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Sensor-Friendly Highways: Investigation of Progressive Roadway Changes to Facilitate Deployment of AHS

James A. Misener, Paul Griffiths, Lee Johnson, and Andy Segal

Abstract. Intelligent "driver assistance" systems which utilize in-vehicle forward-looking sensors can be supplemented by vehicle-vehicle and vehicle-highway cooperative elements to comprise a "sensor-friendly" highway environment that would enhance the operational efficiency, and ultimately, the safety benefits of these systems. In our research, we have identified the current limitations of autonomous sensing systems in target/background discrimination with cluttered highways. Based upon this, and by limiting ourselves to "sensed" (and not wireless) systems, we have conceived relatively inexpensive vehicle-highway cooperative systems to allow those limitations to be mitigated. Emphasis has been placed on 77 GHz (millimeter wave) automotive radar sensors – a sensor type which is in current use and when improved, will result in improved longitudinal safety products in the near-to-mid term, up through the longer term vision of full vehicle-highway automation. In the work reported here, we introduce the concept of sensor-friendly high systems, describe roadside signatures, and using these as bases, discuss our concepting and experiments several cooperative vehicle-highway concepts.

We describe experiments and results from prototypes of three of the potentially nearest term means to realize a cooperative collision avoidance systems, which we regard as the first step toward sensor-friendly highways[1]. We describe three potential systems:

- Light Emitting Diode Brake Light Messaging
- Roadside-Mounted Corner Cubes, and

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[1] Most of the prototype development and testing was funded from a complimentary Federal contract, US DOT Contract No. DTFH61-98-C-00100. It is included in the MOU 368 Final Report to provide closure;

- Passive License Plates.

We believe that while experimental results point toward the need for further proof-of-concept refinements, these systems potentially represent technologically sound cooperative vehicle-roadway components, and that indeed, "sensor friendly" systems, when put to the test, can eventually translate into significant benefit in terms of lives saved.

Key Words. Forward Collision Warning, Forward Collision Avoidance, Sensor-Friendly Highways, Cooperative Vehicle-Highway Systems, Clutter, Radar Cross Section, Obstacle Detection

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EXECUTIVE SUMMARY

The Sensor-Friendly Highway (SFH) project provides the scientific basis on which to effect a strategy toward retrofitting roadway and roadside features to facilitate a progressive deployment toward an Automated Highway System (AHS) from the starting point of emergent Advanced Vehicle Control and Safety Systems (AVCSS) forward-looking sensor-based systems.

MOU 368 "set the stage" in data collection and requirements definition; the prototypes realized initial versions of systems that might meet those requirements.

The end products of this effort are:

- a characterization of the current background signature of highways, and
- an investigation of changes to roadway and vehicle features which enhance target discrimination (i.e., recognition and classification of other vehicles, fixed infrastructure and/or obstacles).

The perspective of this project was remote sensing, with vehicle-borne sensors the focus; moreover, this was constrained by the recognition that minimal changes to the roadway design is most practical. In other words, the underlying premise is that modest and relatively cheap improvements or design guidance will substantially improve target discrimination potential of emerging AVCSS sensors, and the impractical and expensive solutions can be ruled out. ***The objective, therefore, was to determine practical methods to make roads and future sensors more compatible.***

Time and budget limited this characterization and subsequent recommendation to the most likely near- to mid-term application, Forward Collision Warning and Avoidance (FCW and FCA), which dictated the most likely sensing alternative, 77 GHz Doppler automotive radar. This focus is highly relevant, as this application is expected to provide the shortest-term and highest (safety) yield. Moreover, the case is made that if the infrastructure does not "participate" in the posited SFH mode, then perhaps FCW or FCA will never materialize, due to high inherent system unreliability borne from the high levels of background clutter prevalent in typical forward sensing environments.

Finally, the sensor type we investigated – automotive radar – is anticipated to progress from the current generation used in Adaptive Cruise Control (ACC), to obstacle avoidance functionality for FCW and FCA. They all focus on longitudinal warning and control. These functions on this sensor are direct antecedents to a major component of AHS; hence, "sensor-friendly" developments with an automotive radar focus, and investigated here, are expected to be encountered early in the pathway toward deployment of AHS. An enabling "safety waypoint" in this pathway, represented by SFH, would conceivably generate realizable safety benefits while leading to deployment of fully automated vehicle-highway cooperative systems.

As a complimentary ending section, we describe experiments and results of three of the potentially nearest term means to realize a cooperative collision avoidance system, which we regard as either a supplement to or a simple replacement of present single vehicle-based systems[2]. We describe three potential systems:

- Light Emitting Diode Brake Light Messaging
- Roadside-Mounted Corner Cubes, and
- Passive License Plates.

These technologies all focus on improving the signal-to-noise ratio of a collision avoidance sensor. The LED brakelight messaging and passive license plates increase the signal, by making it easier to detect real vehicles on the roadway (and, in the case of LED brakelight messaging, to provide information on the trajectory of that vehicle). Corner Cubes serve to mark clutter, such as bridge abutments or overpasses, that cannot be moved. We believe that experimental results point toward further proof-of-concept refinements, but in general, that these systems potentially represent technologically sound cooperative vehicle-roadway components and that indeed, "sensor friendly" systems, when put to the test, can eventually translate into significant benefit in terms of lives saved.

BACKGROUND

The emergence of in-vehicle, autonomous driver-assist devices and features holds great promise for driver comfort, convenience, and ultimately, safety [1, 2, 3]. Systems such as ACC, FCW, and FCA, and single-vehicle roadway departure (i.e., lane keeping) warning and avoidance are

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[2] As stated in the first footnote, most of the prototype development and testing was funded from a complimentary Federal contract, US DOT Contract No. DTFH61-98-C-00100. It is included in the MOU 368 Final Report to provide closure; MOU 368 "set the stage" in data collection and requirements definition; the prototypes realized initial versions of systems that might meet those requirements.

under active research, both in industry [4,5,6,7] and government [8,9]. Many of these systems, however, have what can be charitably defined as a rolling U.S. market introduction -- continually deferred to several years hence. Moreover, beyond this, wide-scale market penetration may take many more years. There are a myriad of intertwined reasons: high initial unit production costs; concerns about legal implications of less-than-perfect systems; and doubts about marketability.

A root cause for all these reasons, however, is operational reliability. In other words, using terminology from [3], can the system provide a low enough rate of false positives, false negatives, nuisance alarms, and perceived non-alarms to allow drivers to safely and comfortably use the system under a wide variety of roadway configurations and traffic conditions (e.g., around curves, and in dense traffic)? An obvious route to increased operational reliability is to continue engineering and refinement efforts of these systems; this is being done (for example, [5,6,7]). Another route is to investigate whether targets can be somehow marked -- actively and/or passively -- to enhance the signal-to-clutter, that is, to enhance desired target features within the sensor field-of-regard to stand out and to suppress undesired target features. Discussion in this final report is primarily focused on the possibility of this type of cooperative marking.

It is important to note that a fundamental assumption is that sensing systems should not be dependent on any special infrastructure or State- or Federally-mandated vehicle markings; rather, supplemental infrastructure or vehicle markings can serve as an independent measure to improve the performance of autonomous intelligent vehicle sensing systems. In that manner, the default operating mode would be in the absence of cooperative markings, but if they do exist, our hypothesis is that system effectiveness of driver-assist systems could be enhanced.

In this final report, a general research methodology leading to testable specifications for SFH is forwarded, followed by descriptions of two-interrelated generic components of such a workable system: sensing systems and cooperative markings. These are given to support the argument that cooperative markings could indeed be a valuable supplement – and perhaps even an enabler – to intelligent vehicle safety services.

SENSING FUNDAMENTALS

Any discussion of the benefits of *sensed* sensor-friendly vehicles and roadways must begin with sensing fundamentals. We cover them here in brief.

Highway Application of Detection and Recognition Models

The block diagram model within Figure 1 puts detection theory to highway practice. It illustrates the large potential number of variables or "levers" that sensor and cooperative marker designers have at their disposal. These variables include clutter, sensors (to include processing), and target (obstacle) signatures. The variables are *all,* to various extents, available for the sensor and marker design to change. Potential changes to these variables were used to derive notional cooperative markings discussed in **RESEARCH RESULTS**.

In Figure 1, the detection and recognition process can be partitioned into seven categories of models: Sensing System Models, Target Signature Models, Clutter Models, Weather Models, Sensor Signal-to-Contrast Ratio (SCR) and Receiver Operating Characteristic (ROC) Models, and Sensor Processing Models. These are described below as individual links to form an overall process where targets and background are threaded together to represent detection range and time to collision estimates.

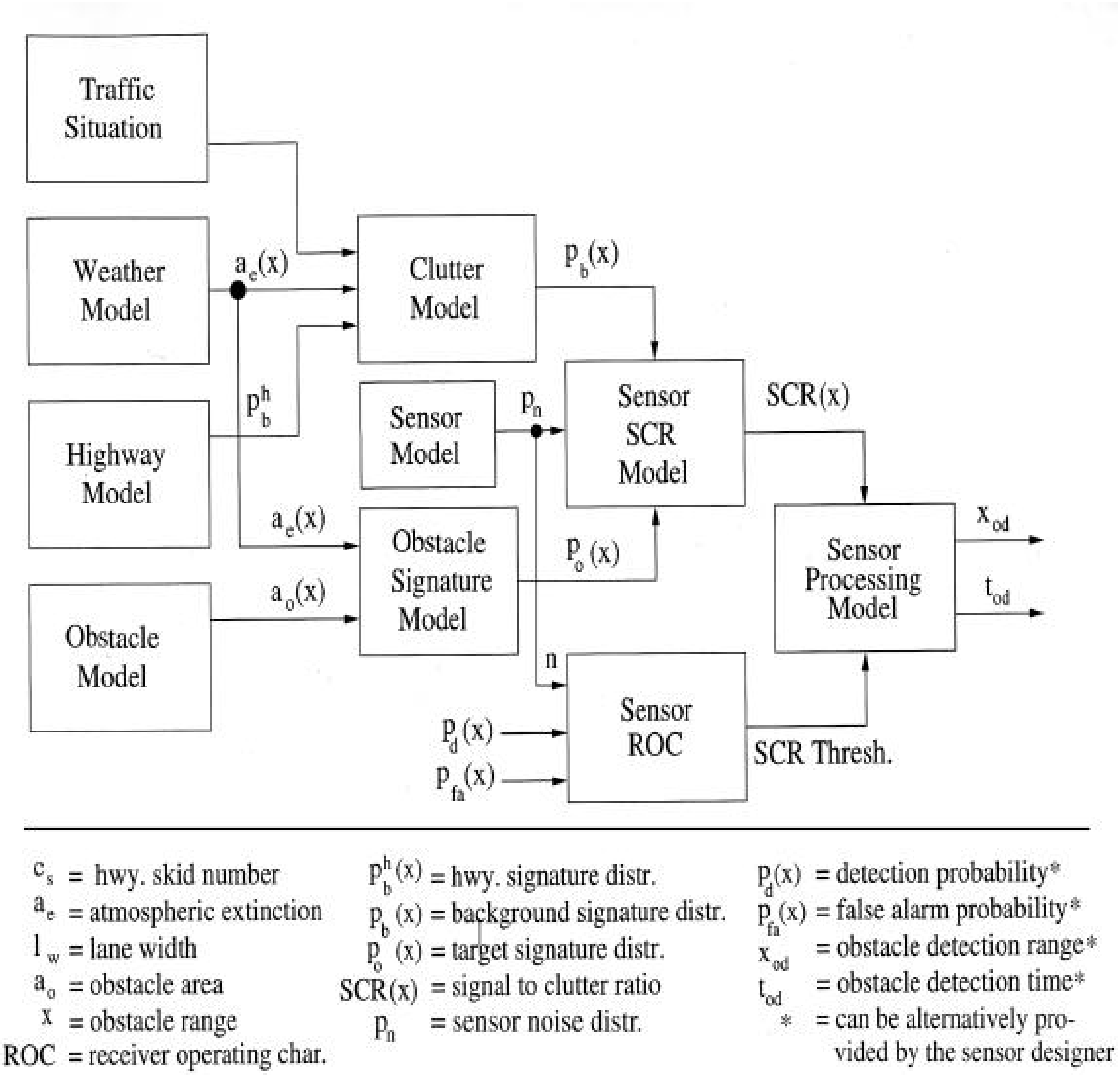

Figure 1. Schematic of Generalized Sensing System Modules for Detecting Highway and Vehicle Features

To describe target/background discrimination first requires a general model of how targets are detected. First, through *acquisition* (defined for our purposes as proximal obstacle or vehicle detection probability P_d at range x) and then through *tracking* (defined for our purposes as deceleration x' relative to the driver). Because this discussion is provided primarily to introduce the reader to common elements of sensing systems in order to make a case for cooperative markers, acquisition will be the remaining focus of this introduction, and tracking will not be discussed. Object tracking methods can be very sensing- and processing-system specific (see [9]), and driver-assist applications will vary to the extent that a general discussion may not be applicable.

For our discussion, target *acquisition* will be further divided into *detection* and *recognition*.

Detection

The detection function can generally be written as:

$$P_d = a_e r_d f_{sensor}\left(p_a^f, p_{md}, SCR, p_n, a_o, \frac{p_o(x)}{p_b(x)} \right)$$

where a_e is the atmospheric extinction, and the sensor processing function f_{sensor} is written in terms of a combination of obstacle-descriptive parameters (area a_o, range x, target signature distribution $p_o(x)$), background-descriptive parameters (background signature spatial distribution $p_b(x)$), and sensor and sensor processing parameters (sensor noise distribution p_n, false alarm probability p^f_a, missed detection probability p_{md}, detection range r_d, signal-to-clutter threshold design point SCR).

Recognition

Each sensing system possesses unique detection decision criteria which comprise the factors within f_{sensor}, and as such, f_{sensor} has a wide design space. For example, a longitudinal range/range rate radar designer will likely specify what is termed a Neyman-Pearson or likelihood ratio receiver [10], where p^f_a and p_{md} are stochastic distributions. The compromise or design point between these distributions can be specified by first determining the likelihood ratio SCR/p_n [10].

A non-radar system designer will typically approach f_{sensor} using different terms but in an essentially equivalent manner. The Neyman-Pearson receiver of the radar designer is in the vision case simply an application of the Theory of Signal Detection (TSD), which is a binary decision process comprised of two PDF's [11]. Given a user-input P_{fd} requirement (or design parameter), the TSD can be invoked to determine whether or not the target is detectable. The P_{fd} is the area under the interference (clutter and noise) PDF to the right of the SCR threshold, and the P_d is computed as the area under the obstacle PDF, also to the right of the threshold. In this manner, $p^f{}_a$ is related to p_d for each unique target/background/vision/processing device combination via a curve known as the receiver operating characteristic (ROC). The ROC is an empirical measure to specify or test to either p_{fa} or p_d.

Whatever the detector, to make the application of TSD complete, distributions of target and background signatures must be derived. One way is to base it on a data set populated with specific background imagery, then sensor jury tests could be conducted. Hence, to make this model applicable for highways, appropriate vehicle, obstacle and highway scene data (i.e., background signatures) must be first gathered and fit. The specific driver-assist sensor systems would then be methodically tested against specific highway configurations. The data set could be large, as variations such as the diurnal cycle, different highway topologies and obstacle types must be considered; however, given a contained and very specific scenario, a reasonable data set with a high degree of realistic visual cues could be collected, i.e., glint, glare and other spatially or temporally unique features.

