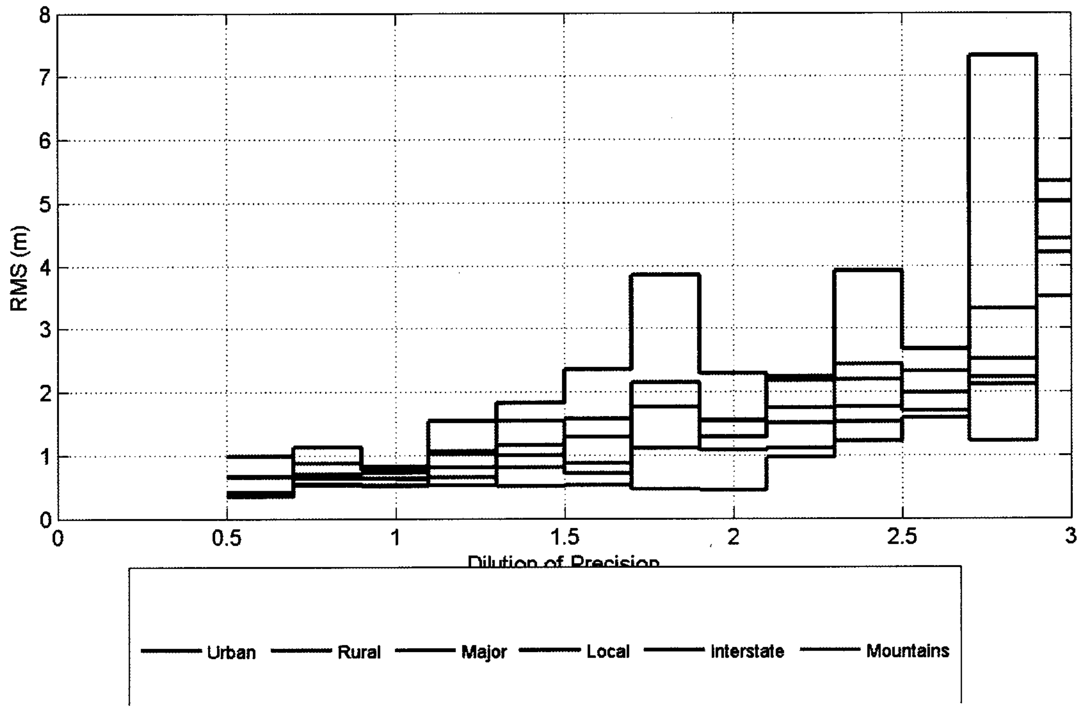


Figure 9-5: Horizontal RMS Error in IVV versus HDOP for (AW-AW), DPOS, for each Environment

Figure 9-6 shows that, as for the number of satellites, the correlation between DOP and accuracy is much weaker for (BW-BW) than it is for (AW-AW).

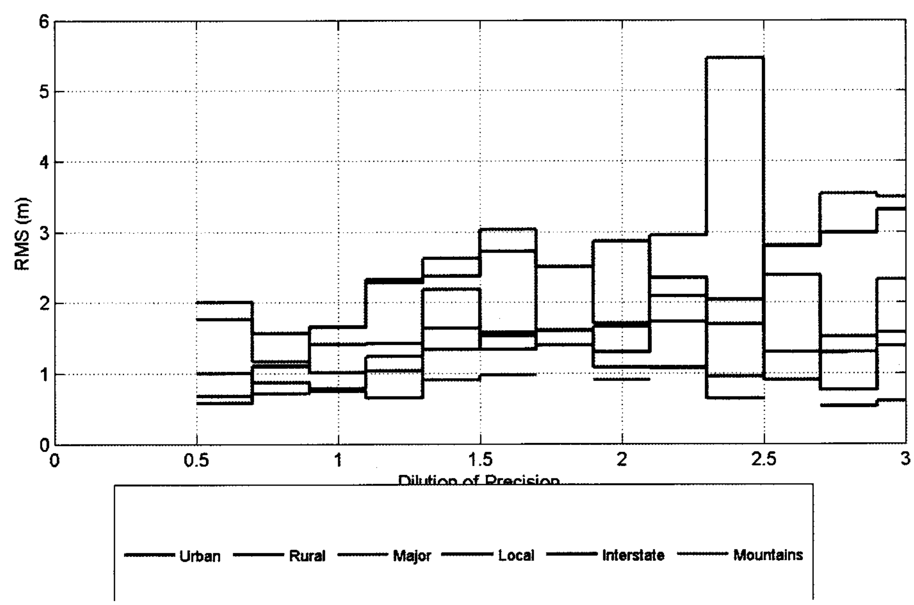


Figure 9-6: Horizontal RMS Error in IVV versus HDOP for (BW-BW), DPOS, for each Environment

9.3 Inter-Vehicle Distance

The distance between antennas is commonly used to estimate position accuracy obtained using some form of differential processing; however, this is typically reported as parts per million in applications where antenna separation is on the order of kms. The antenna separation for V2V positioning in this project was always less than 300 m.

Figure 9-7 and Figure 9-8 show the horizontal position error as a function of the distance between the vehicles for the DPOS method and the (AW-AW) and (BW-BW) receiver combinations, respectively. Figure 9-9 and Figure 9-10 show the horizontal position error as a function of the distance between the vehicles for the RTK method and the (AW-AW) and (BW-BW) receiver combinations, respectively. The typical vehicle separations were less than 100 m; therefore, the number of samples in each bin of the data where the vehicle separation is greater than 100 m are limited.

The figures indicate that there is no substantial and definitive correlation between vehicle separation and the accuracy of the IVV estimate for the typical inter-vehicle distances used herein. To truly determine the presence or absence of a correlation would require extensive dedicated tests.

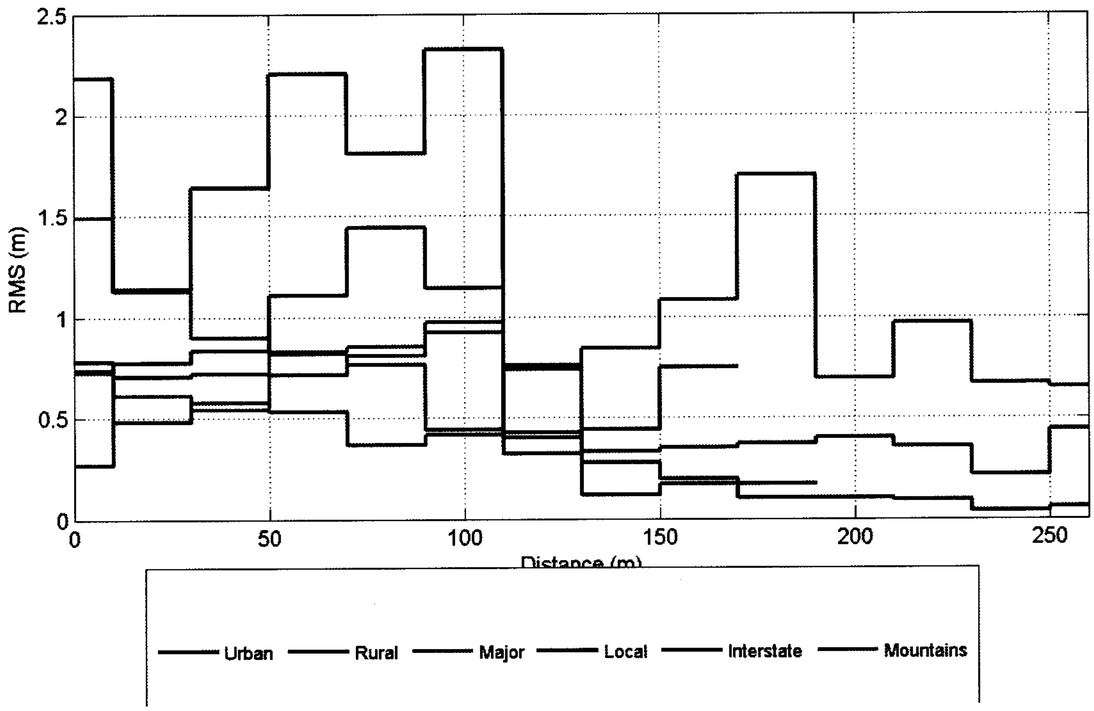


Figure 9-7: Horizontal RMS Error in IVV versus the Inter-Vehicle Distance for (AW-AW), DPOS, for each Environment

