4A.6

VEHICLES AS MOBILE SENSING PLATFORMS FOR METEOROLOGICAL OBSERVATIONS: A FIRST LOOK

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1. INTRODUCTION

Weather analysis and short term forecasting in the United States currently relies on a primary network of approximately 2,000 fixed, surface-based automated weather stations. Many of these stations provide data only once per hour. Imagine instead if there was the ability to collect millions of mobile observations at any time of the day or night from both urban and rural areas to support weather operations. This exciting vision is part of a program by the U.S. Department of Transportation (DOT) called the Vehicle Infrastructure Integration (VII) Initiative.

The aim of the VII program is to deploy and enable a communications infrastructure that supports vehicle-to-infrastructure, as well as vehicle-to-vehicle communications, for a variety of vehicle safety applications and transportation operations (ITSA, 2005).

The premise behind VII is that automobile manufacturers will install two-way radios in passenger vehicles that are connected to the computers that operate and monitor onboard systems. Roadside transceivers will be installed at many of the nation's intersections and along interstates and primary routes. Vehicles would provide "snapshots" of the status of their internal systems back to the roadside infrastructure. These snapshots could include direct observations of atmospheric phenomena (such as ambient air temperature or windshield wiper state) or indirect observations of weather or pavement conditions through modern safety devices such as vehicle traction control or antilock breaking systems.

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The Federal Highway Administration (FHWA) worked with Mitretek Systems to explore the feasibility of using observations from vehicles as a new, rich dataset for the weather and surface transportation communities. During the winter of 2005-2006, a project was launched that included several specially equipped vehicles that collected data during a variety of weather and road conditions. An analysis was performed that provided some initial estimates of temperature biases from vehicles versus in situ platforms (Mitretek, 2006). The analysis also explored whether other factors such as vehicle speed, traffic volume or different weather phenomena (such as sun angle, cloud cover, wind speed, or precipitation) had an effect on these readings. This paper will describe the methodology that was used for the data collection and provide summaries for many of these findings.

2. TEST VEHICLES & SENSORS

The key asset used in the data acquisition phase of this project was Mitretek's Mobile Wireless Laboratory (MoWL). The MoWL, developed in 2004 as part of a collaborative effort between Mitretek and FHWA, is a sophisticated mobile communications laboratory (Figure 1A). Among its instrumentation, the MoWL contains a 48 foot pneumatic mast with a pan/tilt video system, a full antenna array including satellite signal tracking sensors and a complete wireless networking facility. Inside, the MoWL contains four full height 19 inch equipment racks and three workstation terminals (complete with a 50 inch flat panel display) for viewing instrumentation.

In addition to the MoWL, Mitretek purchased two late model passenger vehicles of similar make, year and model to use as mobile probes during the experiment. Both were 1998 Ford Crown Victoria full size automobiles. One vehicle was light blue and the other was silver (Figure 1B).

To support the meteorological and pavement sensing requirements for this task, the vehicles were outfitted with numerous test instruments which included:

- Control Products "Surface Patrol 999J" (referred to simply as 999J): This dual sensor system consisted of an external thermometer for measuring ambient air temperature and a downward facing infrared (IR) radiometer for measuring pavement temperature. The 999J was only installed on the MoWL and was used for ground truth comparisons. The IR sensor was placed on the outside of the front bumper (Figure 2A). The air temperature sensor was placed inside the front bumper (Figure 2B). Both of these sensors had an accuracy of 0.5 °F and a sampling frequency of 10 observations per second.
- Watchport/T® Thermistors: A thermistor is a thermometer that contains thermally sensitive resistors. Three Watchport thermistors were placed at specific locations in each of the vehicles:
    - Inside the front bumper
    - Near the engine air intake cowling inside the engine compartment (Figures 2C and 2D), and
    - Inside the rear bumper

  These locations were selected to identify heat signatures in the vehicles and to provide insight into how important sensor position might be for obtaining accurate temperature readings. The Watchport thermistors had an accuracy of 0.9 °F and a reported sampling frequency of one observation per eight seconds.

In addition to using supplemental instruments, the project made use of many sensors that exist as part of each vehicle's on-board diagnostic (OBD) system. OBD-II, a second generation standard introduced in the mid-'90s, provides almost complete engine control and also monitors parts of the chassis, body and accessory devices, as well as the diagnostic control network of the car (OBD-II, 2006).

During this study, a PC-based OBD-II monitoring tool was used to collect data from several vehicle sensors, including the intake air temperature, engine coolant temperature and vehicle speed. These data were collected and logged at a frequency of every 2 seconds from all three vehicles.

The Microsoft Street and Trips 2005™ PC-based global positioning system (GPS) package was installed on each vehicle and used to collect time-specific location data. The GPS provides a location tag for the data collected by the array of environmental sensors on each vehicle (i.e., the GPS system provides a time/location stamp for all mobile data).

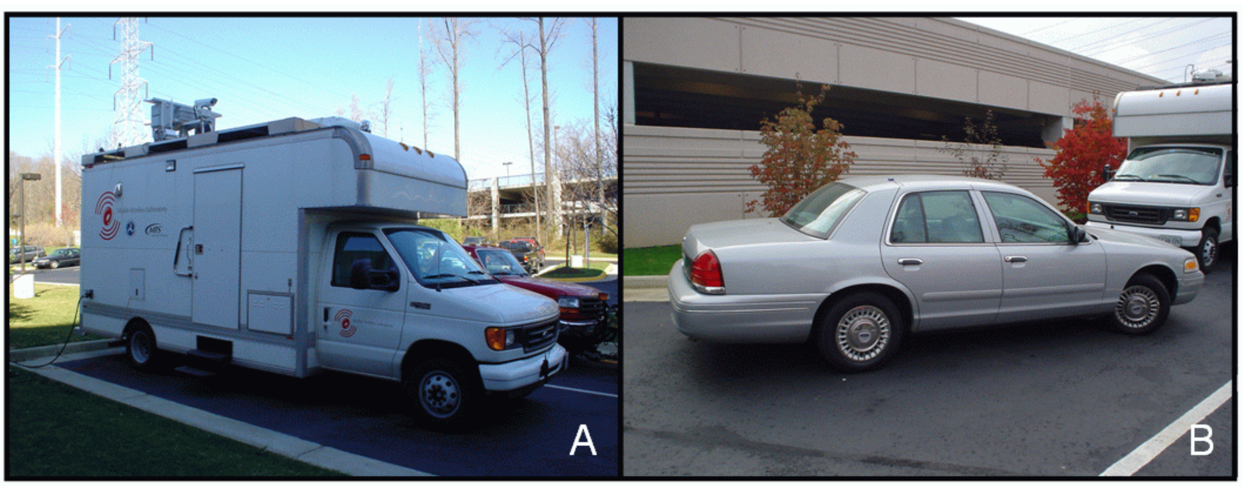

Figure 1 – (Left, 1A) The Mitretek Mobile Wireless Laboratory (MoWL). The 999J IR sensor can be seen facing downward on the front bumper. (Right, 1B) The blue 1998 Ford Crown Victoria. This was one of two similar passenger vehicles used to collect temperature data during the project.