In any event, when we consider that $p^f{}_a = f(SCR/p_n)$, f is highly dependent on the specific processing design. In addition, *a priori* knowledge – or assumptions – of the range of target and background signature characteristics is necessary in determining *SCR* and ultimately, $P_{d.}$

The detection and recognition process can be partitioned into seven categories:

1. Sensing System
2. Target Signature
3. Clutter
4. Weather
5. Sensor Signal-to-Contrast Ratio (SCR)
6. Receiver Operating Characteristic (ROC), and

7. Sensor Processing

These are described below as individual links to form an overall process where targets and background are threaded together to represent detection range and time to collision estimates.

1. *Sensing System.* The following categories of devices may apply:
    - passive electro-optical sensors (imaging and conical reticle; visual, near infrared, thermal infrared);
    - active electro-optical systems (ladar); and
    - radar (millimeter wave (mmw); pulsed and FMCW waveform; normal, moving target indicator (MTI) and constant false alarm rejection (CFAR)/feature extraction).

2. *Target Signatures.* The apparent (or measured) signatures of targets can be derived by convolving source signatures with atmospheric models. Outputs could be signature characteristics (spatial, spectral, temporal, polarimetric), relative motion (position, velocity, acceleration, jerk) to user-defined accuracy, resolution and time lags. Source signatures may be predicted, or they may consist of measured values.

3. *Clutter.* The roadway and other object apparent signatures will represent occlusions, multi-path interference effects and signatures from any other source within the sensor field of view, as modified by the effects of the intervening atmosphere. Geometries, to include grades, curvatures and physical clutter will be represented, along with the sensed surface conditions/coefficient of friction, and spatio-spectral bi-directional reflectance distribution function.

4. *Weather.* These will represent extinction due to normal and inclement conditions (rain rate, snow rate, blown snow rate and speed, dust obscuration) and also due to solar/diurnal and artificial illumination conditions (e.g., glare, ambient illumination/cloud cover, direct illumination).

5 and 6. *Sensor Signal to Contrast Ratio (SCR) and Receiver Operating Characteristic (ROC).* The SCR combines signal and clutter to provide a "threshold" ROC curve, assuming either CFAR processing (a straight-line mapping of the detection probability P_d vs. the false alarm probability Pf_d) or some other unique relationship provided by the sensor designer. In the case of CFAR processing, the sensor designer would have to provide a slope; in either case, the ROC curves should be target signal- and highway background-clutter specific.

7. *Sensor Processing* . The process represented by this discussion shows a single thread linking these concepts and therefore makes the explicit assumption that a single sensor is involved. However, sensor fusion and the governing filters or decision making rules (e.g., Bayesian, Dempster-Shafer Theory of Evidence) can be implicitly fit into the process by threading multiple, parallel SCR and ROC inputs into the sensor processing models. These fusion models also provide for formally incorporating the obstacle-threat categorization (i.e., pending, unknown, assumed friend, friend, neutral, suspect and hostile) into the decision-response process [12].

SENSOR TYPES FOR SFH APPLICATIONS

We transition from fundamentals to a discussion of the classes of sensors available for SFH. Although we provide broad coverage for the reader, we point out that currently available sensors for automotive applications operate in the millimeter wave regime. Several factors contribute toward this:

- (relative) reliability, which include less degradation due to weather;
- no necessity for “super clean” optics; robustness to shock; and,
- potential for inexpensive mass production.

Hence, to state our conclusion up front, ***although other spectral regimes are covered, the manifold advantages of sensors in the millimeter wave spectrum led us to conclude that this is the sensor regime of choice for SFH.***

In understanding which sensors are currently being considered for SFH applications, the full electromagnetic spectrum was considered with respect to the current state of the art and in particular to target/background discrimination. The spectrum can essentially be regarded as five (slightly) overlapping regimes, with somewhat different technology application for each:

- millimeter wave region of radio frequency (mmw)
- microwave region of radio frequency (RF)
- passive infrared (IR)
- active near infrared (laser, or ladar) (NIR)
- visible/TV (VIS)

The parameters which influence the utility of these spectral regions and combinations are many and very complex. For this discussion the spectral regions will be divided into two groups, radar (RF and mmw) and electro-optical (NIR and VIS, IR).

MMW and RF

The RF covers the region of 2-24 GHz. Generally, active radar is considered the primary sensor implementation with automotive applications of RF; however, for the cooperative marking application, roadside or on-vehicle emitters combined with the active radar used in passive, radiometric (i.e., sensing for signal) capability is also included. The strengths of RF are maturity, good weather and obscurant penetration, long range performance and the availability of range and range rate information. For relatively small and inexpensive AVCSS applications, range accuracy is marginal for many targets, and the beamwidths make the discrimination of targets from background clutter difficult.

The next spectral region of consideration is the mmw covering 35 to 240 GHz; however, most efforts stemming from DoD applications are in the 35 and 94 GHz regions, with early (ERIM, FOCAS) roadside object characterization efforts conducted at 94 GHz. The FCC has approved for automotive radar approved at 77 GHz (which, to be more precise, 76.5 GHz), as have the Japanese. The strengths of this regime are good weather/obscurant penetration and high range resolution. The main weak areas are the active nature, and the range, power and resolution limits for some applications; these limitations could be further exacerbated if used in a radiometric mode (e.g., with weakly emitting cooperative targets), which will drive the power requirements of the emitter.

In the current state of practice, aimed at ACC systems, at ranges exceeding about 20-ft, the Doppler shift from the target return is incorporated as the ground clutter discriminator. This means that stationary targets – the detection of which is pivotal in most conceivable AVCSS services – cannot be detected unless a less-accurate (but simpler) radar processing technique is adopted.

NIR and VIS

Two potential sensors for obstacle detection are stereo video and ladar. For vision and ladar systems, unlike radar, the spectra used are close to the spectrum visible to the human visual system. This means that most objects appear substantially the same to a ladar or video sensors as to the human visual system.

Stereo

Stereo vision works by finding the same object in two or more cameras, then triangulating to fix the location in 3-D. For a vision system, phenomena of concern include:

- High dynamic ranges. For example, on entering or exiting a tunnel, the vision system will not be able to see both the deeply shadowed area and the brightly sunlit area. Modern CCD cameras perform a little worse than humans; the newer CMOS cameras do not have problems with blooming, and therefore may have better performance.
- Low texture. Stereo vision can get fooled on bland surfaces, such as newly paved roads or blank roadside walls.
- Repeated texture. Occasionally a stereo vision system will misregister repeated elements of a texture pattern, as in looking at a snow fence, and will hallucinate a distance too close or too far. This can often be overcome by using more than 2 cameras.

- Low lighting levels. At night, dark objects are hard to see. Again, the general level of visibility is about the same as with the unaided human eye.
- Specularity. Shiny surfaces, particularly wet roads, can cause problems for stereo vision systems. The vision system is not really “seeing” the object; it is “seeing” the reflections of some other object, and will therefore generate an incorrect match and an incorrect range value.
- Thin objects. Stereo typically does not match single pixels; it works by matching windows. If a thin object in the foreground is narrower than a window size, and is set against a highly-textured background, then the best match for the window may be a background-to-background match, ignoring the object in front.

Ladar

Ladar calculates range by measuring the time of flight of a laser, from the source to the target and back to the detector. Time measurements can either be direct (time of flight of a laser pulse) or indirect (FMCW, similar to sonar or radar processing). The direct time of flight systems require fast electronics to get accurate measurements – a nanosecond time error equals 30 cm laser travel error, which gives 15 cm range error (out and back). But they have the advantage that they can be built with more tolerance to atmospheric obscurants. A CW system inherently averages all returns within a single measurement, so the distance returned averages in the distance to snowflakes or fog in the optical path. A time of flight system can be set up to take the last return it sees. Hence, returns from rain drops or snow can be ignored, provided that a measurable amount of energy makes it all the way through to the target and reflects back.

Ladar sensing has the following concerns:

- Specularity. A shiny surface will reflect at mirror angles. Depending on the orientation, a smooth surface will either reflect a large amount of energy back to the sensor, possibly saturating the detector; or will reflect all the energy away, and return no signal to the detector.

- Polarization. Ladars can be polarized, and the polarization of the returned signal can be measured to see if it is consistent with a reflection from a single surface.
- Retroreflectors. Reflectors are inexpensive and reliable.
- Daylight saturation. Typical ladars work better at night, when there is less sunlight in their operating wavelengths to interfere with their signal.
- Reflectance. Most ladars measure range and reflectance, so there is some indication of object appearance as well as range. In particular, it is often possible to see lane markings in the reflectance channel.
- Cross-talk. In CW systems, there is often cross-talk between the range and reflectance channels, so an abrupt change in reflectance may show up as a range jump, also.
- Narrow objects. If a laser is focused into a tight beam, and fired at regular intervals during a scan, it is possible to have adjacent beams be separated by more than a beam width. This means that a narrow vertical object could fall between measurements, and could be missed.

IR

The last region discussed is the thermal IR (taken here to mean the region of 2 to 14 micrometers, and incorporating what is sometimes defined as the Mid Wave Infrared (MWIR) atmospheric window from 2 – 5 micrometers and the Long Wave Infrared (LWIR) atmospheric window from 8 – 14 micrometers. Current development emphasis is imaging IR (IIR) utilizing high-density two dimensional focal plane arrays, in the MWIR. The strengths of current and developing IIR technology are high resolution and reasonable fields of view that can fit in very small automotive packages. The most obvious weak points of IR are the obvious weather and obscurant (spray) penetration limitations and the expense of IR-transmitting windows and optics. In addition, under overcast skies and wet conditions, there may not be adequate thermal contrast in a scene (e.g., road surfaces, lane markings, and surrounding objects) for good IR imaging.

RESEARCH RESULTS

Research results are reported in roughly the sequence to the tasks conducted in the SFH project. As reported through the conduct of the project, these tasks differ from what was originally proposed. When this occurs, reasons are reported.

Task 1. Investigate Current Highway Standards and Practices

At the onset of the project it was realized that radar signatures, i.e., radar cross section (RCS), is highly sensitive to small scale (approximately 1/8-in or less) fluctuations in objects, and yaw of vehicles. The highway environment is replete with both designed an unspecified small internal cavities (dihedrals or trihedrals). At this scale they both "talk" to each other and scatter the incident radar wave. This is even more evident with ground vehicles. The signatures of mostly (but not entirely planar) sides are high near the cardinal 90-deg points, with high angular fluctuation at points in-between.

The above means that if the either the roadside object target vehicle is slightly off angle, or is slightly different in shape, the scattered return may be quite different. Modeling the RCS in light of the sensitivity to this fidelity of geometric (and material) detail, and also in light of the effect of slight geometric perturbations would yield inaccurate results. To add to the complexity, the institutional component (that is, standardization), plus the millions of miles of highways already constructed, render consideration of construction practices relatively unimportant. Therefore, the strategy for including SFH features should focus on: (a) recognizing where gross features would add noise signatures; and (b) considering retrofit solutions that “mark” these gross features.

Hence, Task 3, originally “Produce a Simple Highway Radar Model” was transformed into “Collect Data to Characterize Highway Radar Clutter”. Task 3’s objective would supersede the original Task 1 objective, and in the end, catalog the highway clutter that would spoof automotive radar and provide cues to SFH solutions.

Task 2. Review Available Signature Data

Our search for available *published* RCS data on roadways was not fruitful. It appears that most RCS roadway characterization efforts are conducted by automotive manufacturers or suppliers for their internal use and are therefore unpublished. Two sources were located and are discussed below. However, data could not be obtained despite repeated inquiries.

ERIM Data Collection

As part of the NHTSA Systematic Methodology for Assuring a Reduction in Vehicular Traffic (SMART) program, ERIM-International and TRW performed radar, vehicle and roadway element characterizations [13]. At the time of this writing, despite several requests to ERIM and also to the GM-Ford-ERIM CAMP program, roadway characterization data has not been received. However, radar cross section (RCS) signatures are expected to be highly angularly dependent, since many roadside objects are man-made (and therefore, aesthetically flat and smooth, intersect other man-made objects and surfaces at 90-deg (comprising a "dihedral" resonate cavity), and are generally highly conductive. These factors all lead to RCS signature "spikes" of but a few degrees azimuth. In highway practice, these "spikes" will emanate from what is likely to be a large envelope of directions. Therefore, the target scene will probably be replete with a large array of constantly-changing background clutter.

University of Michigan / NAHSC Radar Polarimietry

Polarimetric RCS signatures, however, may be an ideal method of discriminating targets from backgrounds in a non-naturalistic environment. Generally, each reflection elicits a change in polarization, so for example, a vertically-polarized emitting signal will yield a horizontally-polarized return. The NAHSC sponsored a University of Michigan study, where polarimetric radar backscatter response to various targets were obtained for various roadway elements, to include road surfaces [14]. These signatures were analyzed as functions of material type (i.e., dielectric constants) and geometries (to include surface roughness). The preliminary conclusion is that polarization gives important cues to the geometry of objects (e.g. flat road vs. vertical objects) and their composition, including cues to snow covering on roads. This project was terminated prematurely with the end of the NAHSC, so definitive results are not available.

Task 3. Produce a Simple Highway Radar Model

High fidelity "Ray Trace" models such as XPATCH exist. The XPATCH tool is a far-field RCS prediction code originally designed for the USAF, an agency which cares about long stand-off distances. Hence waves are plane-parallel, and multi-path (multi-bounce) considerations are not accounted. An alternative would be a primitives-based RCS estimator. In this, RCS of constituent component shapes, roughness and materials composition are estimated, then combined to provide an overall RCS estimate.

Both methods are replete with uncertainty and almost unbounded and uncertain error.

Hence, model-based techniques are not recommended; rather, empirically-generated characterization of the roadside environment were undertaken instead as the best way to understand the "real world" phenomena that contribute to different-than-virtual signatures: clutter, multipath, dirty vehicles (and thusly different dielectric properties), unmodeled details.

Task 4. Produce a Simple Highway Near Infrared Model

Based on the project focus on nearer term FCW sensors, namely mmw radar (see **SENSOR TYPES FOR SFH APPLICATIONS**), the NIR regime was not considered, and this task was eliminated.

Task 5. Collect Highway RCS Data

Background

For this task, we acquired, installed, tested and evaluated the latest generation of vehicle radar, an Eaton Vorad EV300 radar (24 GHz). The primary purpose of this data collection was to identify highway features that may limit the performance of an automobile radar. The results of the test indicate the EVT-300 generally works well to accurately provide range and range rate, but there were some failure modes with periodic structures such as chain link fences and rows of vehicles.

Data Collection

The radar was mounted on a PATH vehicle and tested for several days. A serial communications protocol developed by Eaton Vorad was used to operate the radar and run on a Pentium-based computer with the QNX realtime UNIX-like operating system. Several channels of data were sent by the radar every 100 msec. These channels include:

- time
- track ID
- target range in feet (accurate to 0.1 ft)
- target range rate (accurate to 0.1 ft/sec)
- target azimuth (accurate to 0.002 radians)
- target strength (an estimate of SNR, accurate to 0.543 dB), whether the target is "locked-on" in the tracker over the last 8 data frames.

Also, the wheel speed was recorded to enable the absolute velocity of the lead car to be calculated. The channels were supplied by the EV300 for the seven highest SNR targets, although for most of the data collected there were fewer than seven tracked targets.

Table 1 lists the name, start and stop times and as short description of the data collected. Along with the radar data, a video recording of the run was saved in AVI format to refer back to when the radar data was being analyzed. This enabled correlation of the radar data with objects seen in the video data.

Table 1. Descriptive Parameters for SFH Data Collection

Name	Start	Stop	Description
ev112145.dat	00:00	03:52	580 Westbound, Bayview to Richmond Parkway
ev112607.dat	03:58	08:16	Richmond Parkway eastbound
ev113142.dat	08:29	12:53	Richmond Parkway westbound. Two cars cut between target car and radar.
ev113831.dat	13:26	17:04	580 eastbound
ev114314.dat	17:17	21:35	580 westbound, lost target car for a while.
ev114804.dat	21:44	25:09	Richmond Parkway eastbound
ev115247.dat	25:20	29:24	Richmond Parkway westbound
ev115828.dat	29:34	33:17	580 eastbound
ev120308.dat	33:29	37:25	580 westbound, car between target car and radar at beginning.
ev120734.dat	37:33	40:55	Richmond Parkway eastbound
ev121226.dat	41:10	44:56	Richmond Parkway westbound
ev121804.dat	45:22	48:20	580 eastbound, got behind tanker and lost target car for a while. Exit Regatta instead of Bayview.