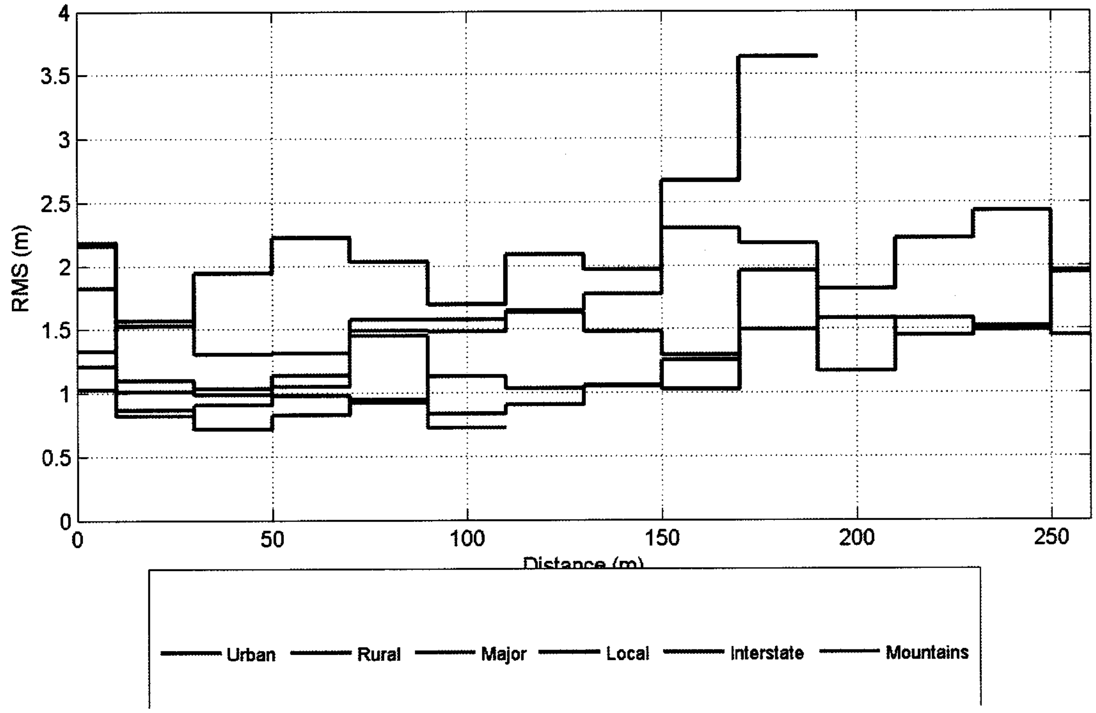


Figure 9-8: Horizontal RMS Error in IVV versus the Inter-Vehicle Distance for (BW-BW), DPOS, for each Environment

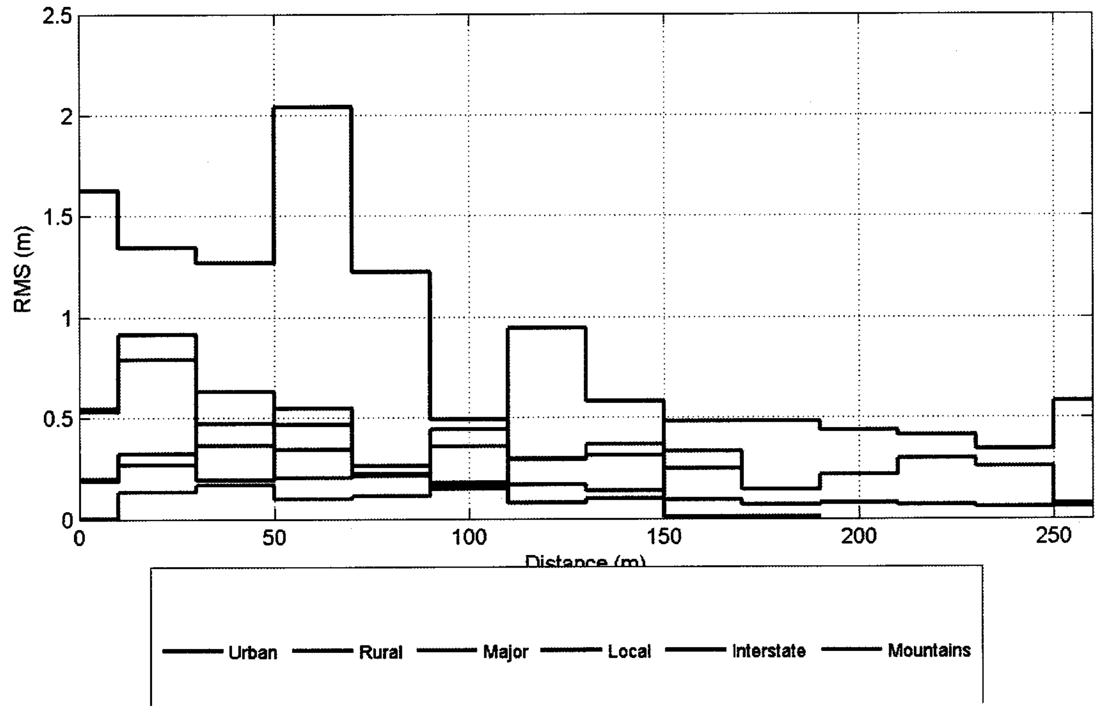


Figure 9-9: Horizontal RMS Error in IVV versus the Distance for (AW-AW), RTK, for each Environment

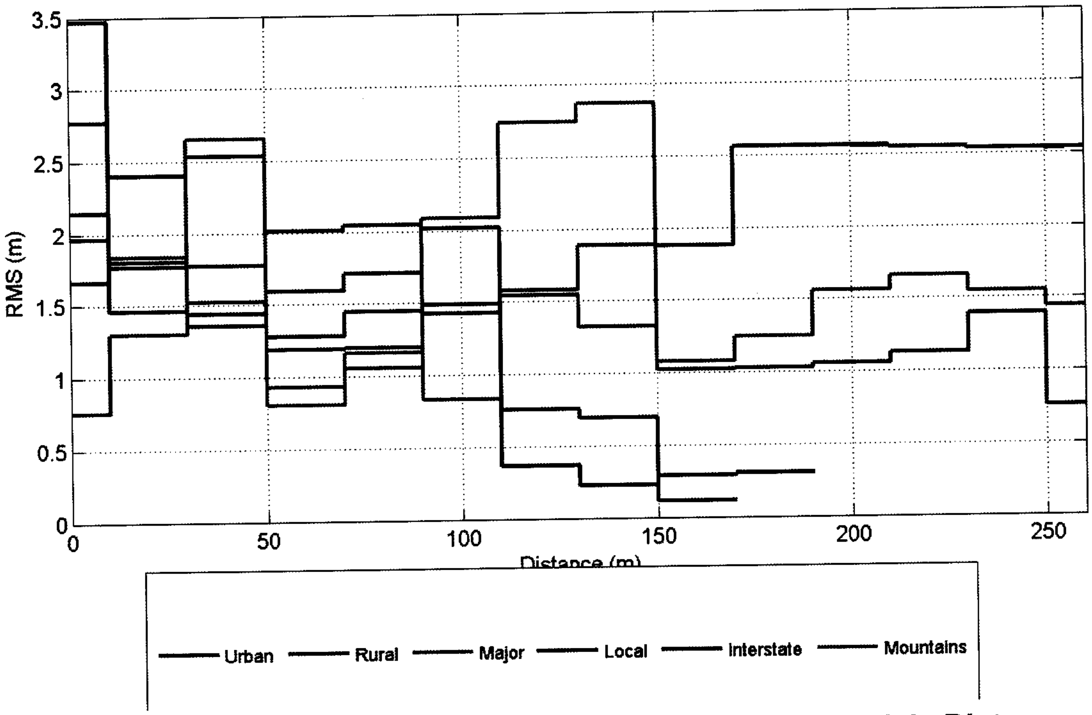


Figure 9-10: Horizontal RMS Error in IVV versus the Inter-Vehicle Distance for (BW-BW), RTK, for each Environment

9.4 Vehicle Speed

Figure 9-11 and Figure 9-12 show the horizontal error in the IVV as a function of the vehicle speed for the DPOS method using (AW-AW) and (BW-BW) combinations, respectively. Figure 9-13 and Figure 9-14 show the same relationships for the RTK method.