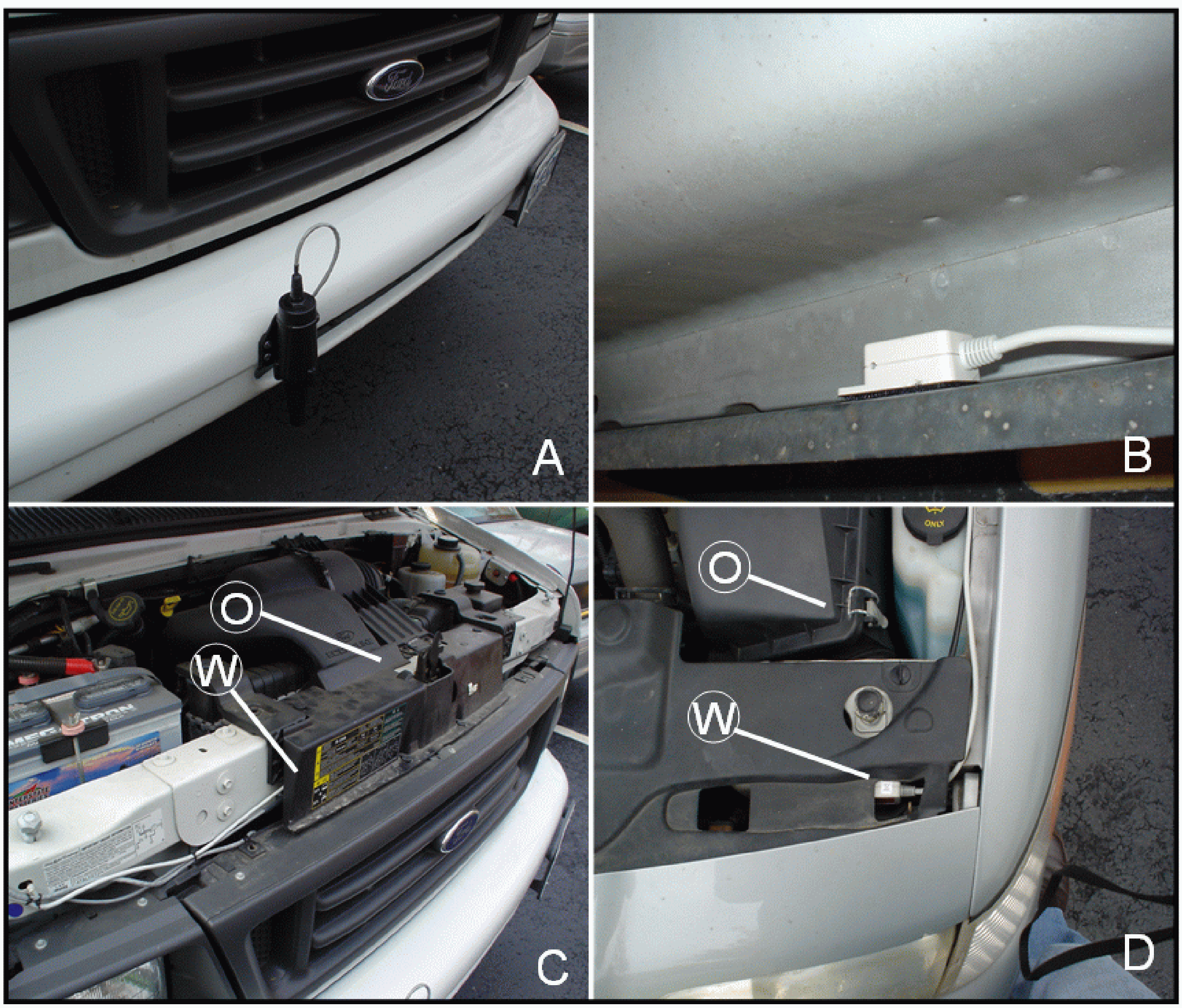

Figure 2 – (Top Left, 2A) The downward facing 999J IR radiometer on the front bumper of the MoWL. (Top Right, 2B) A WatchPort/T Thermistor located on the inside of a front bumper. (Bottom Left, 2C) Locations of sensors inside the engine compartment of the MoWL. The "W" shows the location of the Watchport/T Thermistor near the intake cowling. The "O" shows the location of the OBD-II engine air intake sensor. (Bottom Right, 2D) Locations of sensors on the Crown Victoria. The "W" shows the WatchPort/T Thermistor at the opening of the air intake cowling. The "O" shows the location of the OBD-II engine air intake sensor.

As part of the testing methodology, all accessible sensors (e.g., Watchport and 999J) were inspected for damage or contamination prior to each data run. Sensors were cleaned as needed. The Watchport and 999J sensors were tested weekly using an Omegascope HH22 digital thermometer. An Omegascope handheld IR thermometer was used to test and calibrate the 999J IR radiometer.

3. TEST DOMAIN

The Dulles Toll Road (DTR), also known as Virginia State Route 267, was selected as a data collection route for this task because of:

1. its close proximity to Mitretek System's headquarters (Falls Church, VA),
2. the many types of atmospheric and pavement sensors that were located and available along or near the route, and

3. the relatively smooth traffic flow and a minimally complex environment for studying temperature bias.

Figure 3 shows the layout of the DTR and the many in situ sensors that are available. The Virginia Department of Transportation (VDOT) operates two Environmental Sensor Stations (ESS) along the DTR. These are shown as the red circles with the “W” (west) and “E” (east) labels. Each ESS contains air temperature and wind sensors along with several bridge and pavement temperature sensors.

At Dulles International Airport (IAD), the National Weather Service (NWS) operates a Doppler weather radar system and upper air balloon site. The Federal Aviation Administration operates an Automated Surface Observing System (ASOS). Observations from all of the in situ sensors were collected for comparison and analysis with the mobile data.

The DTR is an 8 lane (4 lanes in each direction) limited access highway that extends east-west approximately 14 miles from the Capital Beltway (I-495) on the east to State Route 28 (Sulley Road near IAD) on the west (Figure 3).