During the collection of the data, two vehicles were employed, one with the radar mounted on the front of the vehicle the other was used as a lead vehicle. In addition, since the data was taken on public roadways, normal traffic flow was also seen in the data sets.

Results

The data was processed for all 12 runs. This is an exemplar radar data corresponding video image data set. Results of dataset ev113142 are shown in Figure 2(a-e).

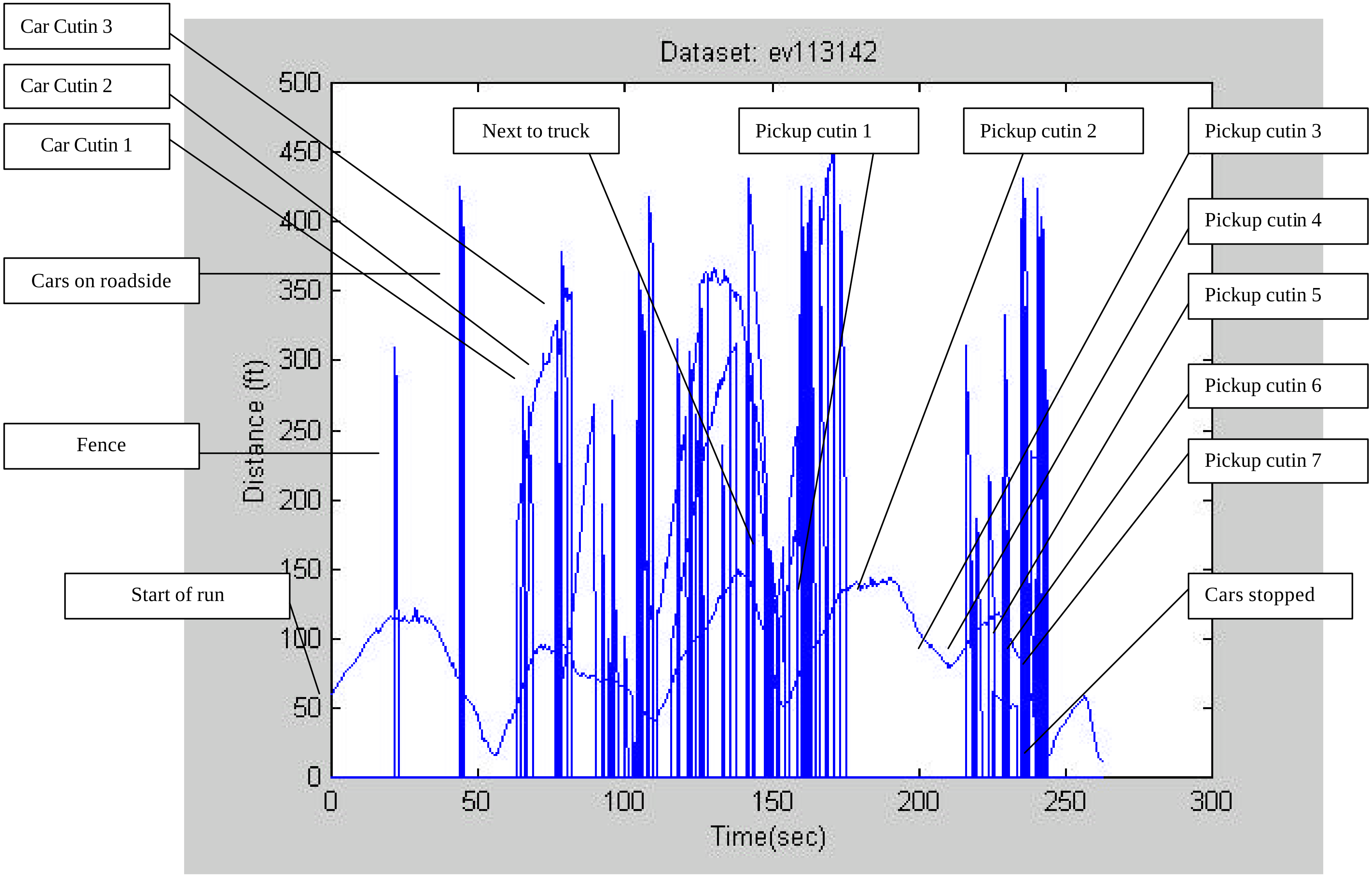

Figure 2(a). All Tracks Recorded by EVT-300.

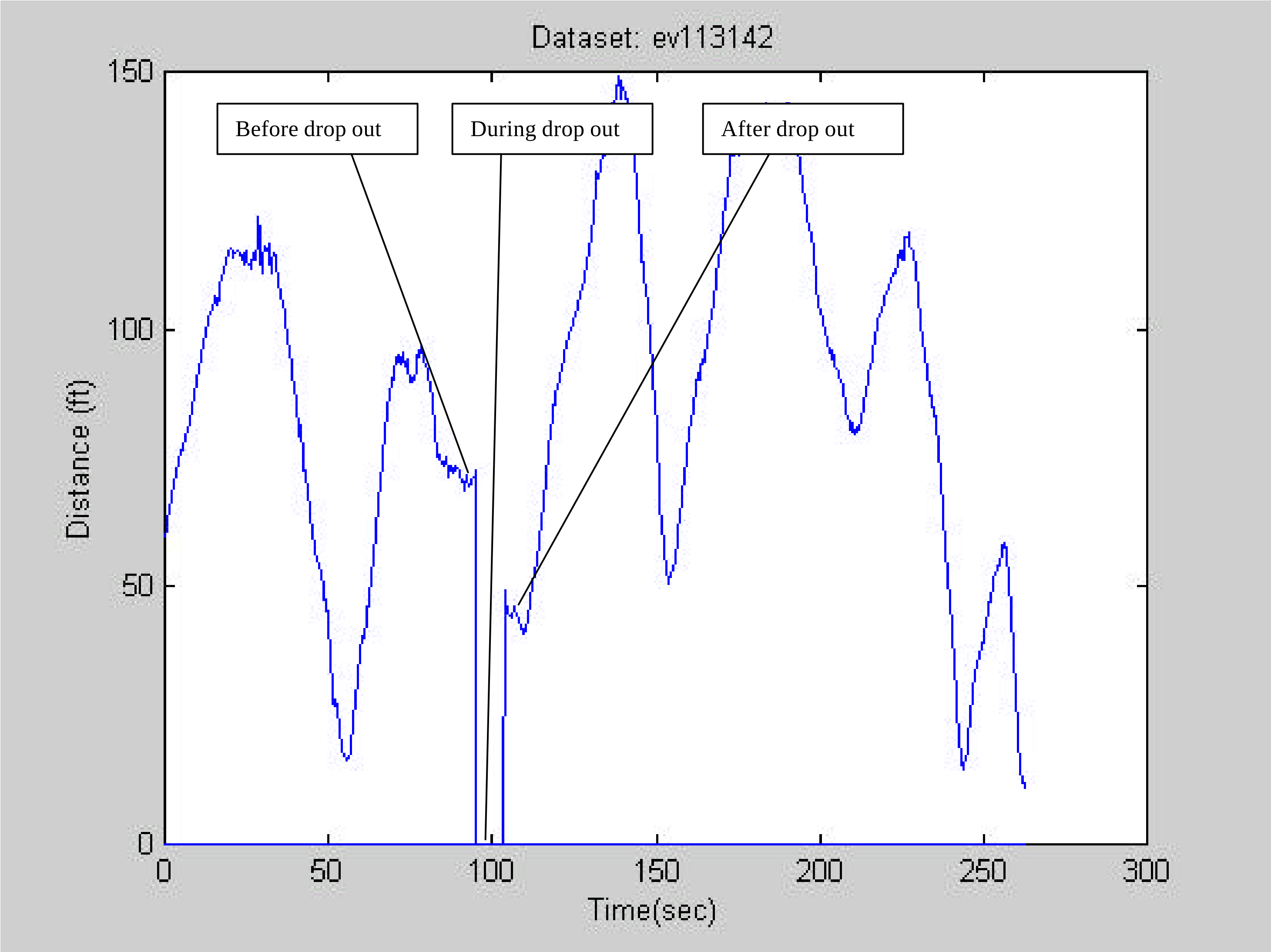

Figure 2(b). Tracks over 10 Seconds.

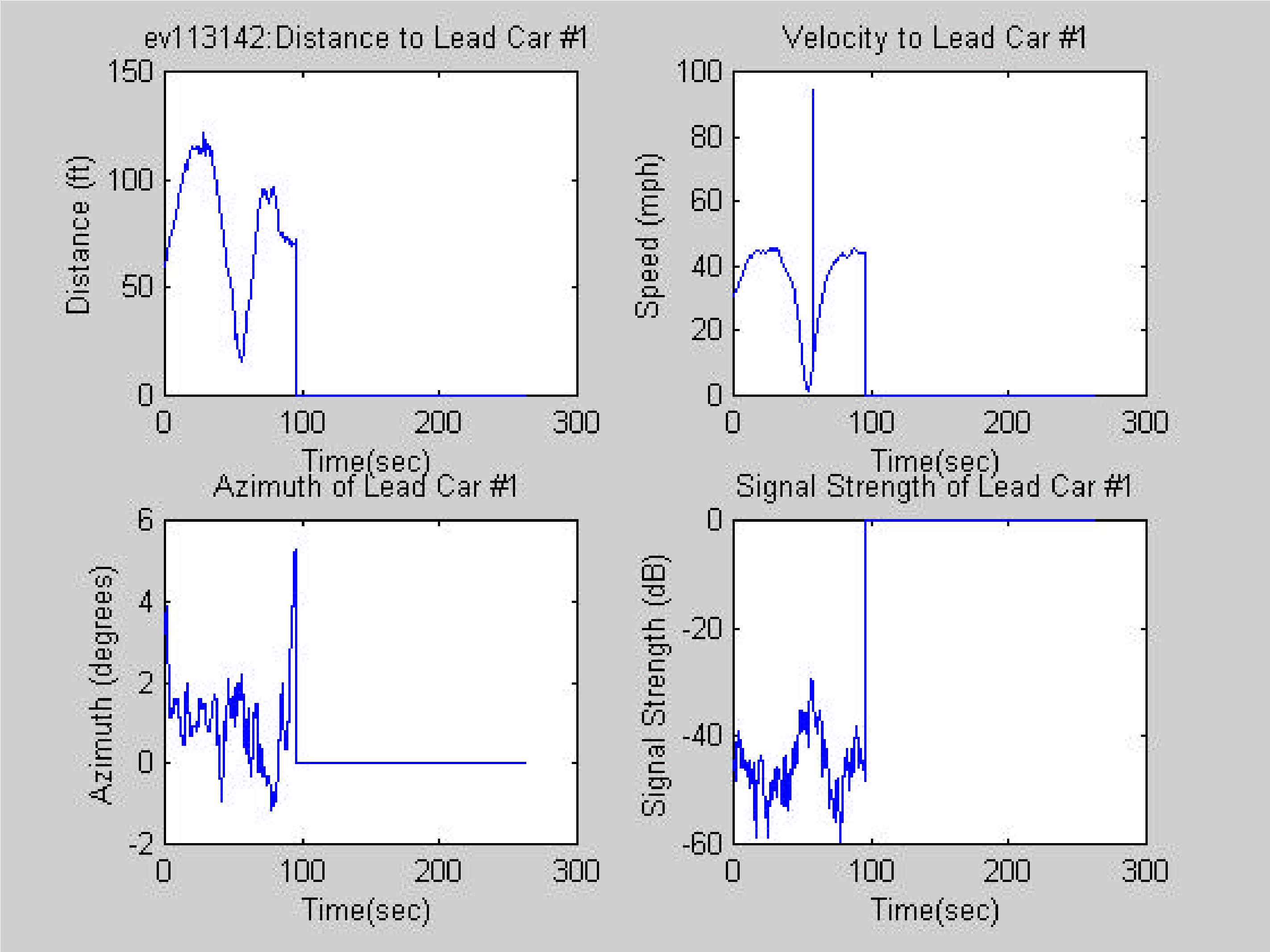

Figure 2(c). Distance, Speed, Azimuth and Signal Strength for the First-track over 10 Seconds.

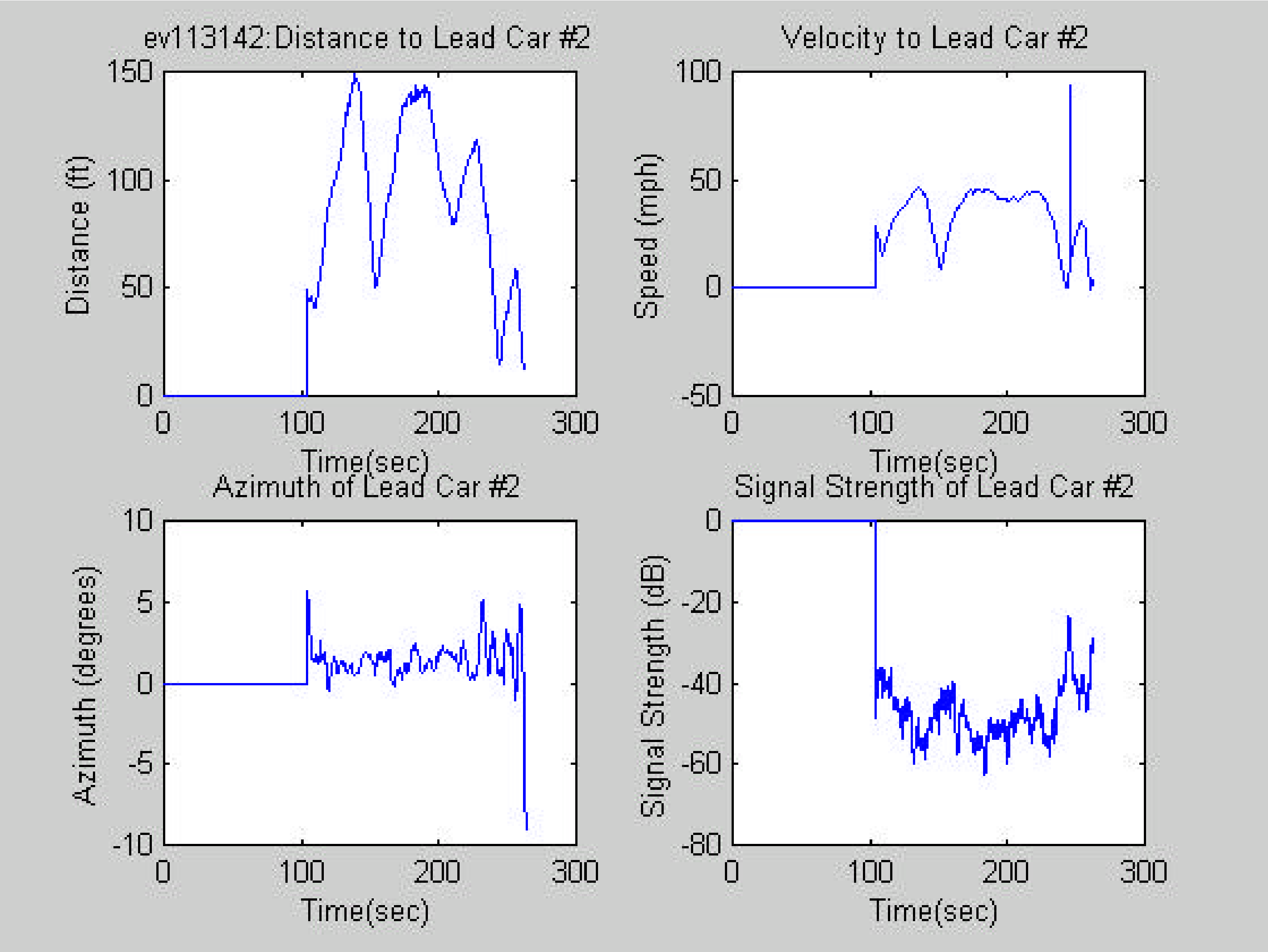

Figure 2(d). Distance, Speed, Azimuth and Signal Strength for the Second Track over 10 Seconds.