The speed limits for each environment set the maximum range of speeds. The distribution of samples for each environment is different depending on the speeds on each of the roads. For example vehicles travelling on an interstate road will rarely be below 50 miles per hour, conversely vehicles were not travelling faster than 40 miles per hour on local roads. This distribution of samples is important to consider when deriving conclusions based on these plots. Sampling of data from different environments was subjected to constraints in those environments. Therefore, comparison of performance in two environments in the same speed range may include effects of sampling.

There is no strong correlation between vehicle speed and position accuracy evident from the results. However, it may be possible to ascertain the environment type that the vehicle is in based on its vehicle speed and other variables, which would help to predict the current relative position accuracy. For example, the slight tendency (observable in Figure 9-11 to Figure 9-14 to a varying degree) for decreasing errors with increasing speeds, is potentially due to an increased likelihood of higher speeds in open areas which tend to have higher speed limits and less traffic.

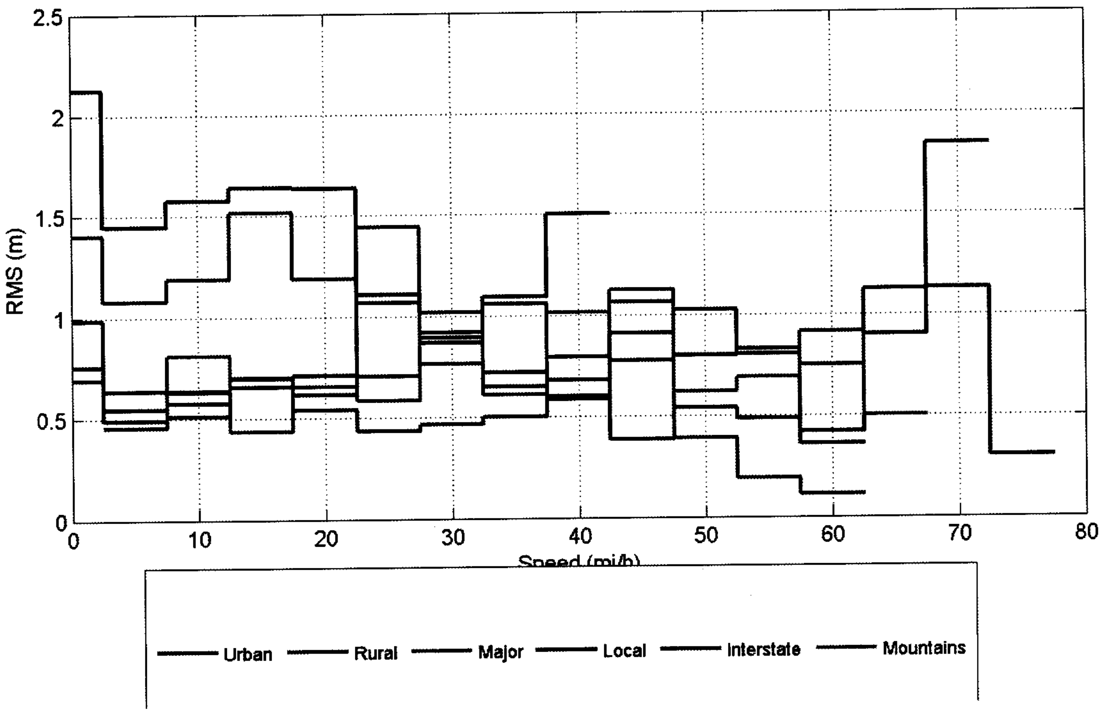


Figure 9-11: Horizontal RMS Error in IVV versus the Speed for (AW-AW), DPOS, for each Environment

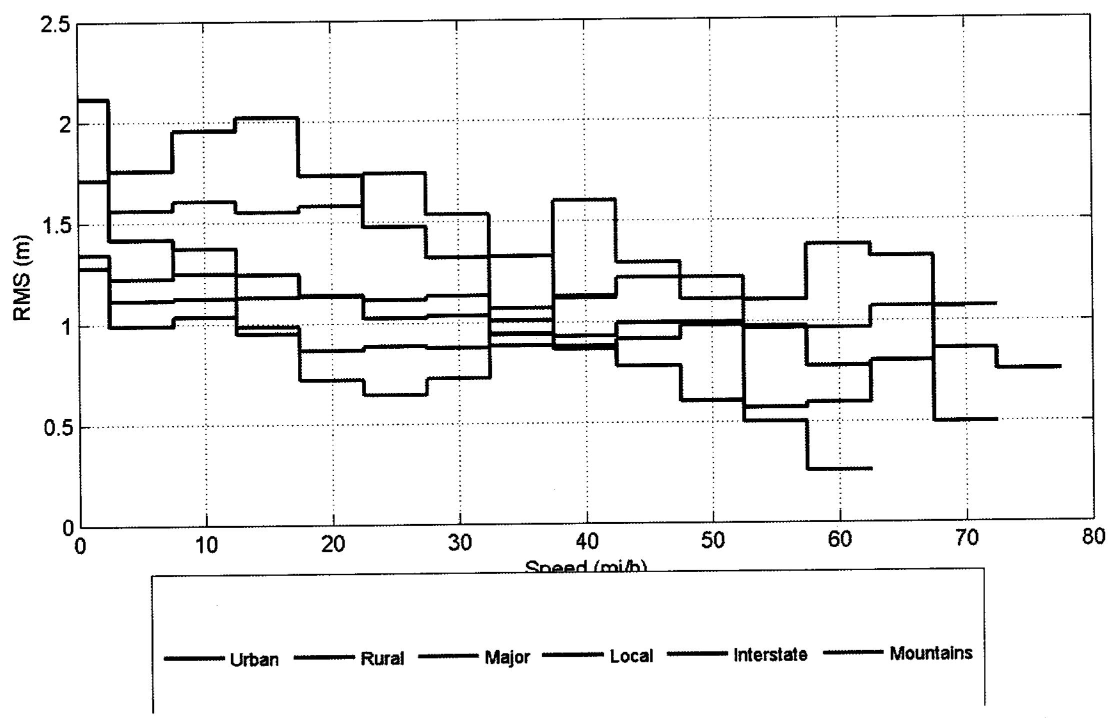


Figure 9-12: Horizontal RMS Error in IVV versus the Speed for (BW-BW), DPOS, for each Environment