GPS were used to precisely locate the start and end points for data collection on the DTR. The start point corresponded with the westbound toll booth near the intersection with the Capital Beltway. The vehicles traveled west to the State Route 28 exit (by Dulles Airport). The vehicles then traversed eastbound on the DTR back to the toll booth by the Capital Beltway. This process typically required 20 to 30 minutes under free flow (light traffic) conditions.

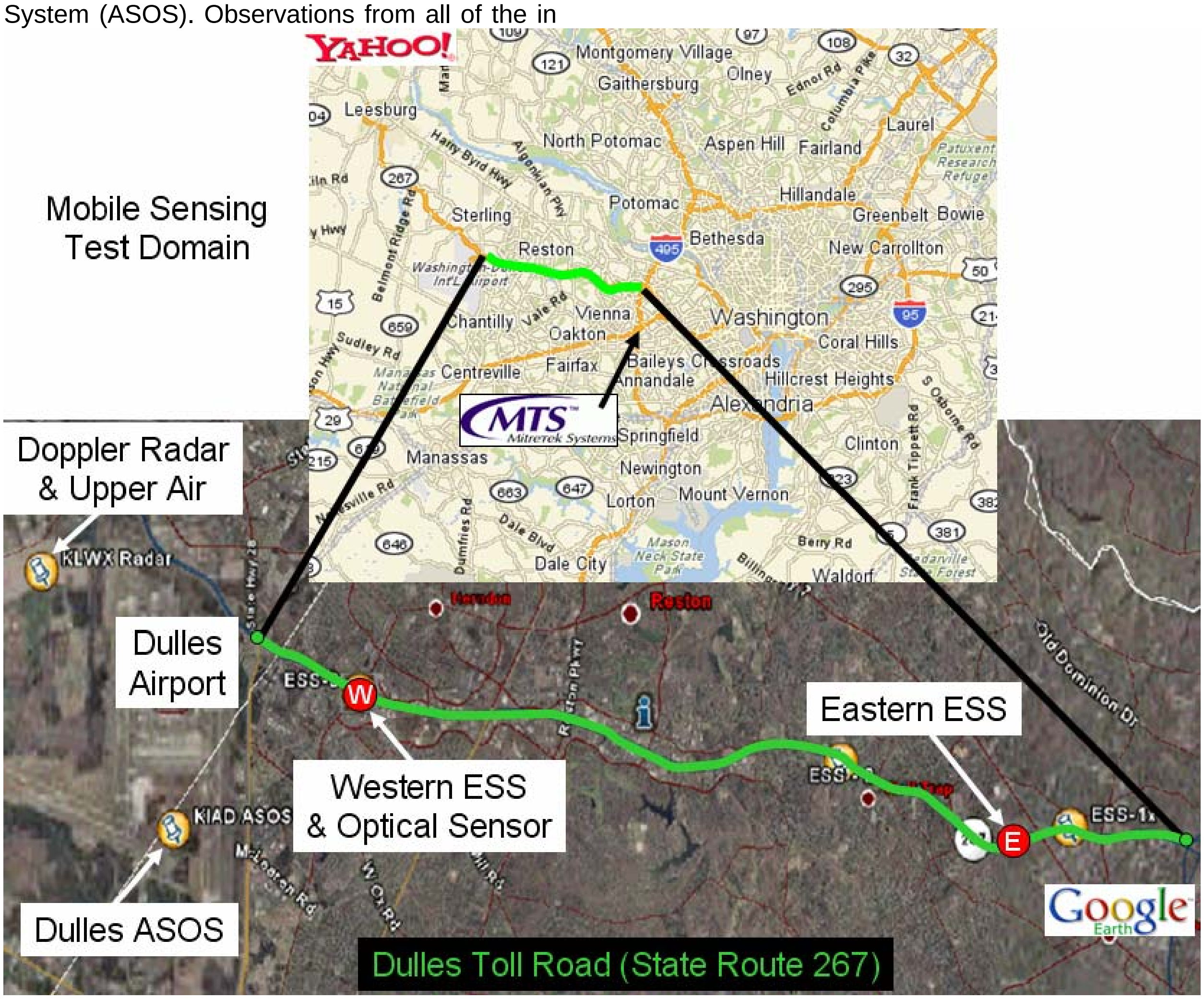

Figure 3 - The mobile sensing test domain; the Dulles Toll Road (green line) extends between the Capital Beltway (I-495) and Dulles International Airport. Environmental Sensor Stations are shown as red circles. (credit: Yahoo Maps top, Google Earth bottom).