Start of run

Fence

Cars on roadside

Car Cutin 1

Car Cutin 2

Car Cutin 3

Before drop out

During drop out

After drop out

Next to truck

Pickup cutin 1

Pickup cutin 2

Pickup cutin 3

Pickup cutin 4

Pickup cutin 5

Pickup cutin 6

Pickup cutin 7

Cars stopped

Figure 2(e). Video samples from Significant Points During Trial ev113142.

Figure 2(a) presents range data with each unique track ID plotted as a function of time. Figure 2(b) is the same data with the exception that individual vehicle tracks lasting less than 10 seconds were filtered out, leaving only two tracks, both of the test lead vehicle. The reason there are two tracks is due to a short interval in which the lead vehicle was outside the 5 degree azimuth tolerance of the radar, as noted on the plot in Figure 2(b). Figure 2(c) shows all the data collected on the first filtered track including range, absolute velocity (including a glitch in the recording system), azimuth and an estimate of the SNR of the target. Figure2(d) is the range, absolute velocity, azimuth and estimate of the SNR for the second filtered track.

With the corresponding video data available for this data set, it was possible to compare the data set with the video and determine the causes of many of the features in the data. This was done, and correlated features were noted in Figure 2(a) with the related video image shown in Figure 2(e).

The following significant observations can be made from comparing Figure 1a) with the still video images of Figure 2(d):

- The chain link fence of the overpass can be clearly visible in radar data for a short time (If the fence was longer, the radar feature would be apparent for a longer time).
- The rows of cars can appear in the radar data.
- The car that cuts off the PATH vehicle is sensed as it accelerates past the lead vehicle, but the radar tracks another vehicle, even with interfering vehicle maneuvers.
- The pick-up truck that cuts in between the lead vehicle and the PATH vehicle is unambiguously detected.
- The radar worked effectively even when the vehicles were stopped at a red light.
- The radar effectively regained track after the lead vehicle went outside the valid azimuth tracking.

The remaining eleven data sets were also processed, and the plots of the radar data is included in the Appendix for completeness.

Conclusion

The results show that the radar effectively tracked the lead vehicle and with some further post processing could be adapted to accurately track a lead vehicle with few lost tracks. However, several instances where periodic structures such as chain-link fences and rows of cars were observed and these situations caused problems for the tracking radar.

The most pronounced outcome is the ambiguity and inconsistency of the radar to returns from roadside objects that might be expected to give more consistent returns (i.e., objects with high reflectance such as metal traffic signs or electroliers were sometimes tracked; at other times, they were not). Sensitivity to roadside and overhead clutter appears to be dependent on the range from the radar unit to the vehicle in front; that is, clutter at the approximate range of the lead vehicle was generally not detected, whereas clutter at ranges greater or less than that of the lead vehicle tended to cause loss of track. This behavior may be a function of the signal-to-noise ratio within the field of view, since at ranges closer than the forward vehicle, clutter returns are high, and at high range-to-clutter ratios, the target signal is relatively small. Data was collected at following distances typically between 25 and 50 meters, so it is not determined whether this sensitivity to clutter holds for much smaller or larger following distances.

The primary conclusion from these data collections is that accurate path prediction is important. However, path prediction is not sufficient. In particular, overhead structures will be detected and classified as in the vehicles travel lane. It is unlikely that automotive radar will have the vertical resolution to distinguish overhead objects from obstructions on the road. Hence, other approaches should be pursued, such as stealthing or marking overhead and possibly other high-RCS roadside objects.

Task 6. Determine “Sensor Friendly” Highway Modifications, and Task 5. Determine Vehicle Modifications

Cooperative markings can take on one of two functions: target feature suppression, or "stealthing", or target feature enhancement, or "tagging". In either case, the objective is to increase the *SCR*.

"Stealthing" Markers

This is perhaps an unconventional way to consider cooperative markers. From [13], considerable target clutter from roadside clutter and from adjoining vehicles is shown to potentially exist within the driver-assist sensor FOR. Multi-path effects would add to this, as would the contribution of roadside geometric elements and signage at curves and at undercrossings. In considering the infrastructure elements, there may be relatively low-cost measures of masking or at least suppressing some of the larger sources that do not necessarily involve expensive "stealth" materials. Examples include:

- where two and three planes could intersect at 90-deg angles (forming dihedrals and trihedrals), ensuring that the intersections be at angles greater than 95-deg, thus greatly decreasing the multiple-bounce "cavity" effect and therefore diminishing the reflected corner cube-like signals;
- placing low-cost, commonly found and low life-cycle cost radar absorbing materials to suppress high signature returns at certain patches; and
- to ensure that NIR background glint is low by removing low-grazing angle, specular surfaces, other than the roadway surface

Principles of Operation

Microwave absorbers are produced by using existing materials and altering their dielectric and magnetic properties. The dielectric properties of a material can be described by its permittivity and magnetic properties by its permeability. Common dielectric materials used for absorbers such as foams, plastics and elastomers are not magnetic, giving them permeabilities of 1. In making Radar Absorbing Materials (RAM) highly magnetic materials such as ferrites, iron and cobalt-nickel alloys are used to alter the permeabilities of these materials. High dielectric materials such as carbon, graphite and metal flakes are also used to modify the dielectric properties.

In general, practical microwave absorbers are one of two basic types: resonant or graded dielectric. The simplest type of resonant absorber is the Salisbury Screen. It consists of a resistive sheet space one-quarter wavelength from a conductive ground plane. The resistive sheet is as thin as possible with a resistance of 377 ohms per square inch, matching that of free space. A wave incident upon the surface of the screen is partially reflected and partially transmitted. The transmitted portion undergoes multiple internal reflections to give rise to a series of emergent waves. At the design frequency, the sum of the emergent waves is equal in amplitude to, but 180 degrees out of phase with, the initial reflected portion. In theory, zero reflection takes place at this frequency, but in practice, absorptions of greater than 30dB (99.9 %) are achieved.

However, the Salisbury Screen has poor flexibility, poor environmental resistance, and poor angular performance (relying in the just-described interference phenonenum). A more practical absorber can be produced by distributing the dielectric and/or magnetic fillers into a flexible matrix, such as an elastomer. This would be a graded dielectric. In a graded dielectric, absorption is achieved by the gradual tapering of impedance from that of free space to a highly lossy state. If this transition is done smoothly, little reflection from the front face will result.

Practical Rules for Highway Application

General physical “rule of thumb” application notes derived from DOD experience are:

1. Elastomeric (rubber) absorbers have better environmental resistance than broadband foam. Some have been used on surface ships for over 30 years.
2. This experience base shows that neoprene is widely used in naval applications because of superior weather resistance. Nitrile is used for fuel and oil resistance. Fluoro-elastomers have an excellent operating temperature range.

3. Broadband foam materials can be used outdoors, but steps should be taken to protect the absorber. Open-cell foams can be filled with low-loss plastics to make rigid panels for use outdoors. Broadband absorbers can be encapsulated in fiber reinforced plastics to form flexible RAM panels that can be draped over reflectors.
4. Adhesives vary with the type of elastomer chosen. In general, neoprene and nitrile are the easiest elastomers to bond. The silicones are the most difficult to bond and generally not used as often for that reason. In some cases, it is necessary to cover a tight radius or complex curvature. An alternative to flat sheet material is conformally molded parts. Conformal molds increase the ease of bonding and reduce the likelihood of applying any built-in stresses into the material.
5. To improve weather resistance, the absorber can be painted. Typically, a low permeability epoxy or urethane-based paint is used. To avoid gaps between sheets, absorptive gap fillers are also produced, thus minimizing any impedance mismatches from sheet to sheet and reducing formation of surface waves and reflections.
6. The useful temperature range of most RAM is -5 deg F to 250 deg F.

The Japanese have been applying radar absorber to structures and bridges to reduce electromagnetic interference for some time[3].

A comprehensive application on highway roadsides would consist of the following elements:

- low cost Salisbury Screen or single layer carbon loaded elastomers to cover overhead signs and bridge structures;
- graded dielectric foam absorber to fill cavities and de-tune trihedrals and dihedrals; and
- addition of dielectric sign material that meets current reflectivity requirements and can incorporate a radar absorbing system

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[3] We understand that Prof. Hashimoto of Aoyama University delivered a paper on the topic during the recent Spring [25 March 99] meeting of the Japanese counterpart to the IEEE, the Institute of Electronics, Information and Communication Engineers. However, we have not yet been able to obtain this paper.

It is anticipated that significant reductions in system returns at 77 GHz can be achieved by topically applying materials. A standard 20 dB reduction should be easily achievable.

Prototype material will cost $15/square foot since small lots of raw materials and special tooling will be required to fabricate the materials. Application of the material will cost $60/hour. (A more detailed estimate can be made if a typical environment is defined.) Production cost could be up to $10/sq ft of treated area. The RAM kit could be installable by normal State DOT operations and maintenance crews, but they would require special TBD training. Given training, a highway worker should be able to install approximately 100 sq ft of treated area/hour.

A systems approach would have to be adopted to develop low cost kits for standard structures. These kits must be be applied easily and be durable. Also, absorbing structure can be developed and applied to bridges that are being modified for purposes such as earthquake tolerance. However, such a comprehensive approach could be quite expensive. It is precisely because of this that the “stealthing” concept is not recommended for widespread application; rather the other concepts described in this report, which we label “tagging” probably hold better promise in terms of the benefit/cost. However, we believe that RAM-based “stealthing” may be potentially useful as “patches” for singular and notorious sources of roadside signal which may be difficult to eliminate by other means (e.g, a complex steel-beam overpass structure or truss).

"Tagging" Markers

In the target feature enhancement case, markings would serve as a beacon, and could be either active or passive. These can be regarded as a type of point-to-point vehicle-to-roadside or vehicle-to-vehicle communication, with the communicated information sensed by on-board driver-assist system sensors rather than received by a dedicated communications antenna. With no formal confirmation protocols and susceptibility to weather, clutter and other contamination effects, the information transmitted would almost necessarily be low bandwidth. An example that might require no additional processing modifications would be simply marking an otherwise low-signature surface such as the side of a panel truck.

Another example which would perhaps require significant processing would be to be to provide a signal stream with time- or frequency-domain modulation from the back end of a vehicle to announce its current braking rate, perhaps with a statement of maximum braking capability; this could provide sufficient information for a following ACC- or FCA-equipped vehicle to accordingly adjust the vehicle-following time gap to a safe spacing [15]. A more near term application could be a device such as the Intelligent Ranging with Infrared Sensors, where the reflected return from taillights and/or the rear license plate frame of a NIR diode emanating from the front of the vehicle could be used to determine range and relative yaw [16]; such a system could be implemented in conjunction with a NIR laser radar.

From an infrastructure standpoint, clearly marking lane boundaries for lane departure warning or lane keeping applications, perhaps with fluorescent paint, is an obvious near-term step. Expanding beyond that, a guard rail that provides the radius of curvature, and even some signal as to the road surface condition could be implemented. Overhead obstacles such as bridge abutments could perhaps also be tagged.

Other examples are bound to exist, with the point being that considerable benefit could be derived in tagging various targets, either for collision avoidance or for information (e.g., road curvature) benefits.

As with "tagging" markers, other possibilities exist.

Prototype Sensor-Friendly Concepts, Approaches And Modifications

In this section, we describe prototypes that transcent the MOU 368 effort and progress from characterizing the operating environment to identifying candidate cooperative devices and systems[4]. A number of concepts deal with 77 GHz automotive radar, where we consider

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[4] As described in footnotes 1 and 2, most of the prototype development and testing was funded from a complimentary Federal contract, US DOT Contract No. DTFH61-98-C-00100. It is included in the MOU 368

vehicles that can be equipped with radar reflectors, either passive, to increase their radar cross-section, or actively modulated, to provide some communication. Roadside infrastructure can be similarly treated in order to make their radar profile distinctive and recognizably different from a vehicle.

Light Emitting Diode Brakelight Messaging

The Light Emitting Diode Brakelight Messaging (LEDBM) system is comprised of modulated LED brake lights, which communicate information about a vehicle's state to any following vehicle with an LEDBM receiver. The LEDBM system is conceived as a supplement to radar in a FCW or FCA system, as identifies only cooperative target and not objects that may confuse road debris, bridges and signs. A key to its implementation, of course, is large-scale market penetration of like systems; however, LED taillight assemblies are beginning to appear on the marketplace due to lifetime cost and space savings. Moreover, modifying circuitry to modulate them is relatively inexpensive proposition. The more complex considerations are providing the sensors, both to sense forward vehicle state and to receive LEDBM signals.

The purpose of the set of tests detailed here was to provide a real implementation of LEDBM system on two vehicles, which could be used to compare the performance of the system on the road with the laboratory results and radar performance. Test goals were:

- Determine the practical range and field of view of LEDBM system
- Determine reliability of system (acquiring and retaining signal lock)
- Test system performance during cut-in maneuvers
- Test system performance through curves
- Test system performance through hills

Equipment and Setup

One vehicle, the “lead vehicle”, was equipped with a modulator, an LED transmitter, a longitudinal accelerometer, a wheel speed sensor and a computer to process the I/O. Additional equipment included:

- On-board computer
- Two-way radio
- Modulation & Power Electronics to drive LEDs
- 2 LED brake light boards in plastic frames
- 2 Plastic frames to hold LED brake light boards on lead vehicles rear bumper
- Wheel speed sensor

This is shown in Figure 3, along with the brake lights and the wire, which leads back to the modulation and power electronics in the trunk.

The other vehicle, “the following vehicle”, was equipped with two receivers, two forward-looking EVT-300 radars, an experimental lidar, a digital video camera to record events and a computer to record the data from the receivers and the radar. Additional equipment included a two-way radio, a video camera mounted near rear view mirror, and two LED receivers on front bumper.

Results

Practical Range and Field Of View. The following vehicle can receive the information if the transmitting vehicle is within the receiver field of view (FOV), shown to be nearly 25 degrees in previous laboratory experiments, and range, shown to be about 60 meters in our field experiments. To accomplish these measurements was not trivial. The "truth" measurements of vehicle state were made by the radar and lidar which have inaccuracies, can lose the vehicle being tracked or can track the something other than the lead vehicle. Moreover, a difficulty in measuring the FOV of the LEDBM receiver is that it that the laboratory measurement shows it is approximatley 25 degrees, whereas the lidar FOV is 16 degrees and the radar FOV is about

12 degrees. To circumvent this, the FOV boundary was determined by looking at the ensemble of on-off LEDBM detection lock-ins using knowledge that this transition was at the edge of an "effective" FOV, as registered through the complete LEDBM signal generation through data acquisition apparatus. This was sometimes effective and sometimes not; however, enough data was present to generate a knowledge of the FOV.

Figure 3. Mounting of LEDBM System and Test Components

Reliability. Results are mixed. A problem with the current hardware is that there is not a narrow FOV and range boundary for the receivers. The result is that the receivers flicker on and off even when the receiver is well within its FOV and range. Better signal locking electronics could improve the LEDBM systems performance in this respect.