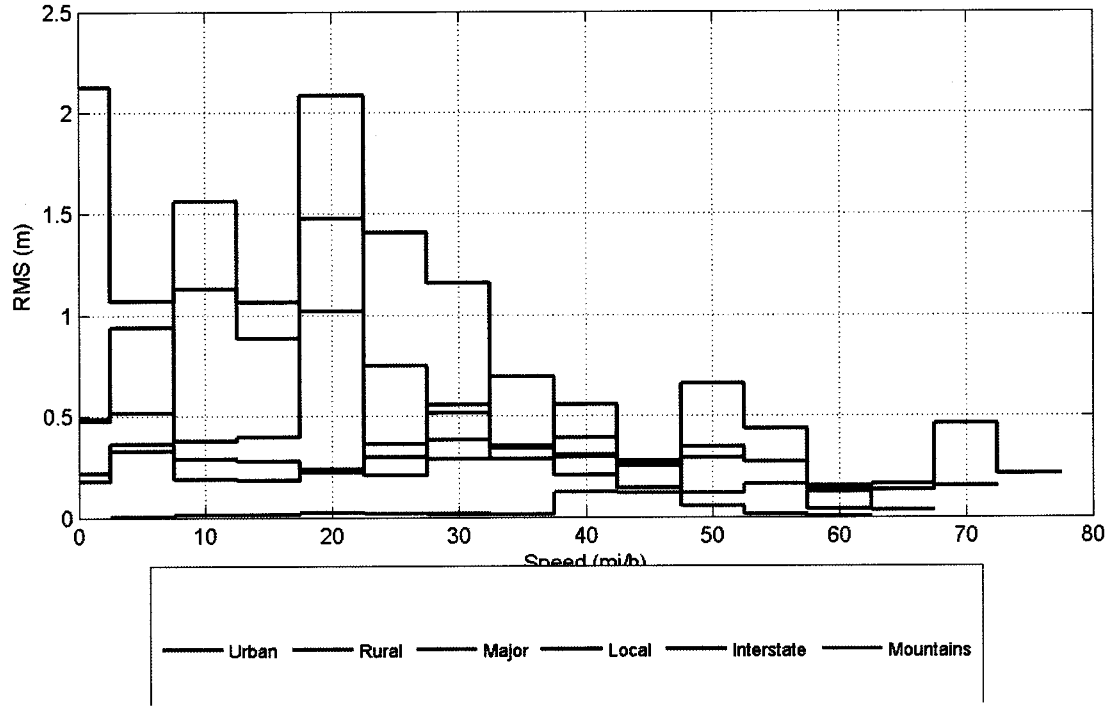


Figure 9-13: Horizontal RMS Error in IVV versus Speed for (AW-AW), RTK, for each Environment

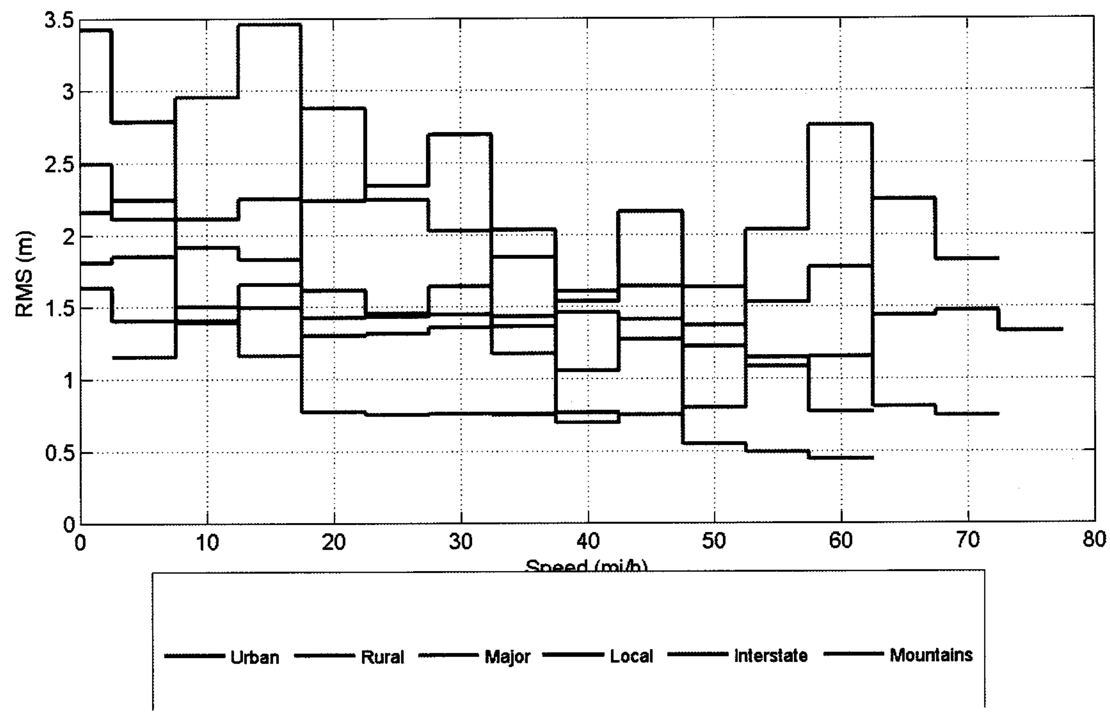


Figure 9-14: Horizontal RMS Error in IVV versus the Speed for (BW-BW), RTK, for each Environment

10 Vehicle-to-Infrastructure Test Results

As discussed in Section 7, V2I data was collected in 5 environment types over 2 days. The requirements for the V2I reference trajectories were much stricter than V2V. This is because any errors in the reference trajectory larger than a few centimeters would be noticeable due to the high accuracy of the (AW-AW) V2I solution. While more than 40 V2I passes were recorded, the accuracy requirements means that they were reduced to 20 V2I passes that are used for the statistics and analysis discussed here. The 20 passes include the 3 coordinated types described in Section 7 in which the vehicles are following each other, approaching each other, and approaching an instrumented intersection with roughly orthogonal directions.

A typical time series plot of the AT and XT components of the errors in the IVV estimate during a V2I pass is shown in Figure 10-1. The errors in four IVV solutions are shown in the figure:

- V2I Single (V2I-S): Solution in which only one of the two vehicles has a V2I solution (only one vehicle within the zone).
- V2I Both (V2I-B): Solution when both vehicles have V2I solutions.
- DPOS: The alternative solution when V2I is unavailable (i.e., when outside the V2I zone, the receivers work in SP mode).
- RTK: Shown for comparative purposes.

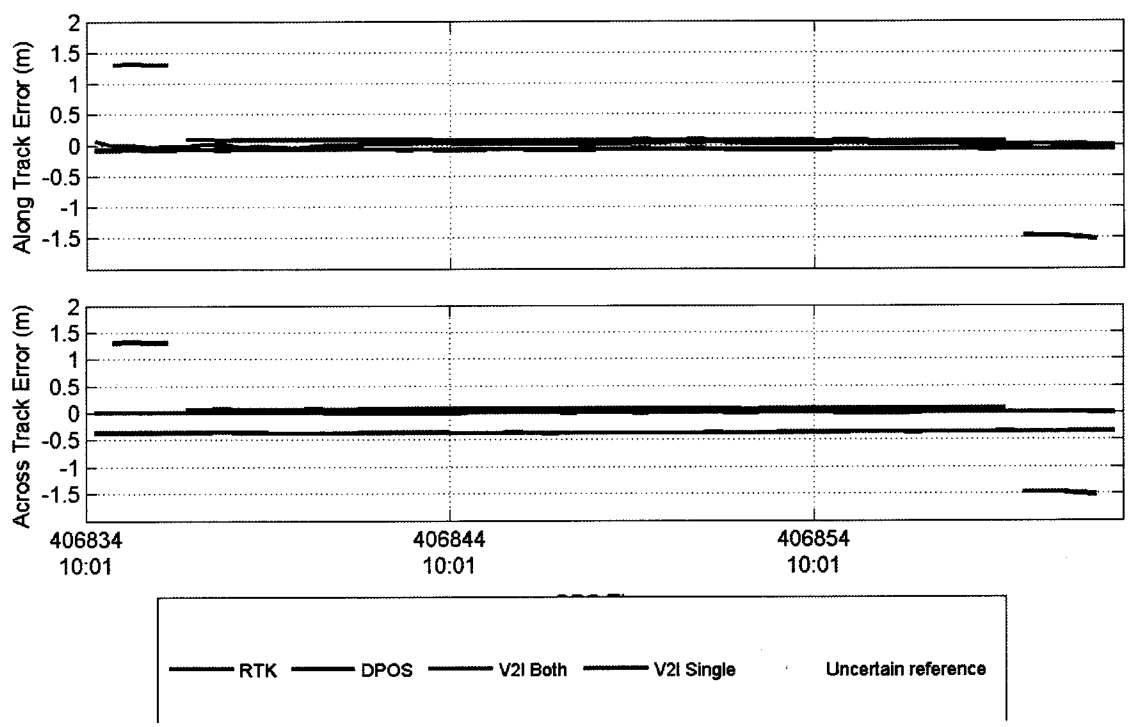


Figure 10-1: V2I Time Series for (AW-AW) for an Interstate Environment

Here, the focus is on three important characteristics of the V2I tests:

- The accuracy of V2I-S
- The accuracy of V2I-B
- The discontinuity in the IVV estimate when one of the vehicles enters or leaves a zone

Only the (AW-AW) and (BW-BW) receiver combinations are discussed in the following sections; although in the accompanying document, figures are presented for each of the receiver combinations used in the V2V DPOS analysis.

Figure 10-2 and Figure 10-3 show the CDFs of horizontal errors in the IVV estimate for the (AW-AW) and (BW-BW) receiver combinations, respectively. Each vehicle pass has a very short duration, usually lasting less than 2 minutes depending on the driving environment and the vehicle speed. A pass was chosen to start and end a few seconds before and after the first and last vehicle entered and left the V2I zone so that all transitions would be apparent. Due to these short durations, the total number of epochs for each of the solutions of interest is very low, especially for the V2I-S solutions. The small number of samples should be considered when interpreting Figure 10-3 and Figure 10-2. With this caveat, the figures show that for both receiver combinations, the RTK and V2I-B solutions are very similar. The V2I-S solutions offer the poorest IVV accuracy. This is because the vehicle with the V2I solution will have an accurate position while the other will have larger errors. In the DPOS case, the errors for the SP solutions are similar and are effectively canceled when the IVV is calculated.

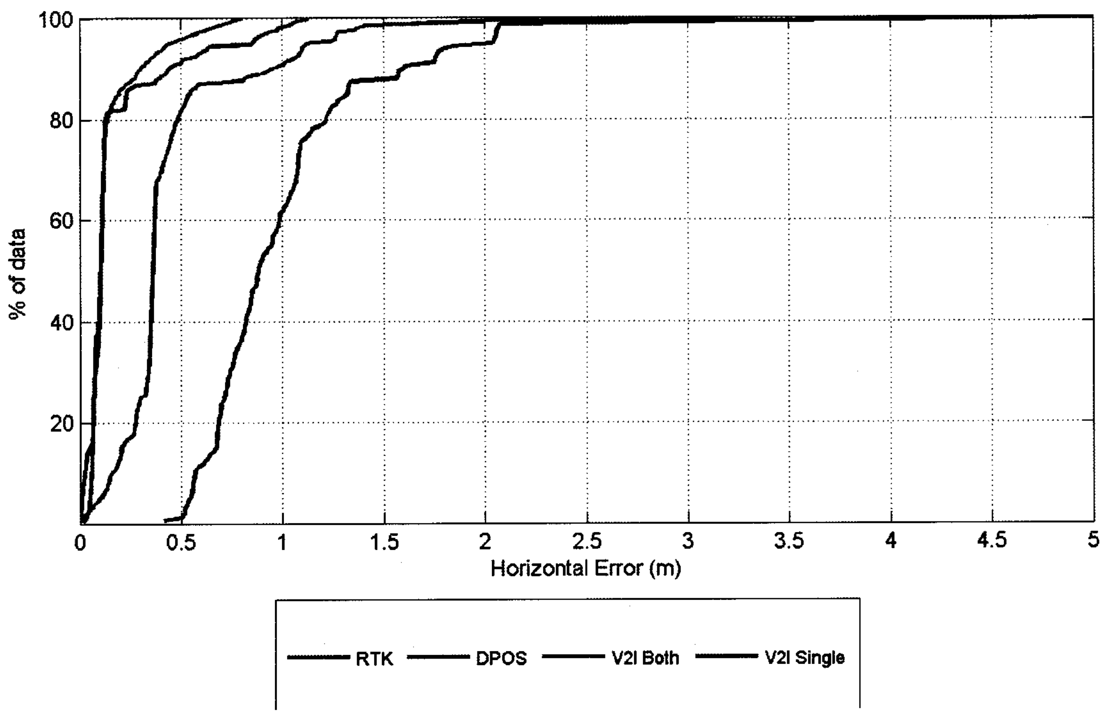


Figure 10-2: CDF of Horizontal Errors in V2I Estimate of IVV, (AW-AW)

The poor V2I-S performance suggests that each vehicle should only switch to the infrastructure solution when both vehicles are using the infrastructure solution. If both the V2I-B and RTK solutions are available, then it may not be necessary to switch from RTK to V2I-B solutions because of their similar accuracy performances.

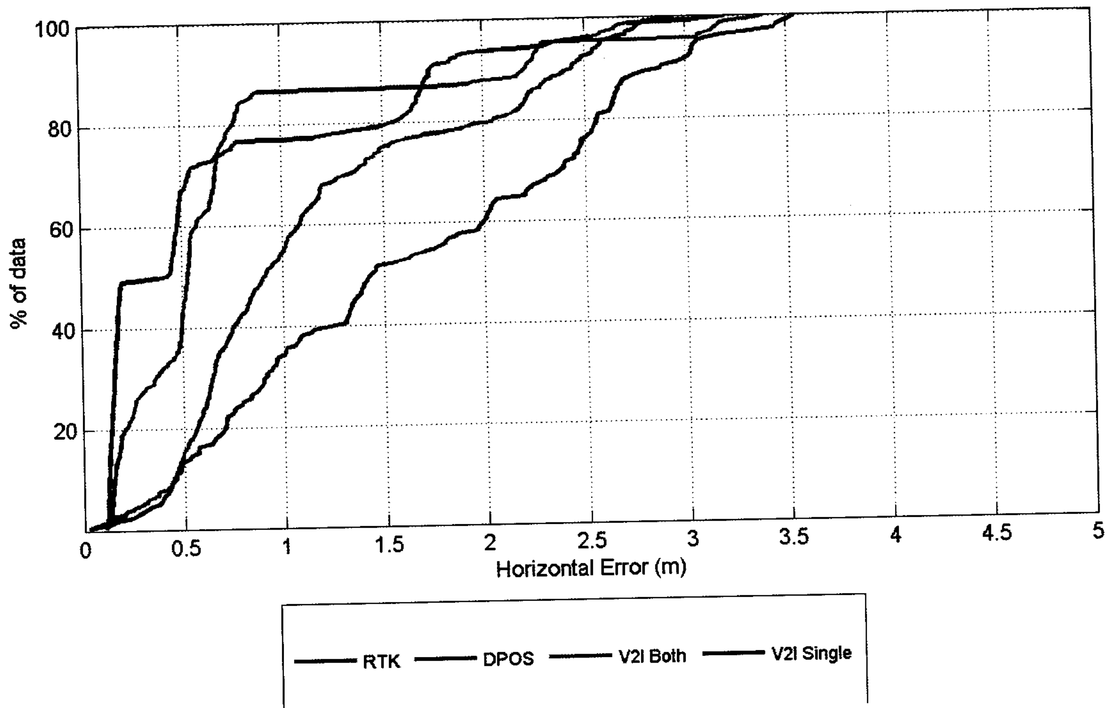


Figure 10-3: CDF of Horizontal Errors in V2I Estimate of IVV, (BW-BW)