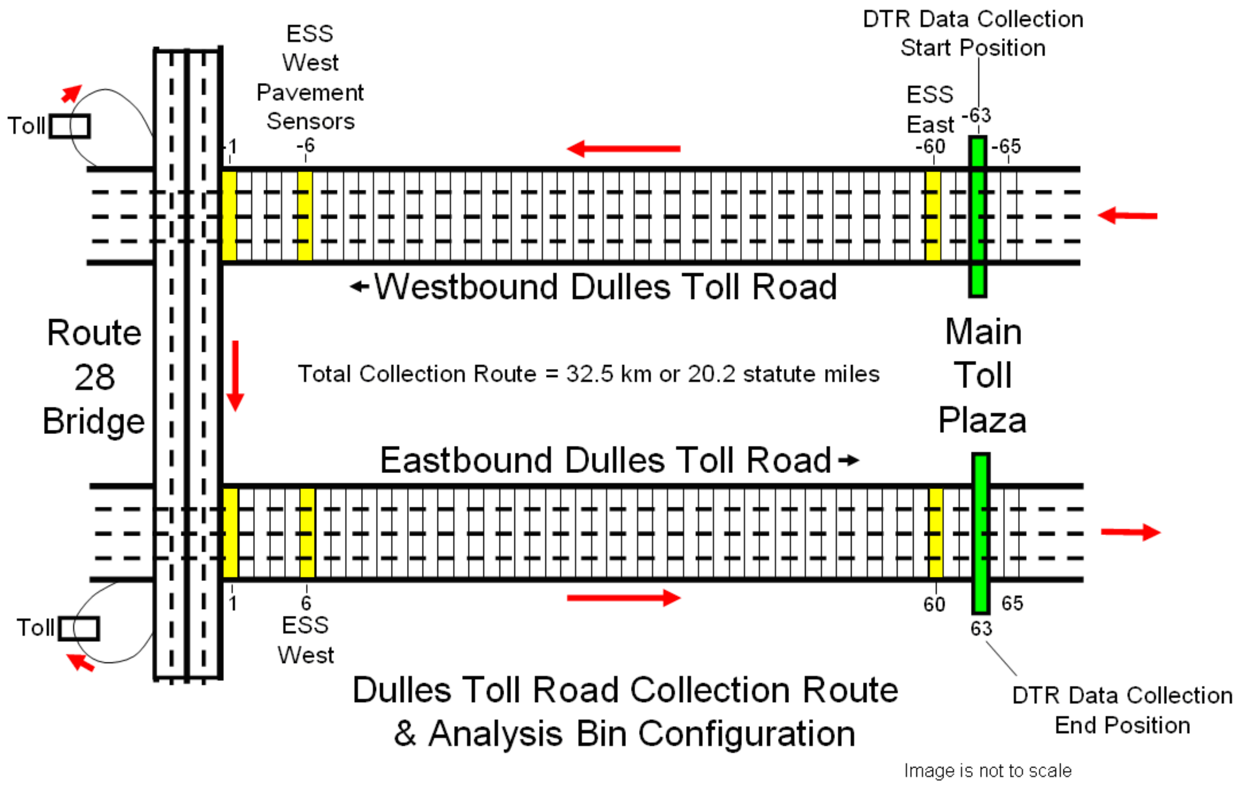

Figure 4 – The Dulles Toll Road (DTR) test route and data bin layout. Statistics were generated from bin -63 to +63 (at the green toll plazas). The yellow bins represent ESS air or pavement comparison bins.

GPS were also used to match test sensor data among the set of vehicles to specific locations and segments along the travel route. GPS provided data every 5 seconds. Given that the Watchport/T reported every 8-10 seconds, a 10 second interval was chosen for data comparisons. This 10 second interval at highway speeds translates to approximately a one quarter km length segment. Thus to compare observations among vehicles the data collection route was partitioned into 0.25 km segments call bins (Figure 4).

The data collection period extended from 15 December, 2005 to 30 March, 2006. During this time, 40 data collection runs were completed. Due to a GPS failure during one of the runs, 39 complete data sets were used in the subsequent analyses and report.

4. Data Analyses

It is acknowledged that this project is of limited scope and data when compared to a nationwide or regional study. However, the analyses performed on the collected data are meant to provide a scientific basis to build a foundation of research around mobile sensing capabilities and biases as well as to promote discussions about the effects of individual vehicle thermal profiles, and the effects of both sensor placement and environmental conditions.

At the onset of this project, five research questions were posed. Each subsection will provide results based on the analyses of collected data during the winter of 2005-06.

4.1 *Data Representativeness*

Question 1: Would mobile-sensed temperature data provide a set of observations that accurately represent the state of the atmosphere (e.g., free of contaminant heat from vehicles or radiated from the road surface)?

It was found that average mobile temperature readings exhibited a small warm bias (around 1.3 ºF) as compared with the Dulles ASOS. Comparisons with the eastern ESS (which had many more samples than the western site) yielded similar results (warm bias of about 1.1 ºF). Details can be seen in Figure 5.

These results were not unexpected during the winter season as the Dulles ASOS is situated in a cold air drainage region and is typically colder than the surrounding suburbs. Air temperature profiles along the DTR also showed that as the vehicles moved east away from Dulles toward the business center of Tysons Corner, Virginia, temperature readings slowly warmed. The readings likely captured the western extent of the urban heat island that encompasses much of metropolitan Washington, D.C.

Sensor Location/Type	Average In-Situ Temperature	999J – In Situ Sensor		
		Mean	Stdev	Count
Eastern ESS, EB Air	47.8	-1.0	1.0	36
Eastern ESS, WB Air	47.7	-1.3	1.4	37
Western ESS, EB Air	52.6	-0.2	1.1	14
Western ESS, WB Air	52.5	-0.3	0.9	14
IAD ASOS	47.2	-1.3	1.1	37

Figure 5 – Statistics comparing average in situ temperatures to the 999J mobile air temperature along the DTR. In all cases, mobile readings contained a warm bias. (EB and WB refer to East Bound and West Bound lane locations for the DTR ESS.

Under free flow driving conditions in this study, mobile-sensed air temperatures provided a set of readings that generally represented the state of the atmosphere, taking the small bias into consideration. The warm bias of just over 1 degree was just twice the sensor precision (0.5 °F). However, under congested flow conditions, the accuracy of the air temperatures exhibited much more variability (see section 4.2).

4.2 *Effects of Vehicle Speed on Temperature*

Question 2: How do mobile air temperatures vary under different travel speeds?

Changes in vehicle speed often correlates to changes in traffic volume or congestion. It was found that vehicle speed does have an effect on temperature bias. Sensor position (on the vehicle) was also important.

Sensors located in the front bumper of the vehicles illustrated the smallest reaction with changes in vehicle speed (Figure 6). Onboard Diagnostics (OBD-II) sensors located in the engine air intake cowling showed significant increases (on the order of a +10 ºF warm bias) as vehicles slowed from free flow to less than 25 mph. Conversely, the WatchPort/T sensors in the engine compartment showed varying results for each vehicle. These variations indicate that congestion could cause deviations that alter the accuracy of mobile temperature readings when compared with overall atmospheric conditions especially when sensor location is taken into account.

Travel speeds were not the only factors that produced temperature deviations. For example, the test vehicles ran their engines for a number of minutes before each trip as the data collection laptops were booted and synchronized. During this time, a certain amount of heat built up around each vehicle. It was also noted that the amount of time that it took for the temperatures to dissipate and settle during free flow speeds was different for each vehicle. Furthermore, the introduction of a traffic incident, police activity or typical commuting congestion that affected only a small portion (e.g., 10%) of the data collection runs could make a profound difference in the temperature bias for the entire test route.

Figure 7 provides a graphic illustration of how traffic congestion can affect the different temperature sensors on the vehicles. This figure shows the temperature traces (colored lines) from the MoWL during a data collection run in March, 2006. In situ sensor readings are displayed as small circles or triangles. Ambient temperature readings were near 50 °F.

The video camera on top of the MoWL captured the increasing congestion as the data collection team moved west on the DTR (inset picture, top right of Figure 7). This picture correlates to the vertical orange bar on the time series graph. As the MoWL slowed with increasing traffic, the temperature sensors inside the engine compartment (blue and brown traces) recorded huge temperature rises on the order of 50 °F in a matter of minutes. The front bumper sensors (both the WatchPort/T and 999J) reported temperature rises of around 10 °F. The rear bumper sensor showed almost no change.