System Performance: Cut-In Maneuvers, Curves, Hills. The LEDBM was shown to probably be an effective potential supplement to radar, as it outperforms the EVT-300 radar used in the experiment in terms of acquiring and holding the signal of the forward vehicle during more complicated driving situations such as sharp curves, tight cut-in maneuvers and quick transitions to hills.

Passive License Plates

A Passive License Plate (PLP) consists of a visually transparent layer of radar cross section (RCS)-modifying superstrate which consists of the outer layer of license plates. With PLP, the RCS signature is modified such that the forward vehicle (with a rear plate) is presented to the subject vehicle as a near-point source of uniform and high RCS over a wide (plus- or minus-45 degree) azimuth. The PLP technology addresses rear end collisions, since if PLP was deployed, subject vehicles equipped with FCW or FCA systems would be able to reliably pick out forward cars, in curves, adjacent lanes or in inclement weather (which might introduce road spray which could otherwise extinguish low RCS from forward vehicles under at certain relative yaw angles).

Two sets of PLP tests were run: laboratory tests to verify the PLP design [4], and on-road tests to gauge PLP performance in the field.

Laboratory Tests

Two prototype designs were made, PLP-001 and PLP-002, both shown in Figure 4. The PLP-001 design has facets at 45 ° from the rear surface. These facets are set at 90° angles between each. The PLP-002 design consists of a series of semi-circular surface contours in a vertical orientation to the license plate. The grooves are then filled with a low dielectric filler material and paint combination to create a flat surface and allow appearance of a typical license plate.

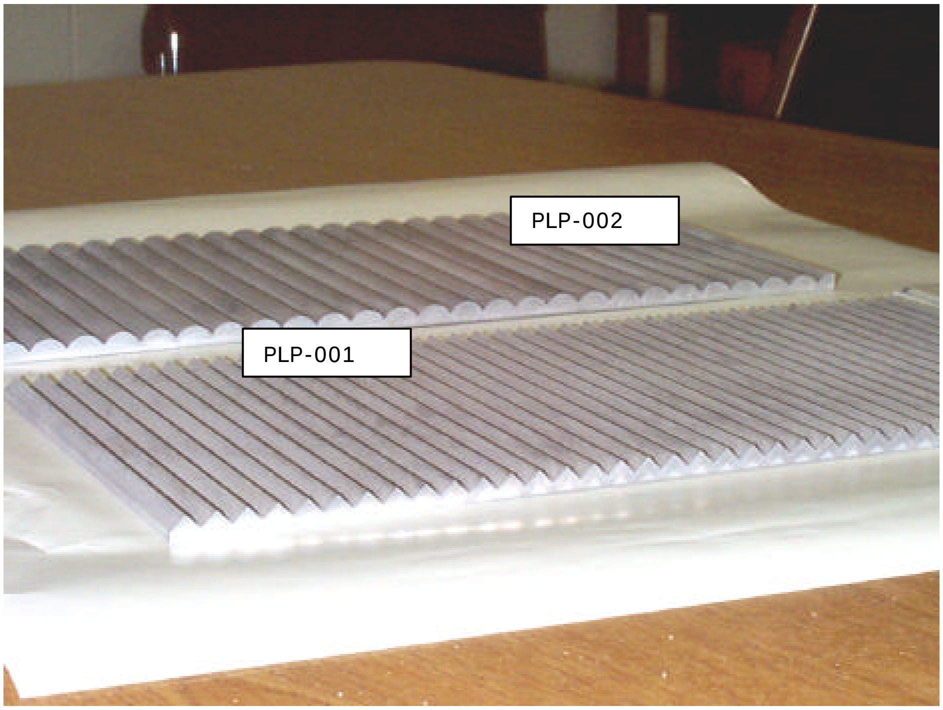

Figure 4 PLP-001 and PLP-002, Minus Dielectric Filler

Proof of concept testing was conducted at the UCLA Center for High Frequency Electronic using a HP 8510 Network Analyzer. Both the designs were tested by taking monostatic measurements at 77GHz. Measurements were taken at the normal, 5°, 10°, 15°, 30° and 45°. Figure 5 shows the test set-up at 45°incidence.

Both prototype designs were tested without any surface treatments or coatings, then as illustrated in Figure 6, grooves on both designs were filled with a low dielectric material to create a relatively smooth surface with a 5 mil skin to illustrate that the RCS modification would work with a highly reflective material.

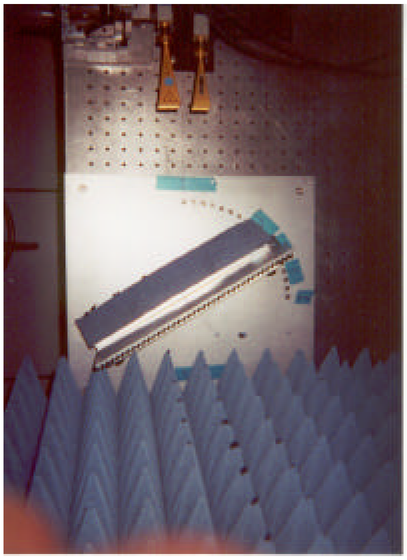

Figure 5. Monostatic Testing at 45°

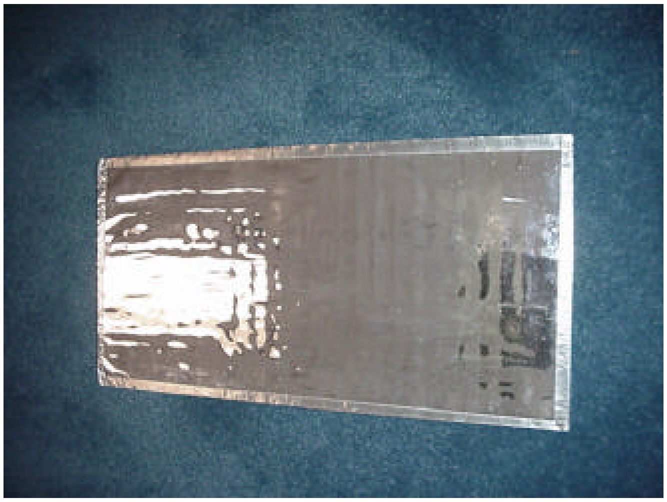

Figure 6. PLP With Visually Reflective Film

Figure 7 indicates test points without the reflective surface (yellow) and with the surface (red), vis-à-vis prediciton (blue). Despite the phase interference between –15 degrees and +15 degrees and some phase addition at 30 degrees and 45 degrees, reflection of up to 30 dBsm is noted over plus and minus 45 degrees – significant azimuthal performance. In principle, the PLP would work at a broad range of angles, affording high target reflectivity to forward looking radars, at a wide range of aspect angles, which in turn affords high tracking efficiencies over a wide range of relative yaw angle and therefore a wide range of curve approach scenarios. The next stage in the proof of principle testing is to translate the promising laboratory results to a field test.

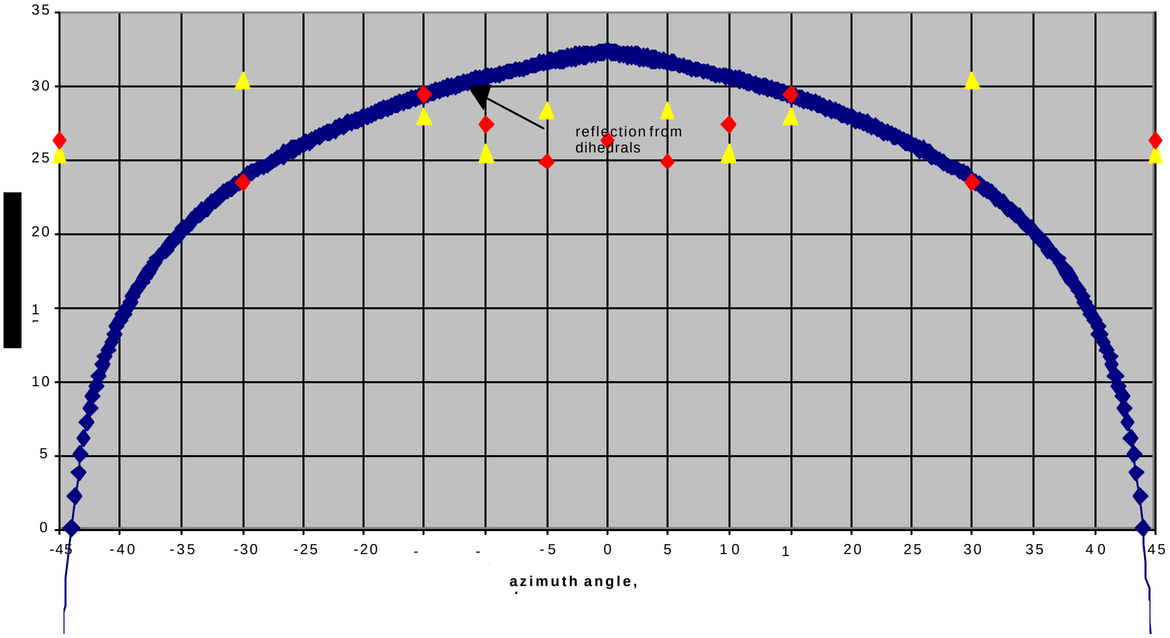

Figure 7. Reflection from PLP

On Road Tests

The PLP-001 was mounted on the vehicle shown in Figure 8, then tested with a 77 GHz radar unit built expressly for automotive target tracking experiments at CMU [5]. This radar has a FMCW processor with a frequency modulation bandwidth of 300 MHz, consisting of a single transmitter and an array of four receivers. The vertical field of view of the radar is 3 degrees, and the horizontal field of view is 12 degrees. The radar outputs range, horizontal bearing and signal amplitude for each detected target. Using the receiver array and a method called wavefront reconstruction, a resolution of 3 degrees is achieved within the horizontal field of view. The resolution in range is approximately 1 meter.

Figure 8. PLP Installation

In the PLP testing the radar was located approximately 19 meters behind the rear end of the test car. There is a significant signal strength difference between a return from the test car with or without the PLP at 0 degrees incidence angle. However, at larger angles, above 22 degrees, the PLP does not seem to make a difference and the difference in signal strength is within the range of fluctuations of the radar signal.

A partial reason for that effect could be that the license plate mounting location is recessed into the backend of the car; thus the area around the license plate represents already a geometric structure that could be expected to reflect a radar signal well, even at larger angles of incidence. At these angles, this effect therefore seems to be more dominant than the additional signal strength gained by the PLP for a stand-alone license plate. Another may be that the PLP installation was atop the rear vehicle, thus allowing multipath reflection from beneath the car and other sources dominate at high incidence angles. Thus, at this time results are ambiguous. It is clear from the laboratory testing that PLP should be a helpful “sensor-friendly” supplement;

however, the small scale field test conducted thus far does not clearly show this for high incidence angles.

Roadside-mounted Corner Cubes

A structure of corner cubes to provide a unique radar signature at 77 GHz – to identify fixed roadside objects – was conceived, built and tested. When deployed, patterns of corner cubes would interact with automotive radars, which would receive spatially modulated sequence of returns to uniquely identify roadside object types, along with other coded information, e.g. curvature, distance.

In order to obtain a unique radar signature from a structure consisting of corner cubes, each must be identifiable in the radar image as a separate target under a variety of viewing conditions. An arrangement of corner cubes in the vertical is not useful, as the radar cannot distinguish separate targets by elevation; moreover, its vertical field of view is small. In fact, given the resolution geometry of the radar, a lateral arrangement of corner cubes may not be desirable since lateral resolution depends on horizontal angle between target and pointing direction of the radar. The ability to resolve laterally adjacent targets would be dependent on target range and achievable only with significant lateral spacing.

Given these considerations, the best solution would be to arrange the corner cube targets longitudinally with respect to the radar, where targets can be discriminated to within approximately 1 meter. In this concept, several corner cubes, e.g., five or six, can be arranged at equal distances such that they would form a unique binary code, where '1' represents a corner cube present in the respective slot and '0' represents a corner cube missing in the respective slot. Specific code formats that are robust against false target detection and noise should be chosen (e.g. provide checksum, etc.).

The question then arises as to where the corner cube structure should be mounted with respect to the road and the roadway object. Possibilities are either overhead, on either side of the road or by using radar reflective stripes in the centre of the lane. Each location has its own advantages and disadvantages, but unfortunately neither one would always be completely visible for each possible traffic scenario. Therefore further analysis would need to be done in order to find an optimal location. However, in order to proceed and for simplicity of testing we decided to mount the corner cube structure on the side of the road.

Tests

When mounting the corner cube structure on the side of the road, there is a choice of either offsetting the consecutive corner cubes in the structure laterally or vertically in order to have each corner cube visible from the radar sensor of an approaching vehicle. However, since automotive radars generally have a fairly limited horizontal field of view, we decided that it was best to offset the corner cubes vertically rather than laterally as is shown in Figure 9. Figure 10 clearly depicts the longitudinal separation.

Figure 9. Corner Cube Configuration: View from Approaching Vehicle

Figure 10. Corner Cube Configuration: View from the Side

We then tested the {111111} pattern of the configuration shown in Figures 9 and 10, then two more patterns, {110101} and {110111}. Results from the {110101} pattern test are shown in Figure 11, and the "0" dropouts at positions 3 and 5 are clearly discernable. These results are promising, and clearly indicate that indeed the use of corner cube patterns are of potential value to "tag" roadside objects which may confuse forward looking radar algorithms; our tests demonstrate that unique longitudinal configurations are clearly discernable, given considered design and placement.

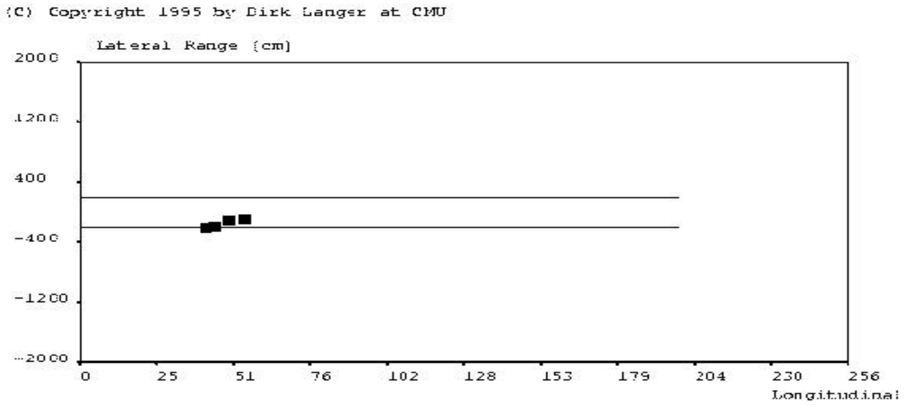

Figure 11. Results from the {110101} Pattern Test

CONCLUSIONS

A motivating premise in investigating SFH is that near-term cooperative vehicle and roadside measures can enhance other autonomous CAS such as FCW and FCA, or lane LDW or LDA. The hypothesis behind is that supplemental cooperative systems in the road or on other vehicles will allow driver-assist systems to perform over a broader range of traffic conditions and roadway geometries, to include curved sections and bridge abutments. Hence, with SFH, availability and reliability of CAS could be enhanced. User acceptance, market penetration, and ultimately, safety benefits could then accrue – in a quicker fashion than with autonomous versions of CAS. In the end, sensor-friendly systems could be a shortcut to CAS deployment.

We have investigated the limitations of autonomous sensing systems in the context of vehicle and roadway signature characteristics; additionally, we have additionally investigated how those limitations could be mitigated through the use of relatively near term methods vehicle-vehicle and vehicle-roadway cooperation, from which we notionalized cooperative concepts. Throughout this process we have kept in mind the screening principle that concepts must be judged as likely near-term candidates for deployment. In our judgement, this the only means to achieve a significant and new vehicle-roadway cooperative system aimed at CAS; institutional and cost issues are complex for any SFVR system, let alone one that is futuristic or overly complex.