The discontinuities in the IVV estimate that occur when switching between modes (e.g., DPOS to V2I-S), are tabulated for the analyzed passes for (AW-AW) in Table 10-1 and (BW-BW) in Table 10-2. The magnitudes of discontinuity show large variability even for the runs in the same environment using the same receivers. For example, in transitions from DPOS to V2I-S using the (BW-BW) combination in the Major Urban Thruway, the magnitudes range from 0.3 m to more than 5 m (AT) and from 0.8 m to more than 5 m (XT). Discontinuities of 5 m obviously make relative position at the lane level (1.5 m) a difficult proposition. Aside from the variability and magnitude of possible discontinuities in the IVV estimate, the major conclusion that can be drawn from inspection of Table 10-1 and Table 10-2 is that the discontinuities are generally smaller for (AW-AW) than for (BW-BW). While it is of questionable value to quote statistics from this small sample size with such large variability, the average magnitudes for the (AW-AW) and (BW-BW) combinations are 0.77 m and 1.47 m, respectively. That the (AW-AW) pair has smaller discontinuities is to be expected since the discontinuity is approximately bounded[11] by the error in the SP solution, and the AW receivers generally have smaller errors than the BW receivers. One would expect the discontinuities for the BN receivers would be even larger, since these receivers do not have the benefit of the WAAS differential corrections.

[11] This bound is only strict if the V2I-B is solution is considered to be exact.

Table 10-1: Discontinuities in the IVV Estimate at Zone Transitions for (AW-AW) Combination

Environment	DPOS → V2I S		V2I S → V2I B		V2I B → V2I S		V2I S → DPOS	
	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)
Major Urban Thruway	0.49	0.99	-0.06	-0.40	-0.05	0.26	0.33	-0.14
	-0.18	-0.09	0.15	0.24	0.63	0.46	-0.38	-0.40
					-0.62	-0.82	0.69	0.88
	-0.53	-0.40	-0.21	0.43	-0.86	-0.67	-0.45	-0.38
Major Rural Thruway	0.24	0.01	-0.43	-0.13	-0.65	-0.87	0.72	0.85
	-1.37	-1.39	1.40	1.43	0.61	0.53	-0.54	-0.53
			-1.02	-0.83	-1.05	-1.16	1.01	0.35
					0.91	0.44	-1.18	-1.15
Local Roads					1.15	1.23	-1.11	-1.47
	1.32	0.71	-0.40	-0.28	-0.77	-0.38	-0.58	0.82
Freeway	-0.28	-0.79	0.44	0.47	1.75	1.69	-1.84	-1.37
	1.80	2.30	-1.97	-1.99	-0.56	-0.58	1.77	0.36
	-1.24	-1.66	1.21	1.24	1.53	1.55	-1.52	-1.18
	1.24	0.96	-0.42	-0.58	-0.89	-0.98	0.76	1.02
	-1.28	-1.05	0.27	0.78	0.31	0.56	-0.21	-0.21
	-1.11	-1.03	-0.19	0.52			0.40	-1.14
Major Roads	-0.08	0.25	-0.08	-0.29	-0.93	-0.90	1.11	1.56
			0.35	0.53	-0.79	-0.98	-0.12	0.09
	1.36	0.60	0.16	-0.96	0.24	-0.40		

Table 10-2: Discontinuities in the IVV Estimate at Zone Transitions for (BW-BW) Combination

Environment	DPOS → V2I S		V2I S → V2I B		V2I B → V2I S		V2I S → DPOS	
	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)
Major Urban Thruway	> 5	>5			0.39	1.08	-0.65	-0.87
	-0.77	-0.88	2.67	0.85	1.33	2.97	-1.78	-3.11
	0.30	1.07	-0.82	-0.99	-1.03	0.07	-0.84	0.18
	1.29	1.42	-5.44	-3.55	3.58	2.09	-3.13	-1.02
Major Rural Thruway	0.80	1.95	-0.82	-1.89	-0.34	1.81	-0.97	-1.37
	1.18	1.35	0.17	-0.49	1.13	2.15	-1.84	-1.94
			1.95	1.03	-1.08	-0.47	-2.26	0.09
			0.96	1.88	-1.86	-3.46	0.19	2.20
Local Roads	-1.85	-0.66					-1.44	1.05
	0.13	-0.09			0.82	1.66	-0.99	-0.26
Freeway	-1.74	-2.61	5.38	4.79	2.31	3.29	-2.33	-2.94
	-0.88	0.15	0.88	-0.25	0.18	0.66	-0.01	-0.78
	-2.02	-2.48	2.71	2.83	1.00	1.70	-1.75	-2.04

Environment	DPOS → V2I S		V2I S → V2I B		V2I B → V2I S		V2I S → DPOS	
	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)	AT (m)	XT (m)
	-0.33	-0.10	-0.44	-0.08	-1.62	-1.44	0.90	1.22
	1.71	-1.20					-0.83	0.40
	0.74	-2.33	-0.42	-0.12	-0.57	-0.58	0.76	-1.14
Major Roads	2.05	2.68	0.40	-1.25	-2.18	0.04	1.13	-0.04
	1.26	-0.69	-1.14	-1.25	-2.59	-1.62	3.02	1.98
	-1.83	-2.64	3.16	3.51	0.80	0.20	-0.86	1.30

11 Conclusions

The conclusions presented below are based on the extensive, multi-environment tests and equipment conducted in accordance with the requirements of the project.

The availability of each positioning method as a function of the receiver combination, constellation utilized, use of WAAS, and accuracy threshold is given in Table 11-1. Although the results are self-explanatory, a few important conclusions are in order. Note that the availability numbers presented here are dependent on the particular mix of environments specified for this testing. For example, increasing the proportion of challenging GNSS environments, such as deep urban, would decrease the availability values. The environment mix was designed to represent the road use of an average driver as given in the FHWA publication on *Our Nation's Highways* (FHWA 2008) [2].

Table 11-1: Availability Statistics for All Receiver Combinations and V2V Processing Methods

Receivers		Proc.	FA	FAWE (1.5 m)		FAWE (5 m)		UNC
Host	Remote	(D)POS/(R)TK	(%)	AT (%)	XT (%)	AT (%)	XT (%)	(%)
AW	AW	R	92	91	91	91	91	<1
		D	97	93	92	96	95	1
	BW	R	84	68	69	83	83	<1
		D	98	62	65	95	95	1
	BN	R	84	73	73	84	83	<1
		D	98	62	70	95	95	1
BW	AW	R	84	81	80	84	83	<1
		D	98	59	68	94	95	1
	BW	R	82	74	71	81	81	<1
		D	100	89	88	97	97	1
	BN	R	80	71	68	79	79	<1
		D	100	82	84	97	97	1
BN	BN	D	100	90	89	97	97	1
B24W	B24W	D	99	89	89	97	96	1

Explanation of acronyms utilized in the table:

- FA: Full Availability
- FAWE (1.5 m): Full Availability With Errors < 1.5 m
- FAWE (5 m): Full Availability With Errors < 5 m
- UNC: UNCertainty (%) in availability due to uncertain reference inter-vehicle vector
- AT: Along Track
- XT: Across Track
- AW: Type A Receiver with WAAS
- BW: Type A Receiver with WAAS
- BN: Type A Receiver without WAAS

1. Full availability percentages with errors less than 1.5 m in both along and across track using the RTK method involving one or two Type B receivers are lower than those using two Type A receivers by up to 20 percent. The experience of the Team suggests this discrepancy is caused by a difference in the quality of the phase lock loops (PLL). The higher quality PLLs of Type A receivers results in a lower number of carrier phase cycle slips and a higher probability of obtaining high accuracy carrier phase ambiguity fixed or partly fixed solutions. Higher numbers of cycle slips in receiver Type B contribute to frequent ambiguity resets resulting in relatively poorer solutions.