There were two additional points of interest associated with this figure. First, the black trace, representing the IR pavement temperature showed a 7 to 8 °F warming as the vehicles slowed. This modification of pavement temperature could be significant during periods of frozen precipitation. Second, once the vehicles increased to free flow speeds, the warm bias on all of the sensors rapidly disappeared, although not at the same rate. These traces show that the rapid changes in vehicle sensor readings, when correlated with speed, may be able to infer traffic conditions.

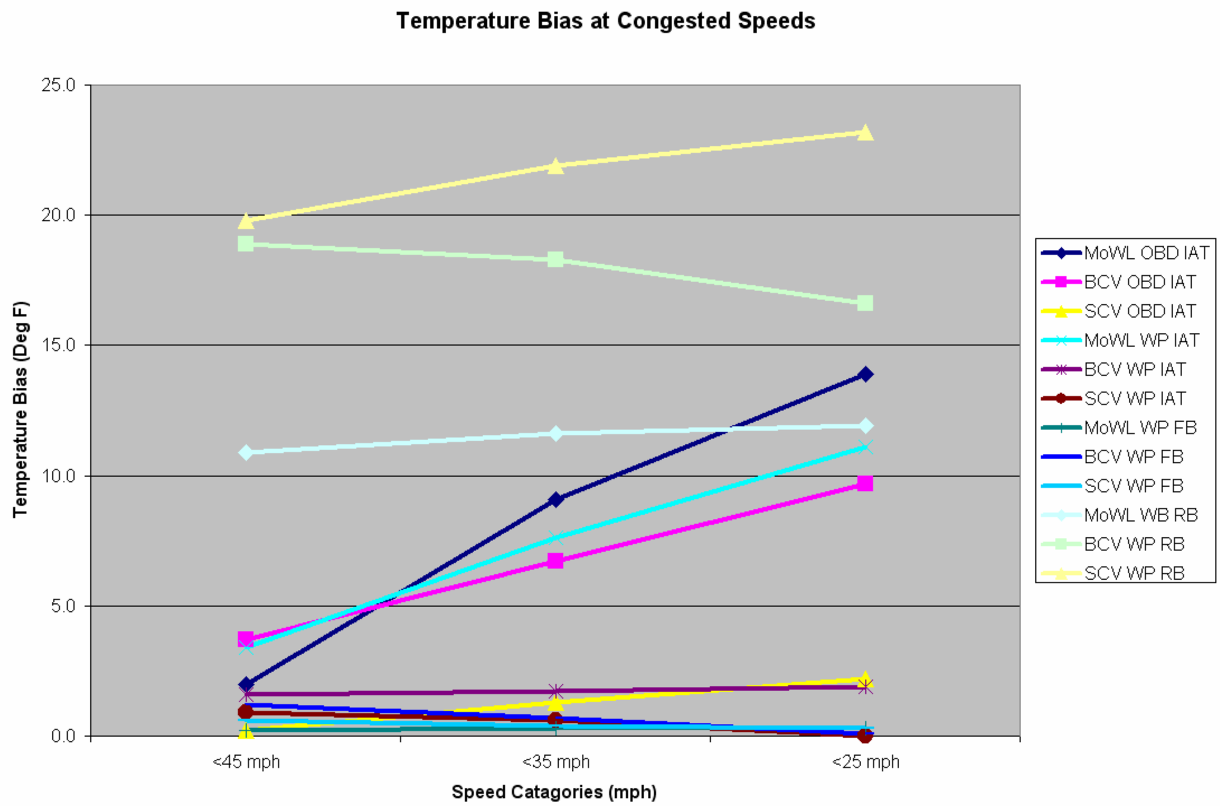

Figure 6 – Temperature bias generally increases as vehicle speed decreases. However, the bias is dependent on sensor location. This figure shows how the bias changes as the speed decreases from free flow (left) to under 25 mph (right). Engine compartment sensors showed the most significant warming as vehicle speeds decreased. [Key: MoWL=Mobile Wireless Laboratory, OBD=Onboard Diagnostics, IAT=Intake Air Temperature, BCV=Blue Crown Victoria, SCV=Silver Crown Victoria, WP=WatchPort/T, FB=Front Bumper, RB=Rear Bumper]