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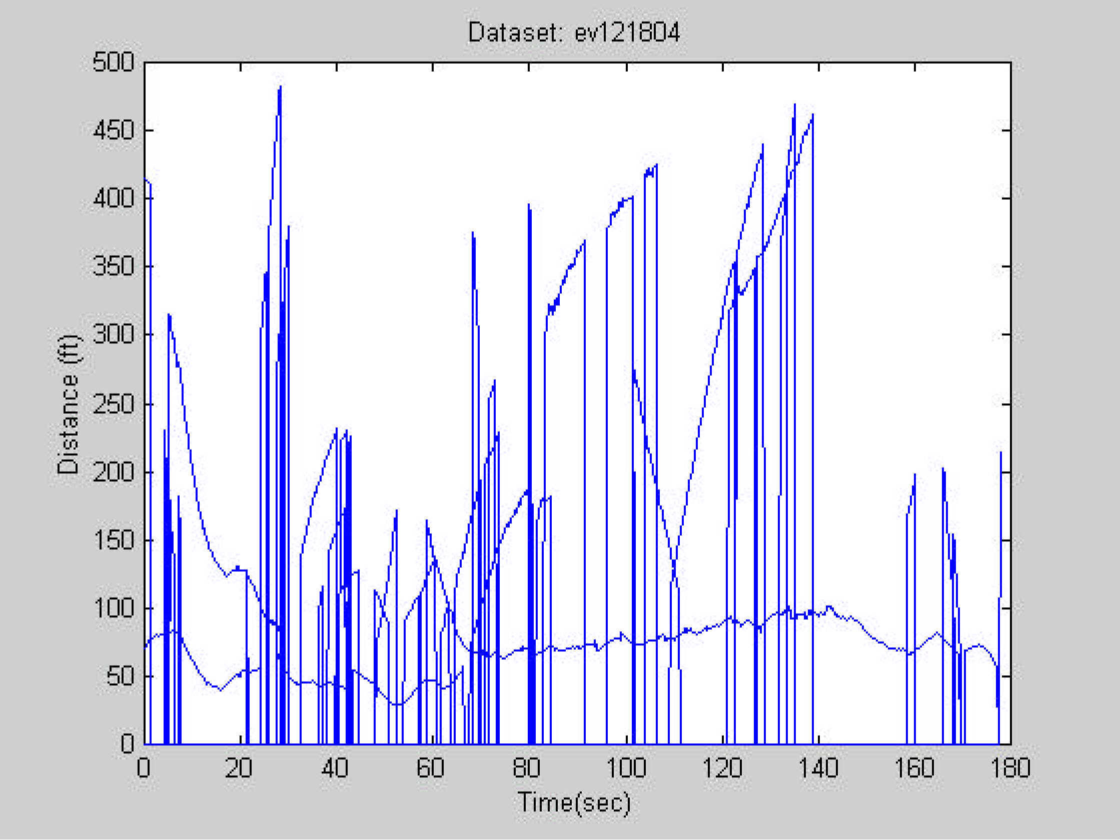
APPENDIX:
PROCESSED ROADSIDE DATA COLLECTION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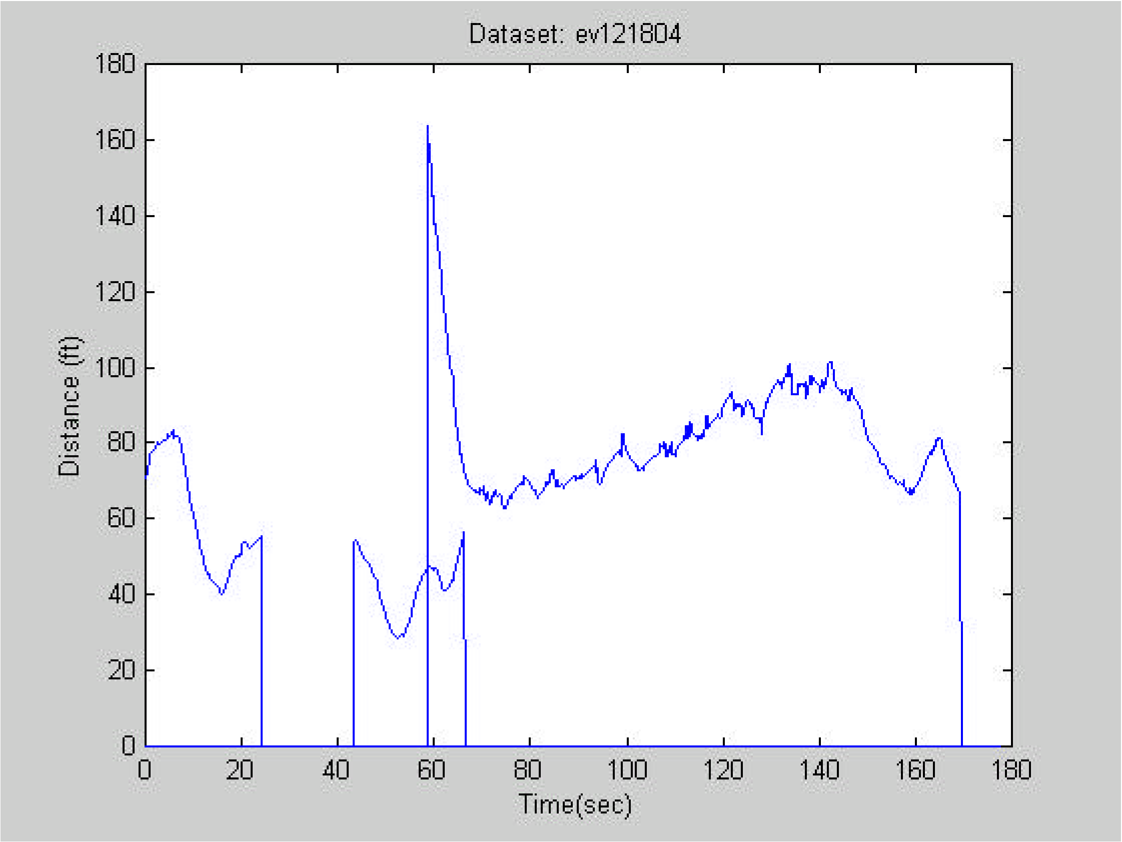
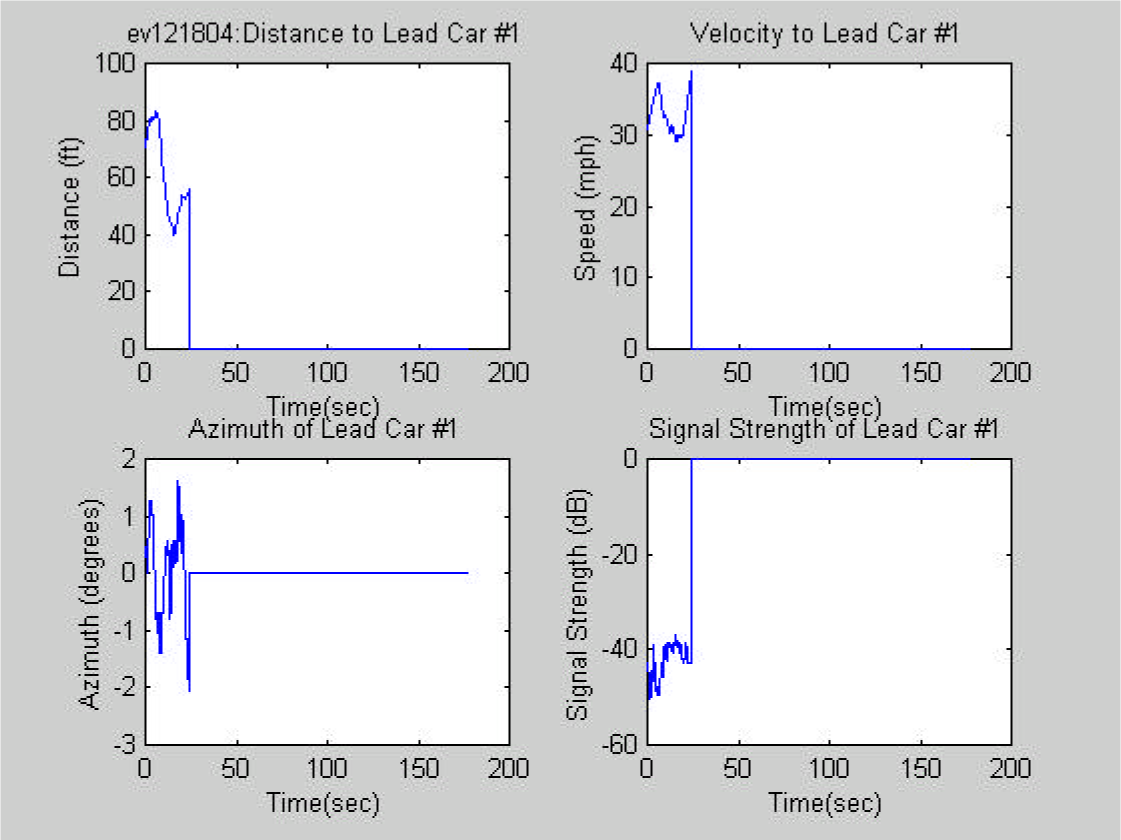
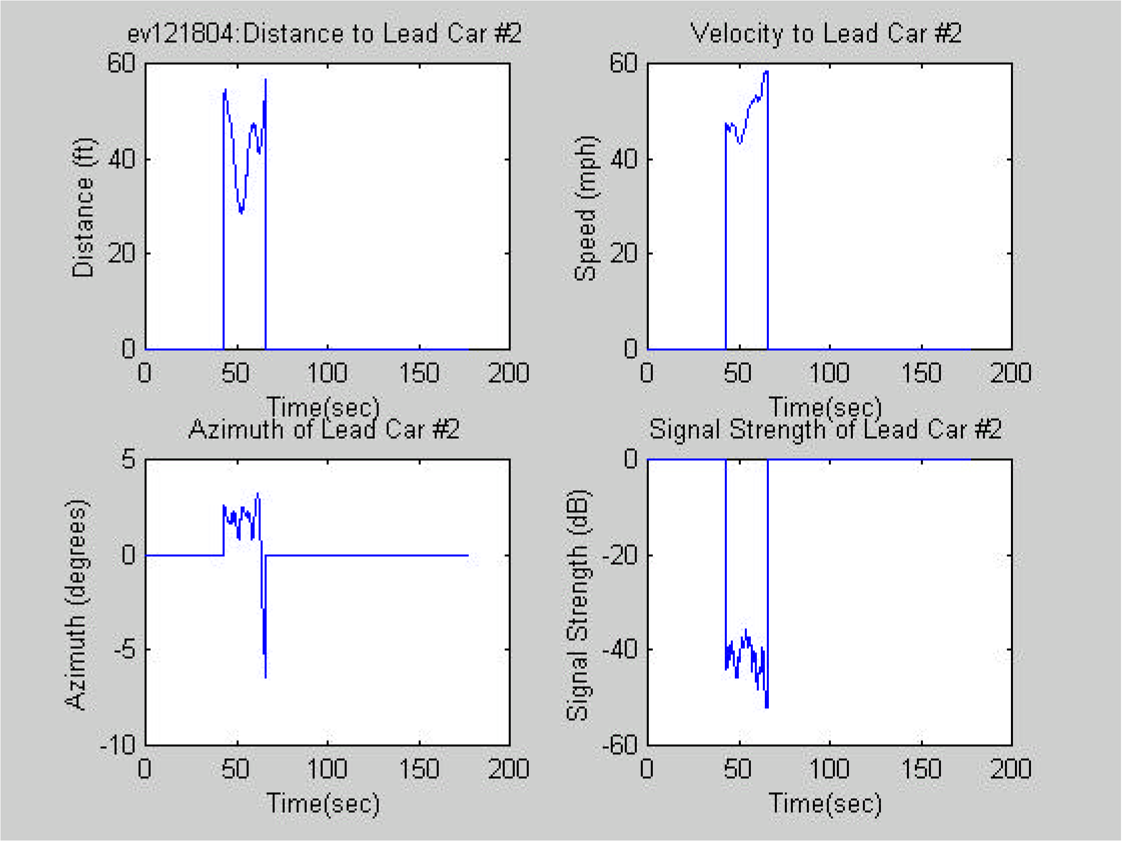
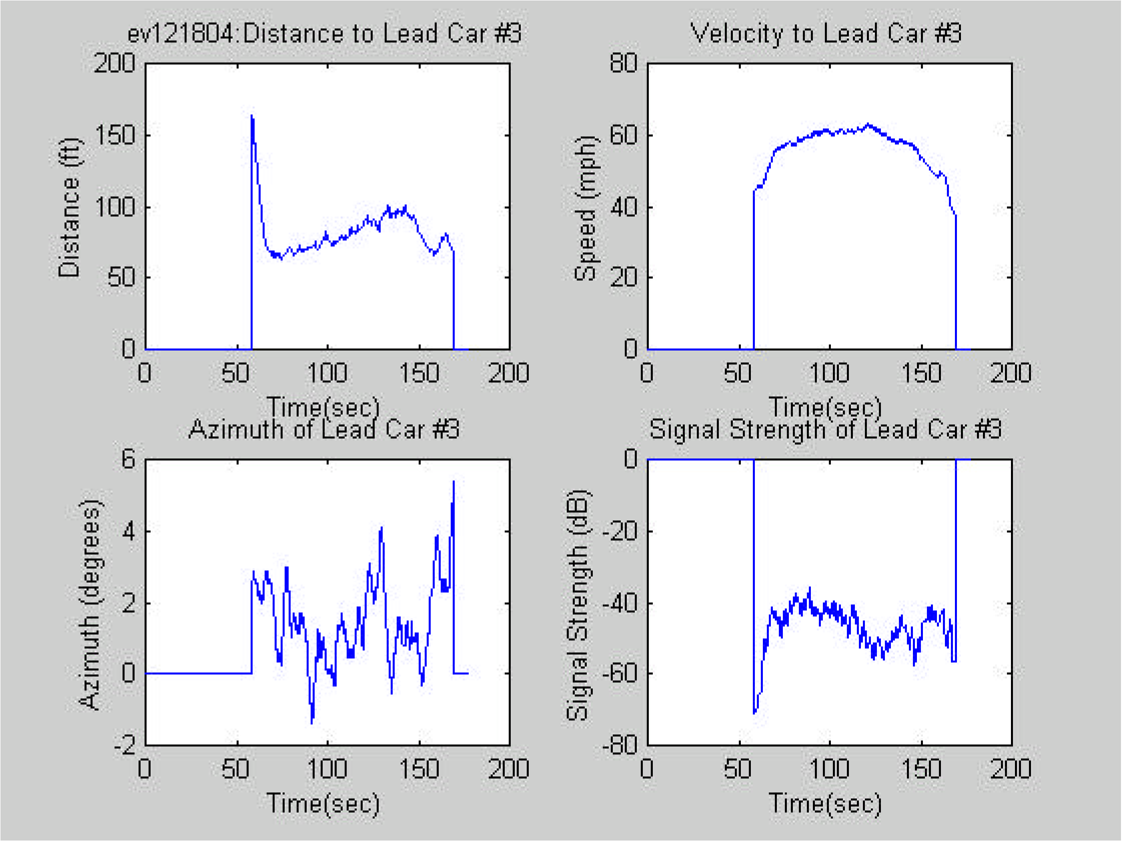
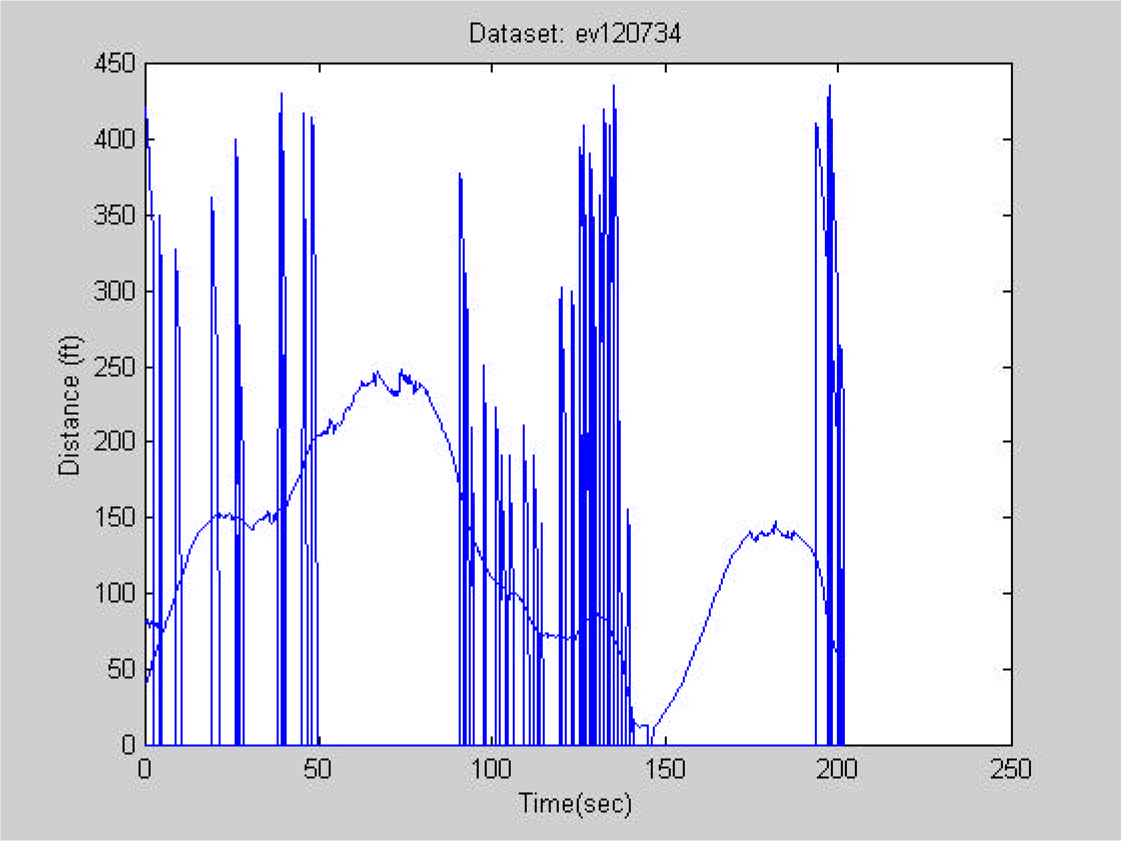
180