2. The best availability percentages with errors less than 1.5 m, namely 90 percent or slightly more, occur with pairs of Type AW receivers in either RTK or DPOS mode or with pairs of Type B receivers, both with WAAS or both with no WAAS, in DPOS mode. When mixing the WAAS and no WAAS options, the availability drops because WAAS satellites provide not only an additional signal but also differential corrections for GPS satellites to improve absolute accuracy. However, unless corrections are applied at both receivers, the IVV accuracy decreases significantly.

3. Full availability percentages with errors less than 1.5 m using the DPOS method with pairs of identical receivers is significantly better than corresponding values using pairs of mixed receivers. The different internal settings used by receivers, such as measurement acceptance criteria, can lead to mismatched satellites between non-homogeneous receiver pairs, while different ionospheric and tropospheric models can lead to dissimilar biases in their navigation solutions.

4. At the 5 m accuracy level, the DPOS method for each of the considered receiver combinations has availability level of at least 95 percent. The detrimental effects of receiver non-homogeneity are not observable at this lower accuracy. For RTK, the availability measures at the 5 m accuracy level are lower and essentially equal to the associated full availability values. These full availability values are highly receiver combination dependent.

5. The RTK SW utilized in the tests did not use WAAS satellites and, therefore, the impact of WAAS on RTK cannot be assessed. However the use of these satellites would theoretically improve all RTK performance parameters.

6. Type B receiver pairs with WAAS generally perform the same as those with no WAAS in the DPOS mode. Under the test conditions prevailing during July-August 2009 when a GPS constellation of 31 satellites was available, the addition of WAAS satellites did not add significantly to the geometry of the satellites. As discussed in Point 2 above, mixing the type B WAAS and no WAAS receivers decreased availability. In DPOS mode, WAAS signals without differential corrections would generally be better to maintain high IVV solution accuracy, although absolute vehicle location accuracy would decrease and, under poor satellite geometry, an IVV solution accuracy might also decrease.

7. Certain anomalous results in Table 11-1, such as the difference in performance between the AW-BW and BW-AW combinations using RTK which is limited to availability of solutions with 1.5 m accuracy, are thought to be attributable to the proprietary RTK SW. Other incongruous results include the availability of solutions with 1.5 m accuracy for the AW-BW and AW-BN combinations using RTK, which since the RTK SW did not use WAAS in the calculations, should be identical. Without precise knowledge of the algorithms used within the receivers and the RTK SW, it is not possible to conclusively state the reasons for these discrepancies.

8. The difference in availability between the 24-satellite nominal constellation and the 31-satellite constellation available during the August 2009 tests was negligible using Type B receivers in DPOS mode. While the B24W-B24W pair used, on average, 1.3 satellites fewer than the BW-BW pair in the calculation of the navigation solution, the average HDOP values for the two pairs were within 0.05 of each other, supporting the similar availability of accurate results. The discrepancy between the two receiver pairs would likely be more evident if a larger portion of the test duration was spent in the Deep Urban environment where satellite availability was limited.

9. Data gap statistics for the roughly 45 hours of collected data are given in Table 11-2. A gap in the data is defined as a time interval when no solution is available due to the lack of measurements. This can be due to transmission problems (for RTK only), insufficient number of measurements, or a combination thereof. Most gaps are less than 15 s and have average durations of 2 to 7 s. The statistics in the table are dependent upon the mix of environments used in the data collection; the majority of gaps occurred in the Deep Urban environment, which accounted for less than 4 percent of the total testing duration.

Table 11-2: Data Gap Statistics for all Receiver Combinations and V2V Processing Methods

Receivers				Gaps < 15 s		15s < Gaps < 30 s		Gaps > 30 s	
Host	Remote	Proc. (D)POS/(R)TK	# Gaps	%	Ave (s)	%	Ave (s)	%	Ave (s)
A	A	R	1459	90	5	6	21	4	72
		D	1123	97	2	2	19	2	77
	BW	R	1375	56	7	31	20	13	67
		D	894	96	2	2	20	2	58
	BN	R	1303	54	6	32	20	14	68
		D	894	96	2	2	20	2	58
BW	A	R	1377	56	6	31	20	13	9
		D	829	97	2	2	20	2	1
	BW	R	1455	53	6	33	20	14	71
		D	8	100	3	0	-	0	-
	BN	R	1601	53	8	33	20	14	68
		D	11	100	2	0	-	0	-
BN	BN	D	9	100	4	0	-	0	-

10. Data gaps for RTK generally occur more often and last longer than those for DPOS using the same receiver combinations. This is particularly evident for the BW-BW pair. While it was not possible to determine the cause for each individual RTK data gap, the Dedicated Short Range Communications (DSRC) radio link between the vehicles was found to be operating properly 99.8 percent of the time suggesting that the majority of gaps were due to insufficient common measurements from the receivers after rejection. The number and duration of gaps could likely be reduced by tuning the SW, although this may lead to a decrease in accuracy and reliability.

11. The dependency of the RTK method on the SW prescribed for the project was not investigated herein. However, the previous experience of the investigators suggests that reputable, independently developed L1-only RTK SW packages used over short inter-receiver distances, such as the 300 m as was the case for this test, will generally give similar results.

12. Discontinuities in the IVV estimates at transitions between DPOS and V2I modes have great variability, but potentially have magnitudes that may make relative positioning at the lane (1.5 m) or road (5 m) identification level difficult.

12 References

[1] Bai, F. and H. Krishnan, *"Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications,"* Proceeding of the 9th International Conference of Intelligent Transportation System, 2006.

[2] U.S. Department of Transportation, Federal Highway Administration, *"Our Nation's Highways,"* FHWA-PL-08-021, 2008.

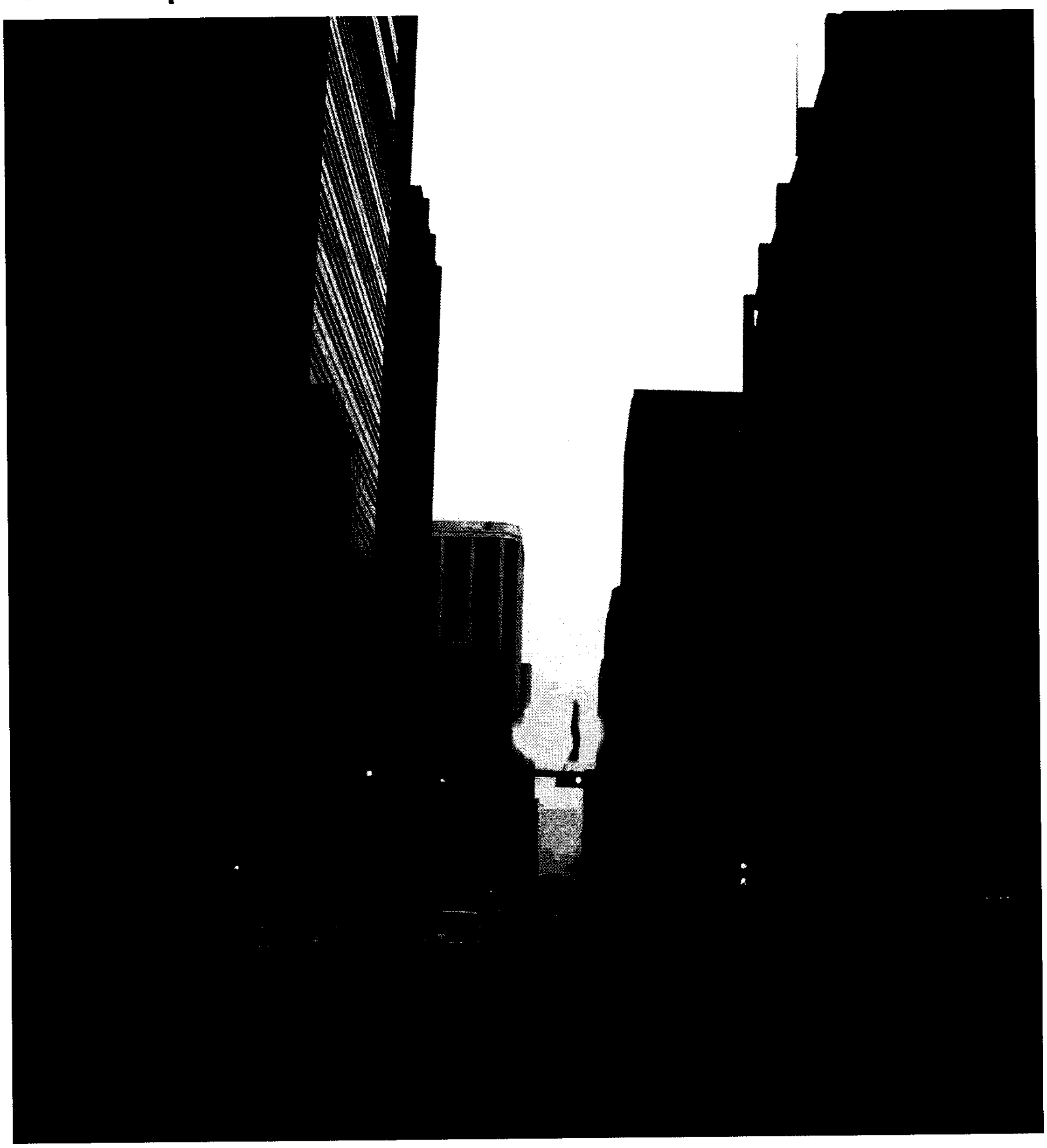
[3] Luo, N., and G. Lachapelle, *"Relative Positioning of Multiple Moving Platforms using GPS,"* IEEE Transactions on Aerospace and Electronic Systems, 39, 3, 936-948, 2003.