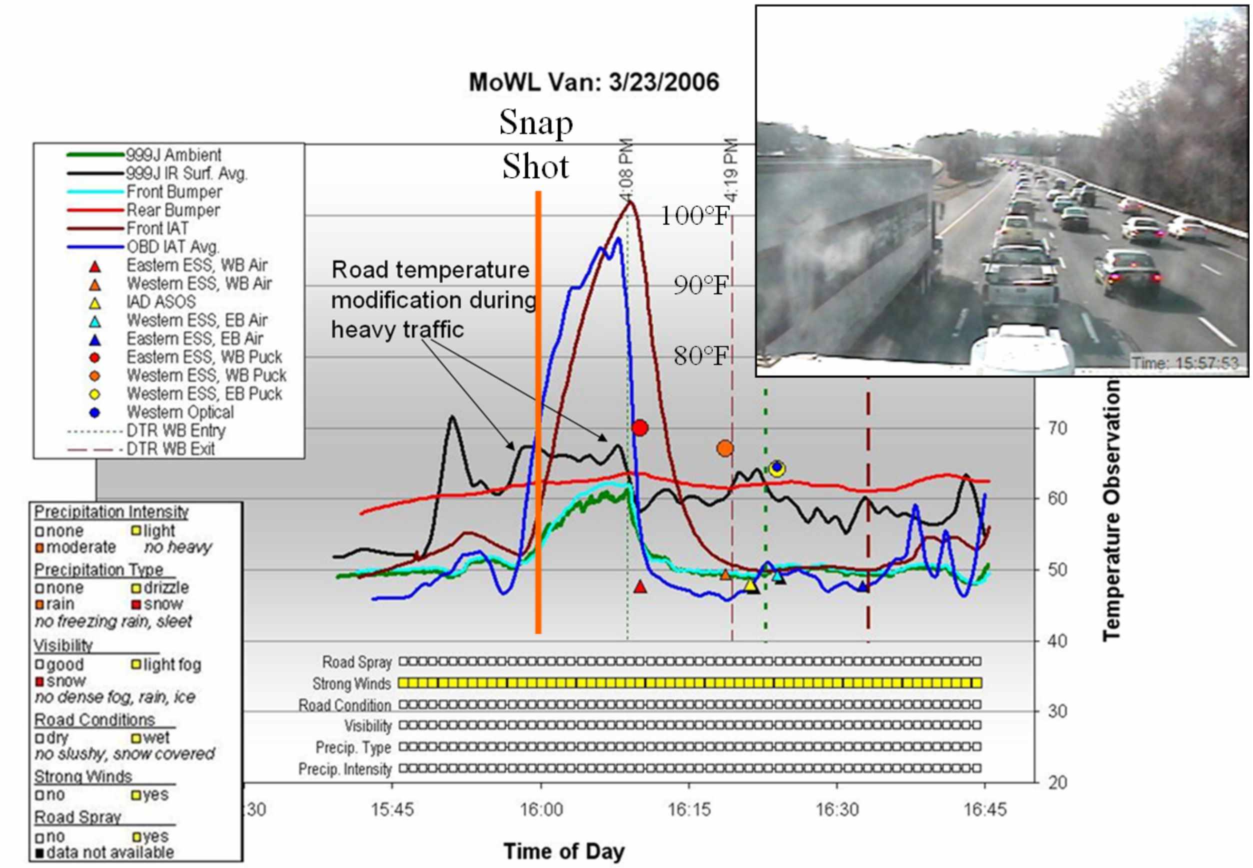

Figure 7 – Time series display of mobile temperature data from the 23 March 2006 data collection run of the MoWL. The picture at the top right corresponds to the vertical orange bar on the graph. As the congestion increased (and vehicle speed decreased) all sensors showed warming with the engine compartment sensors increasing more than 50 °F in minutes.

4.3 *Sensor Position*

Question 3: Does the position of air temperature sensors in the vehicle play an important part in obtaining representative ambient values?

It was found that the position of the air temperature sensor plays a tremendous part in identifying the vehicle's thermal profile. In this project, thermal sensors were placed in the front bumper, in the engine compartment and in the rear bumper in an attempt to identify locations with low bias or significant anomalies. As shown in Figure 8, the location that experienced the least warm bias and the smallest temperature variation was found with the sensors placed in the front bumper.

Placing the sensor in the rear bumper consistently produced a large warm bias, ranging from +12 °F for the MoWL to over +20 °F in both Crown Victorias. This was consistently large and likely due to a combination of heat contamination from the engine and friction from other moving components. However, while the bias was large, the variation in the signal was surprisingly low.

The OBD-II intake air temperature sensors (in the engine compartment) actually produced an overall cool bias in the MoWL and the silver Crown Victoria. However, the blue Crown Victoria exhibited a 2.5 °F warm bias. All three engine compartment sensors generated a warm bias of 1.0 to 1.5 °F. While the magnitude of these biases was relatively small, the variability was much larger than the front bumper readings.

Findings Across 21 Common Run Dates		
	Temperature (°F)	
Sensor	*Mean*	*Bias*
999J Ambient	52.5	
MoWL OBD IAT	51.9	-0.6
MoWL WP Front IAT	53.8	1.3
MoWL WP Front Bumper	52.8	0.3
MoWL WP Rear Bumper	64.7	12.2
Blue Crown Victoria OBD IAT	55.0	2.5
Blue Crown Victoria WP Front IAT	54.2	1.8
Blue Crown Victoria WP Front Bumper	54.0	1.6
Blue Crown Victoria WP Rear Bumper	72.6	20.1
Silver Crown Victoria OBD IAT	52.3	-0.1
Silver Crown Victoria WP Front IAT	53.4	1.0
Silver Crown Victoria WP Front Bumper	53.1	0.7
Silver Crown Victoria WP Rear Bumper	73.7	21.3

Figure 8 – Summary of mean temperature and mean errors for common Dulles Toll Road (DTR) runs. The front bumper location was found to have the best combination of lowest bias and bias variability.

Histograms of mean bias for three of the sensors installed on the MoWL are shown in Figure 9. The top image shows the mean bias trace from the front bumper sensor. The mean bias was +0.3 °F with a standard deviation of 0.2 °F.

The middle image in Figure 9 shows the histogram of mean bias for the MoWL rear bumper sensor. The mean bias was +12.2 °F with a standard deviation of 1.8 °F. Finally, the bottom image of the figure shows the mean bias for the MoWL Watchport/T intake air temperature sensor. The mean bias was +1.3 °F with a standard deviation of 4.1 °F.

4.4 *Thermal Profiles of Like Models*

Question 4: Do vehicles of like make, model and year have identical thermal profiles?

This project used two similar passenger vehicles (except for color) with similarly equipped third party sensors. It was found that these like vehicles exhibited different thermal profiles and reacted differently to travel speed changes. Figure 10 provides mean bias statistics comparing all of the air temperature sensors from all of the vehicles only for those data runs where all data sets were available. This allows for one-to-one comparison of sensor characteristics.

Highlights from Figure 10 include:

- Front Bumper placement: The blue Crown Victoria had more than twice the warm bias as compared with the silver Crown Victoria (1.6 ºF vs. 0.7 ºF) even though the variability was almost the same.
- OBD-II Intake Air Temperature (IAT) placement: The blue Crown Victoria had more than a 2.5 ºF warm bias as compared with the silver Crown Victoria (2.5 ºF vs. -0.1 ºF) with similar variability.
- WatchPort/T IAT placement: The blue Crown Victoria had almost twice the warm bias as compared with the silver Crown Victoria (1.8 ºF vs. 1.0 ºF) with similar variability.
- Rear Bumper placement: The excessively large warm bias was similar among the vehicles (blue Crown Victoria was 20.1 ºF and silver Crown Victoria was 21.3 ºF) with variability of 1.5 to 2.0 degrees.

While this is a very small sample, it appears that vehicles of like make and model can have very different thermal profiles. This may be very important when considering bias removal issues in the VII era.