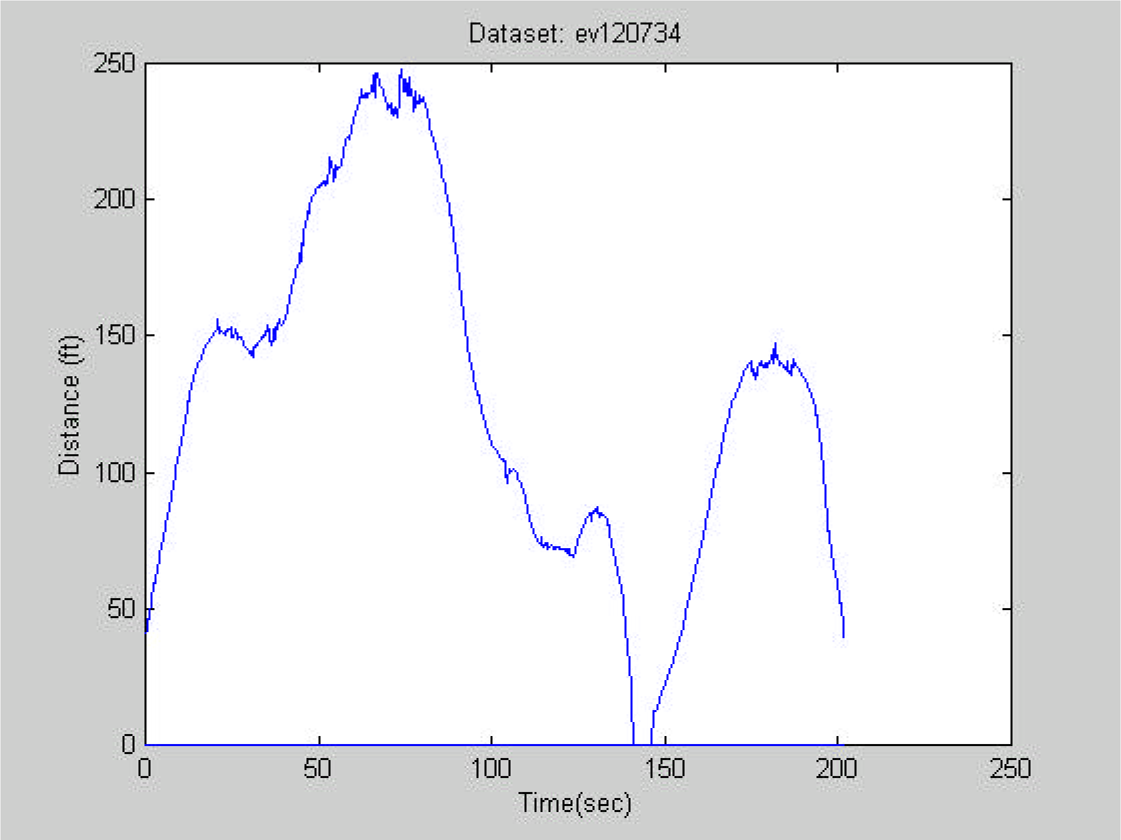

Dataset: ev121804
Distance (ft)
Time(sec)
0
20
40
60
80
100
120
140
160
180
0
20
40
60
80
100
120
140
160
180

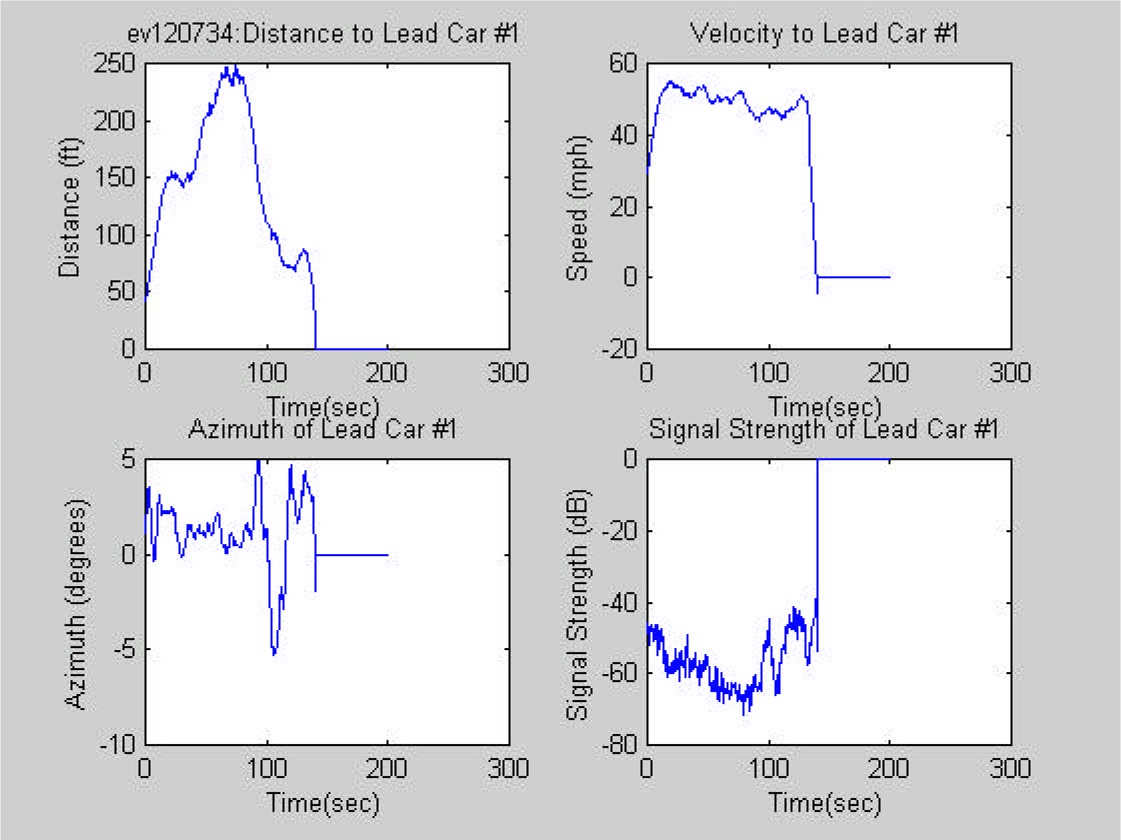

ev121804:Distance to Lead Car #1
Distance (ft)
100
80
60
40
20
0
0
50
100
150
200
Time(sec)
Velocity to Lead Car #1
Speed (mph)
40
30
20
10
0
0
50
100
150
200
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
2
1
0
-1
-2
-3
0
50
100
150
200
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
0
50
100
150
200
Time(sec)

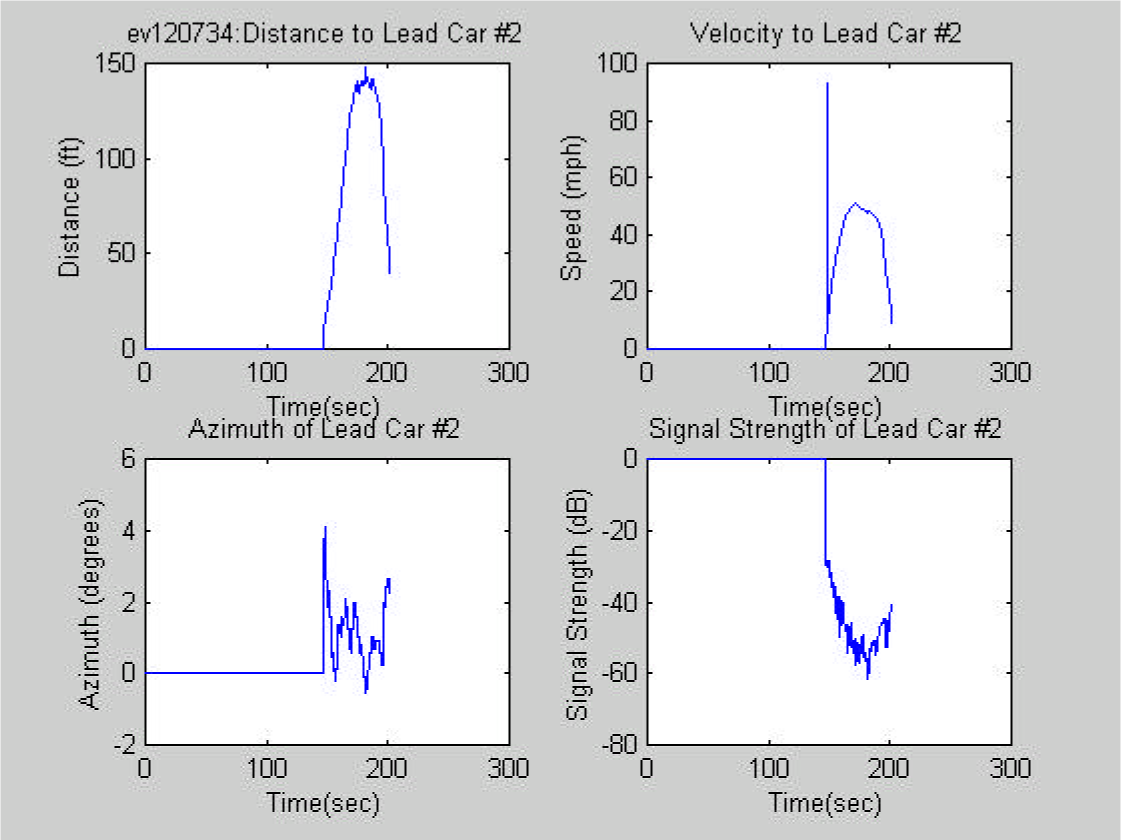

ev121804:Distance to Lead Car #2
Distance (ft)
Time(sec)
Velocity to Lead Car #2
Speed (mph)
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
Time(sec)
60
40
20
0
5
0
-5
-10
-20
-40
-60
50
100
150
200

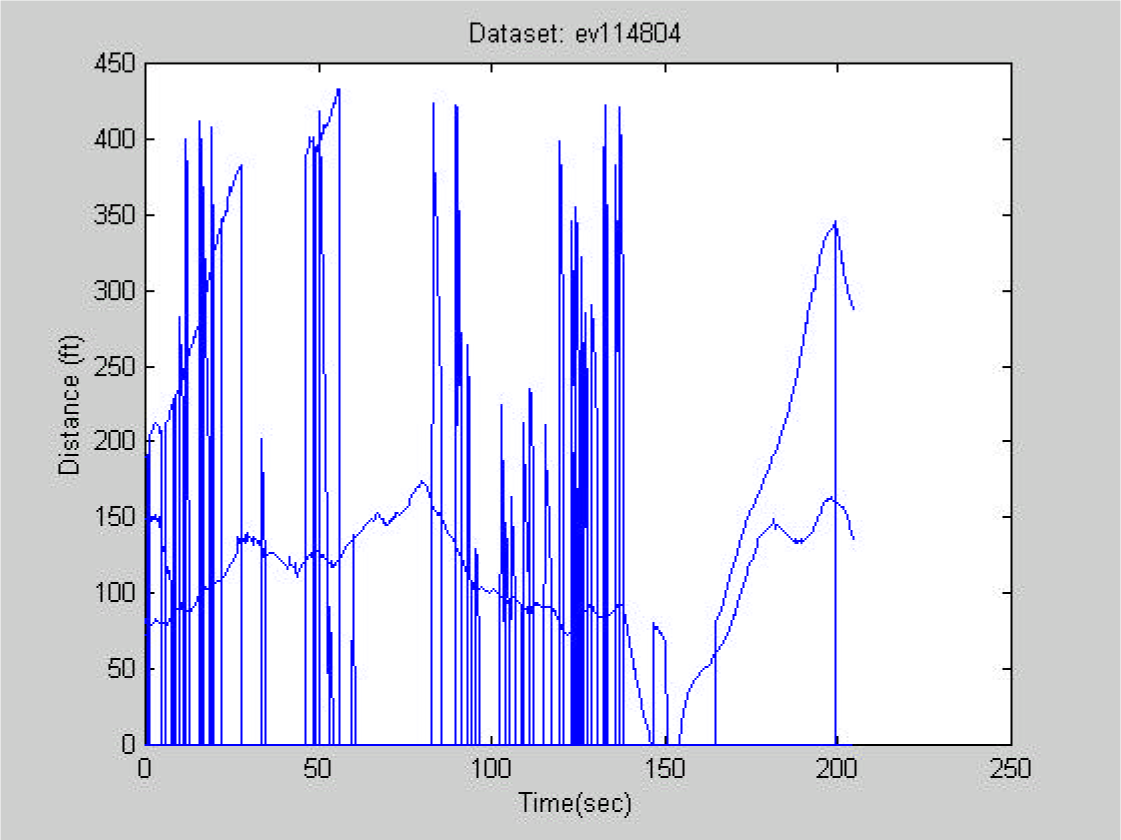

ev121804:Distance to Lead Car #3
Distance (ft)
200
150
100
50
0
0
50
100
150
200
Time(sec)
Velocity to Lead Car #3
Speed (mph)
80
60
40
20
0
0
50
100
150
200
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
6
4
2
0
-2
0
50
100
150
200
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
-80
0
50
100
150
200
Time(sec)