13 Supplementary Material

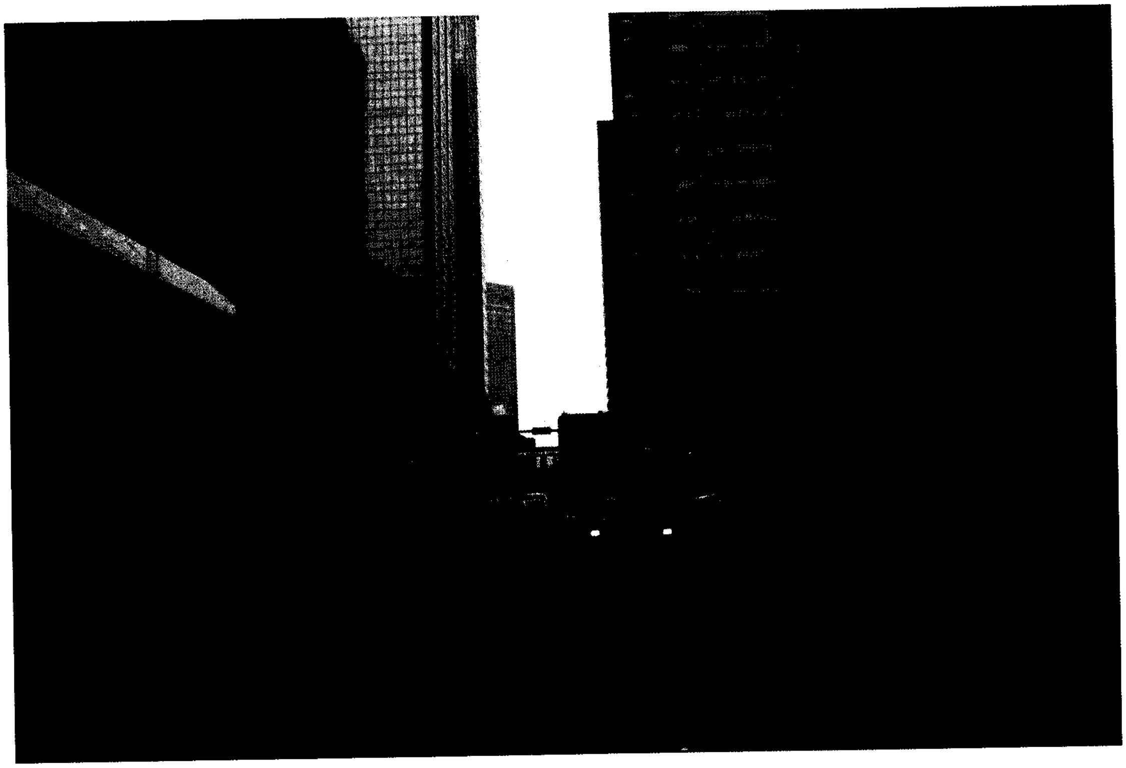
13.1 Photos Illustration of The Data Collection Routes

High definition video was collected for each of the data segments (V2V and V2I) of the final field study. The video camera was positioned on the rear vehicle, facing the lead vehicle. This appendix contains representative photos showing each of the data collection environments.

13.1.1 Deep Urban

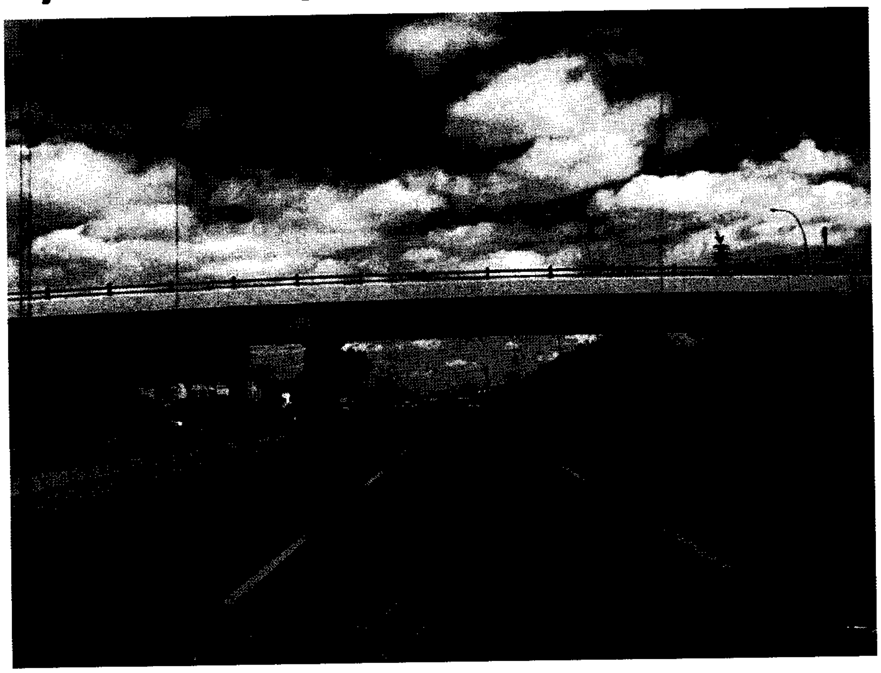


Urban Canyon with 20-30 Storey Buildings



Urban Canyon with 20-40 Storey Buildings

13.1.2 Major Urban Throughway



Major Urban Throughway Road with Overpass and Sloped Road Banks Creating A Natural 10 Degree Elevation Mask

Major Urban Throughway with a Pedestrian Overpass and 1-4 Storey Buildings

Major Urban Throughway Representative of Natural Elevation Mask (5-10 Deg)

Major Urban Throughway Representative of Overpass and High Elevation Mask on Right Side of the Vehicle

Major Urban Throughway Representative of Multiple (2) Overpasses and Road within 5-15 Degree Elevation Mask

Major Urban Throughway Representative of a Parallel-to-Trajectory Overpass, with Increased Wall to Create Poor Across Track Satellite Observability

13.1.3 Major Rural Throughway

Major Rural Throughway Representative of Occasional High Rise Buildings, Electrical Fixtures, and Foliage to Only One Side of the Vehicle

Major Rural Throughway Representative of Typical Open Sky Conditions, but Containing Signs and Lamp Fixtures