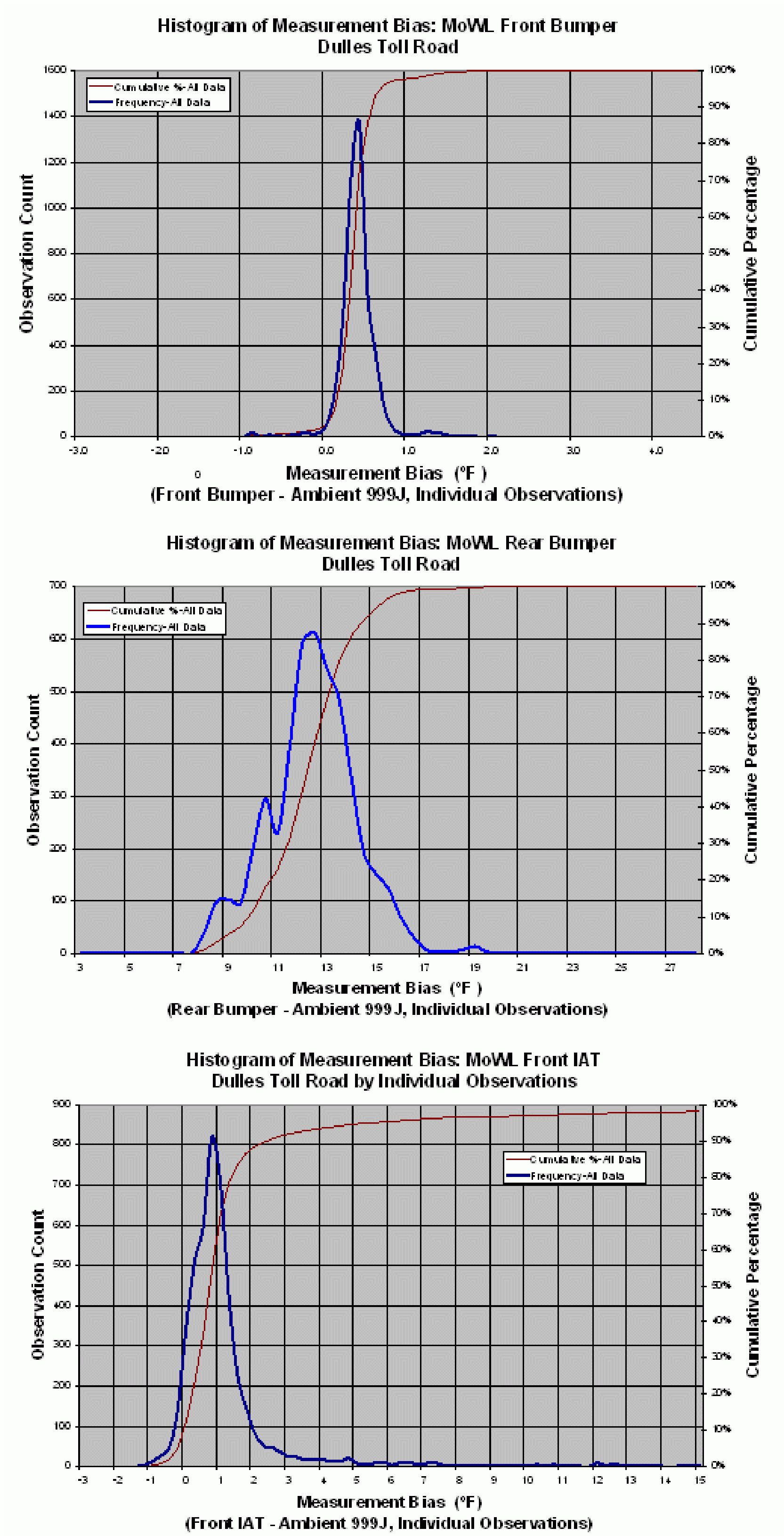

Figure 9 – Histograms of measurement bias from the MoWL sensors. Mean bias from the front bumper sensor (top) was +0.3 °F. Mean bias from the rear bumper sensor (middle) was +12.2 °F. Mean bias from the WatchPort/T intake air temperature sensor (bottom) was +1.3 °F.

	OBD Intake Air Temp			WP Intake Air Temp			WP Front Bumper			WP Rear Bumper		
	MoWL	Blue CV	Silver CV	MoWL	Blue CV	Silver CV	MoWL	Blue CV	Silver CV	MoWL	Blue CV	Silver CV
Mean Error	-0.8	2.5	-0.1	1.2	1.8	1.0	0.3	1.6	0.7	12.2	20.1	21.3
Mean S.D.	1.9	1.3	1.1	1.6	0.8	0.7	0.1	0.5	0.7	1.2	2.0	1.5

Figure 10 – Statistics highlighting the differences in bias between the silver and blue Crown Victoria (CV) passenger vehicles. Even cars of like make, model and year can have very different thermal profiles.

4.5 *External Effects on Mobile Temperatures*

Question 5: Do external weather phenomena, such as strong winds, cloud cover or precipitation, significantly modify air temperature readings obtained from vehicles?

In order to observe if external weather phenomena have an effect on mobile temperature observations, several tests were performed on the data. The first test looked at whether sun angle had an effect (such as a change in bias) during the day.

It was found that during the winter season, the sun angle began to affect temperature readings when it increased beyond 45 degrees. Under these "high" sun angles, the OBD-II intake air temperature sensors in the MoWL and the silver Crown Victoria actually showed a cool bias. The blue car maintained a +1 ºF warm bias. The rear bumper sensor warmed from +12 to +20 ºF under high sun angles. The front bumper air temperature warmed only slightly by a fraction of a degree.

It was found that windy conditions (wind speeds equal to or greater than 15 mph as measured by the Dulles ASOS) did not cause a significant change in bias in the mobile temperature readings.

With respect to total sky cover, it was found that data associated with mostly cloudy to overcast conditions exhibited a small cool bias for the intake air temperature (engine compartment) and rear bumper sensors when compared to clear skies. There was little bias found in the front bumper sensors.

Finally, in order to study the effects of precipitation on mobile temperatures, a technique was developed to correlate radar estimated liquid equivalent precipitation to each one km segment of roadway on the DTR. A program was developed for this project that reads in the NWS Doppler radar data (from the Sterling, VA location) and calculates an estimate of precipitation rates (in inches per hour) over the test roadway.

The radar provides output in a radial format that has dimensions of one degree in arc and 1 km in range. Using a Geographic Information System (GIS) tool, the domain of the major roads around metropolitan Washington was translated onto the radar domain (Figure 11). This provided an easy way to correlate radar estimated precipitation rates to each one km segment of roadway. Each one km bin of radar data then was correlated with four, quarter km roadway segments for generating statistics.

Figure 12 shows the results of the analysis. The columns labeled "none" provide temperature bias data for those times when precipitation was not detected by radar. The columns labeled as "Precip" provide bias information for those times when at least 0.01 inches of precipitation was detected. The difference in these columns provides some initial bias statistics.

- Front Bumper Sensors: The sensors on both cars exhibited significant cooling and a decrease in variability. Conversely, the sensor on the MoWL showed warming and an increase invariability.
- WatchPort/T Intake Air Temperature (IAT) Sensors: In all cases, when precipitation occurred, the data exhibited a significant decrease in the warm bias and a reduction in the temperature variability.
- Rear Bumper Sensors: In all cases, when precipitation occurred, the data showed a small decrease in warm bias and a reduction in temperature variability.

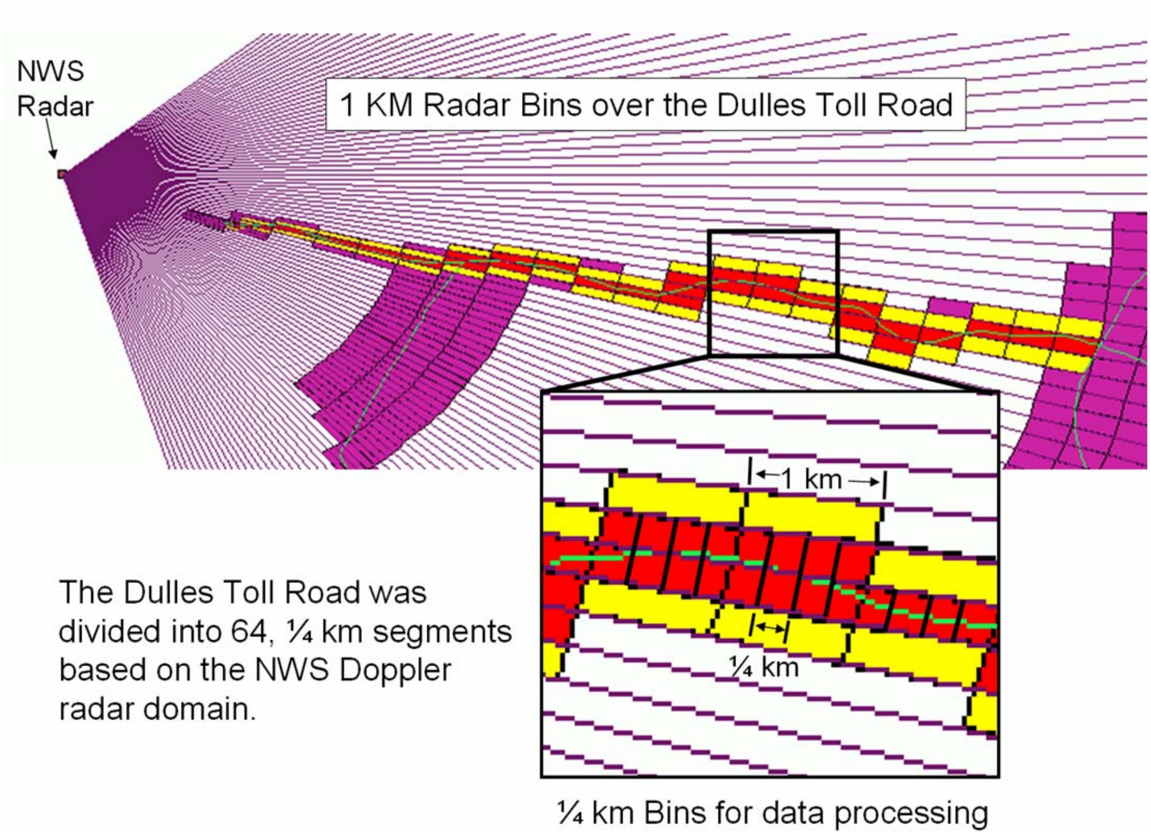

Figure 11 – Translation of the data collection route onto the NWS Doppler weather radar domain. Each one km reflectivity value is converted into a precipitation total (liquid equivalent) that is correlated to 1 km (4 bins) of the Dulles Toll Road.

Precipitation Presence (Radar Observations at Bin Level)								
	Statistics Based on Mean Error at Bin Level							
	Count		Mean		Variance			
Device	None	Precip	None	Precip	None	Precip	P-Value	Overall Mean Error
MoWL Front Bumper	4421	228	0.27	0.56	0.05	0.13	0.00	0.3
Blue Car Front Bumper	4060	243	1.49	0.99	0.50	0.10	0.00	1.5
Silver Car Front Bumper	3027	88	0.73	0.43	0.73	0.08	0.00	0.9
MoWL Front IAT	4405	228	1.43	0.86	17.29	0.68	0.04	1.4
Blue Car Front IAT	4075	245	1.67	0.95	1.21	0.14	0.00	1.7
Silver Car Front IAT	2898	91	1.00	0.82	1.06	0.17	0.09	1.1
MoWL OBD IAT	22532	1329	-0.77	-0.12	6.18	2.82	0.00	-0.8
Blue Car OBD IAT	4441	248	2.45	1.09	4.48	1.49	0.00	2.5
Silver Car OBD IAT	2261	1626	-0.38	0.25	3.07	3.14	0.00	-0.1
MoWL Rear Bumper	4413	228	11.98	10.80	3.27	1.26	0.00	12.1
Blue Car Rear Bumper	4094	242	20.02	18.04	6.18	2.61	0.00	20.1
Silver Car Rear Bumper	3096	150	21.17	20.98	8.05	0.62	0.42	20.9
MoWL 999J IR Surface	45532	2561	7.03	2.16	50.10	5.25	0.00	8.2

Figure 12 – Statistics comparing mean temperature error based on the detection of precipitation over Dulles Toll Road segments.

5. CONCLUSIONS

The ability to observe direct and inferred weather and road conditions from vehicles is still being developed. However, this capability may become reality in the next 5 to 15 years. During that time, the scientific community will need to build upon foundational studies such as this and be prepared to work with this potential new resource. Issues such as data pre-processing for quality checking (bias removal, outlier removal) and trend identification (for congestion or changing weather conditions) will require additional research.

This paper provided foundational research into the characteristics of mobile temperature observations using comparisons of data from several vehicles and in situ observations. From this limited study, it was found that under free flow (traffic) conditions, mobile temperature observations can closely represent values obtained from standardized in situ sites (e.g., ASOS). However, the introduction of external phenomena such as changing cloud cover, sun angle or the occurrence of precipitation can influence the readings. More importantly, traffic congestion and the attendant reduction in travel speed can also cause dramatic changes in temperature readings, depending on where the sensors were located on the vehicle.

Finally, it was shown that the placement of the temperature sensor on the vehicle can have a dramatic effect on the resulting temperature bias. In this case, placing a sensor inside the front bumper yielded the best results (lowest warm bias and lowest variability). It was also found that vehicles of like make, model and year can have very different thermal profiles.

An additional study centered on the temperature characteristics during a summer season was performed from July to September, 2006. Analyses from this second study were released during the fall of 2006 and are available from the authors.

6. ACKNOWLEDGMENTS

The coauthors would like to acknowledge additional Mitretek personnel that contributed to this project by participating in data collection activities or project management:

- Michael McGurrin, Director
- Don Roberts, Senior Manager
- Mark Jones, Manager
- Martin Franke, Onboard Diagnostics Capabilities
- Paul Le, Driver
- Kamran Aquil, Driver
- Markcus Alzona, Driver
- Stanley Park, Driver
- Michael Mercer, Driver
- Michael Waisley, Driver

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