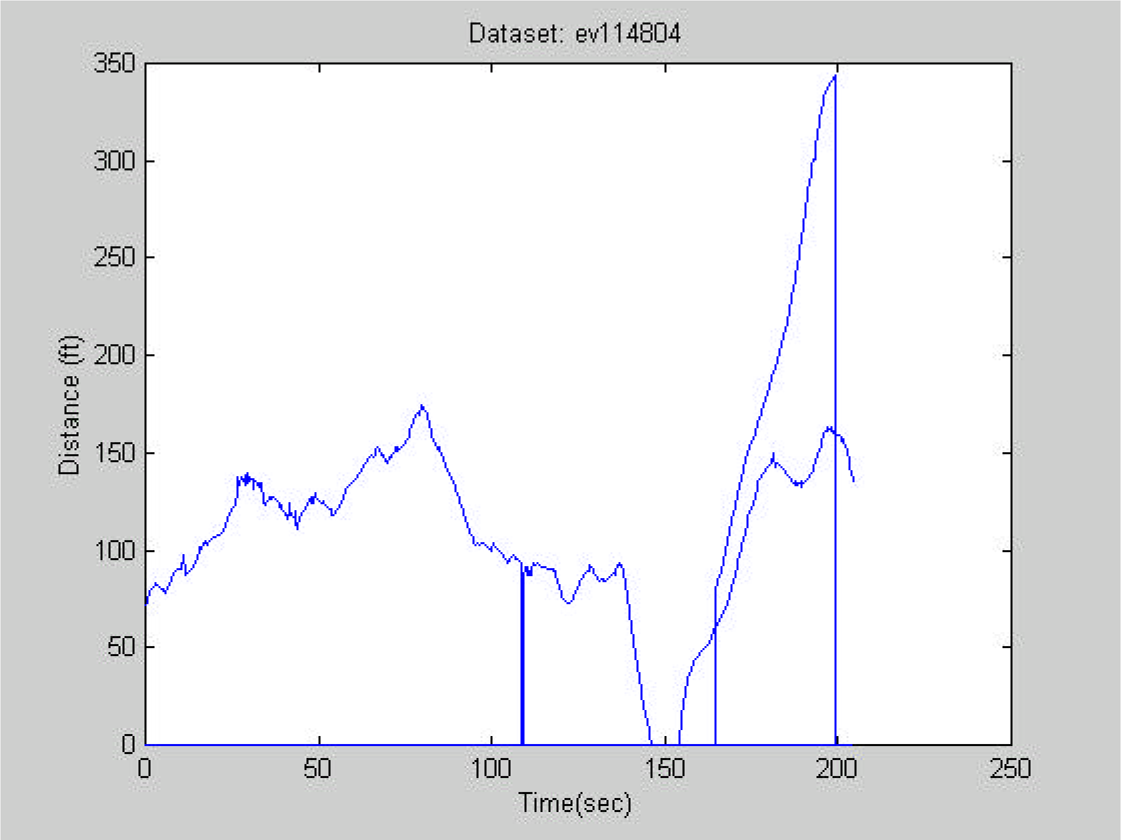

Dataset: ev120734
Distance (ft)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Time(sec)


Dataset: ev120734
Distance (ft)
Time(sec)
0
50
100
150
200
250
0
50
100
150
200
250

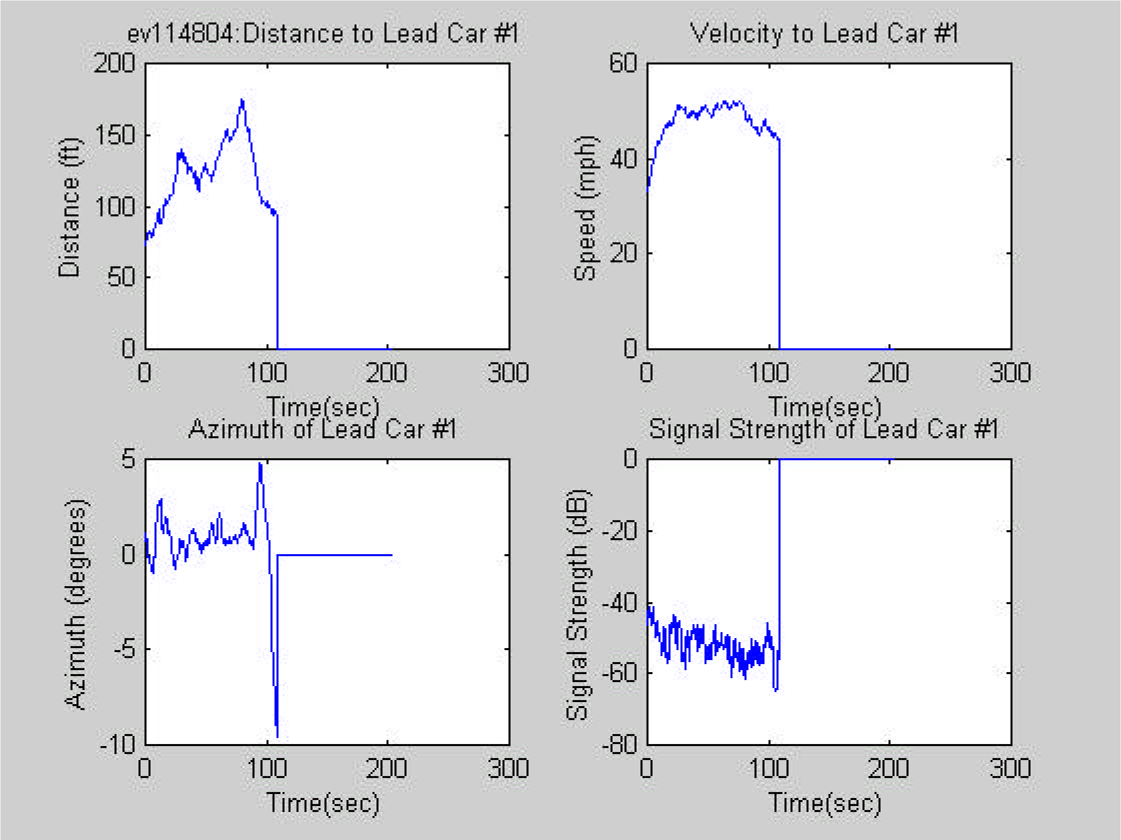

ev120734:Distance to Lead Car #1
Distance (ft)
250
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
-20
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
5
0
-5
-10
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

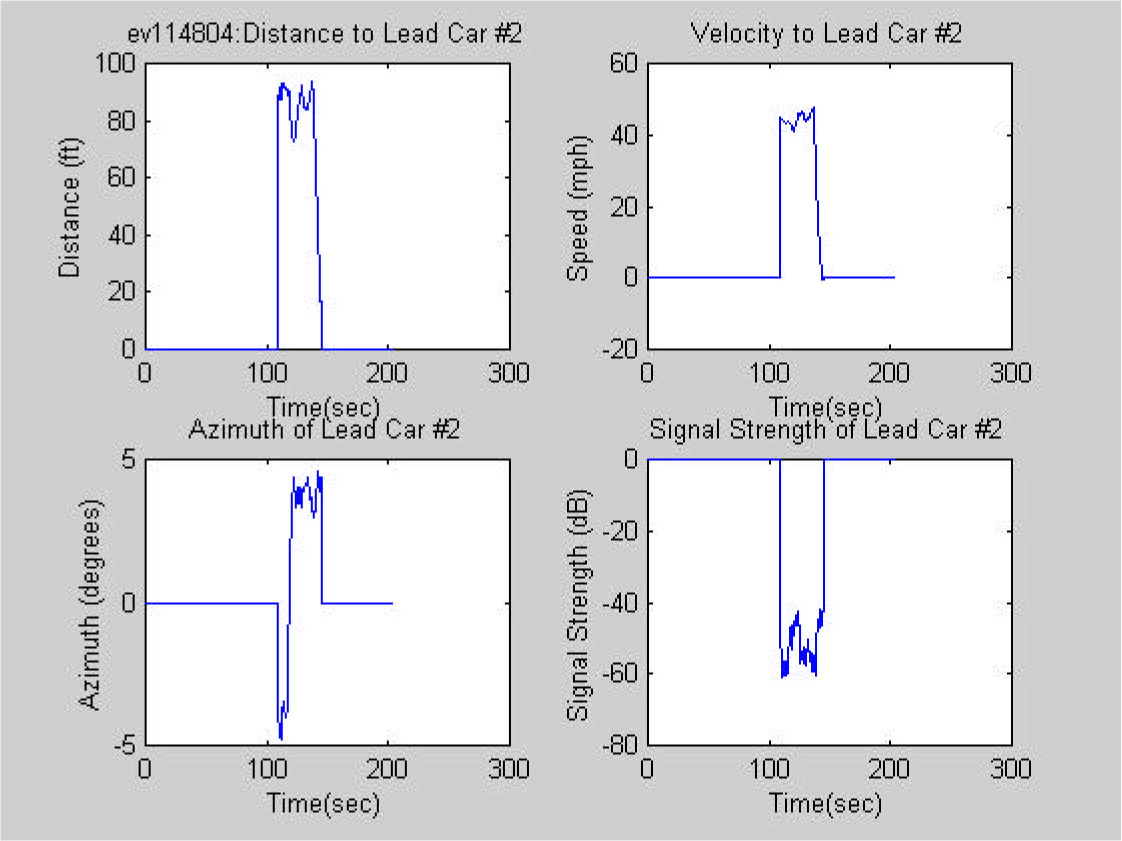
ev120734:Distance to Lead Car #2
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
100
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

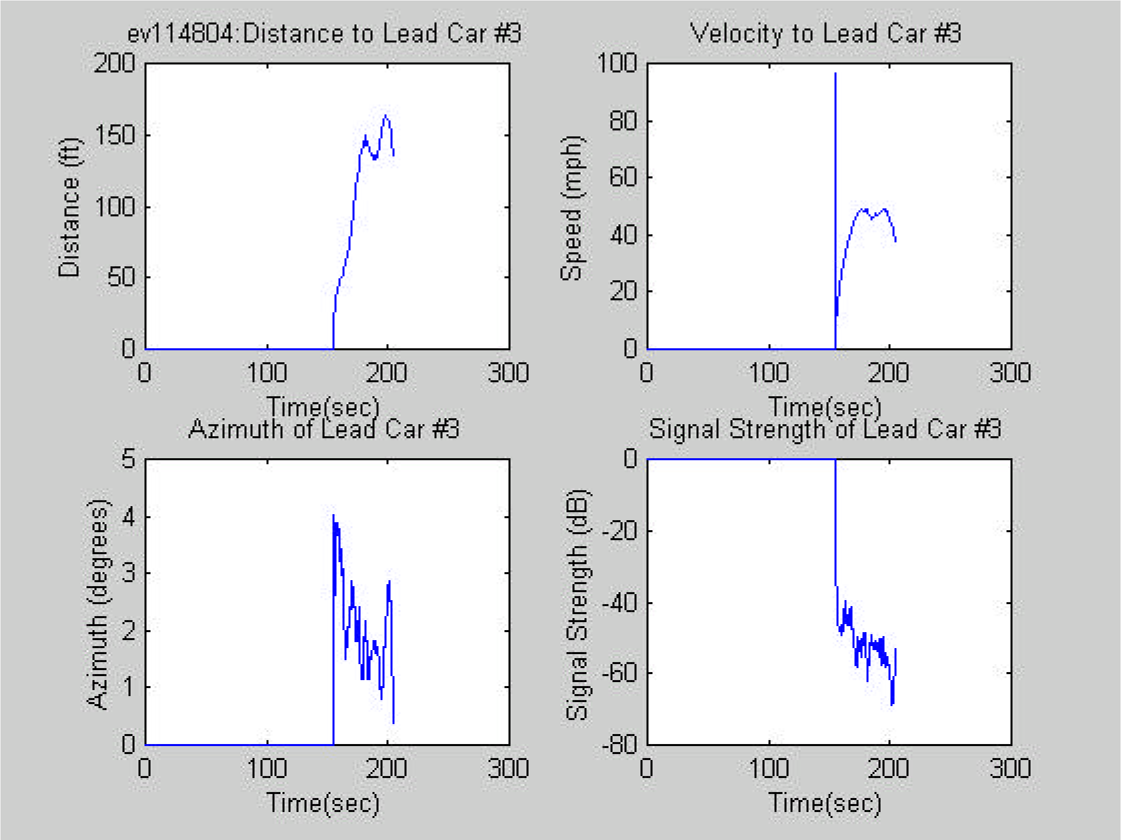

Dataset: ev114804
Distance (ft)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Time(sec)

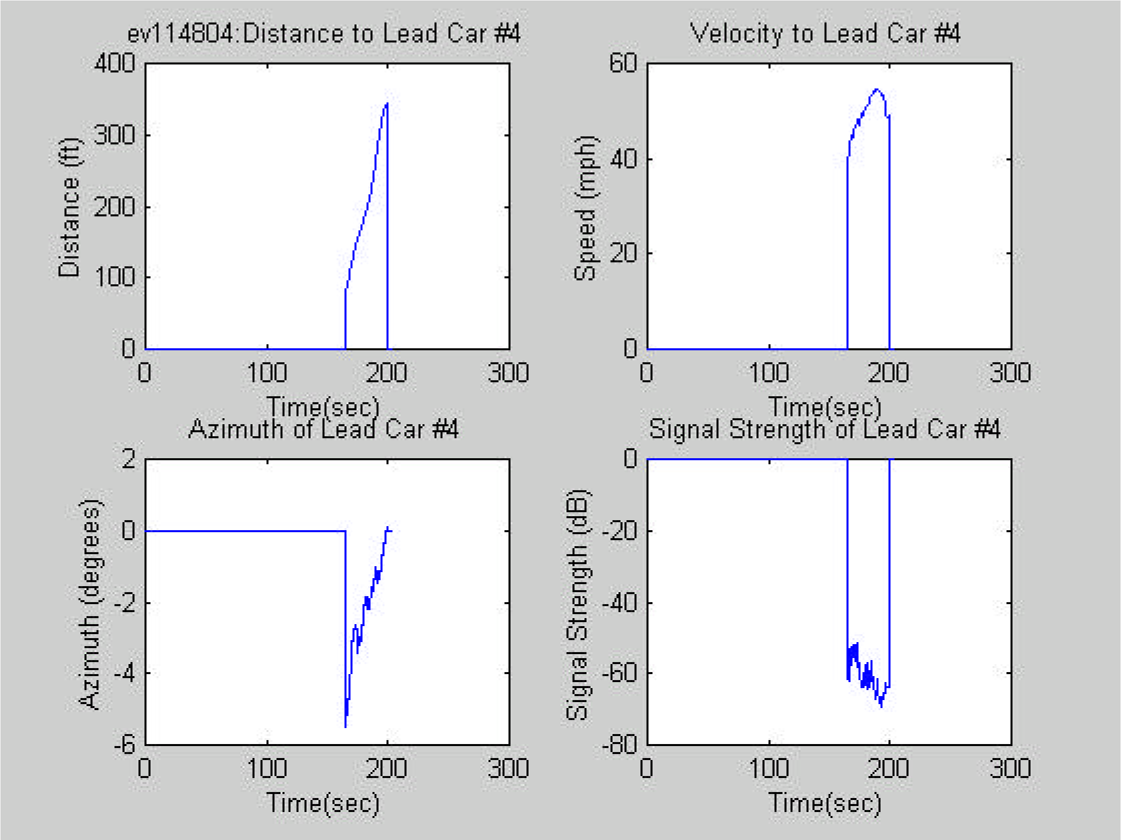


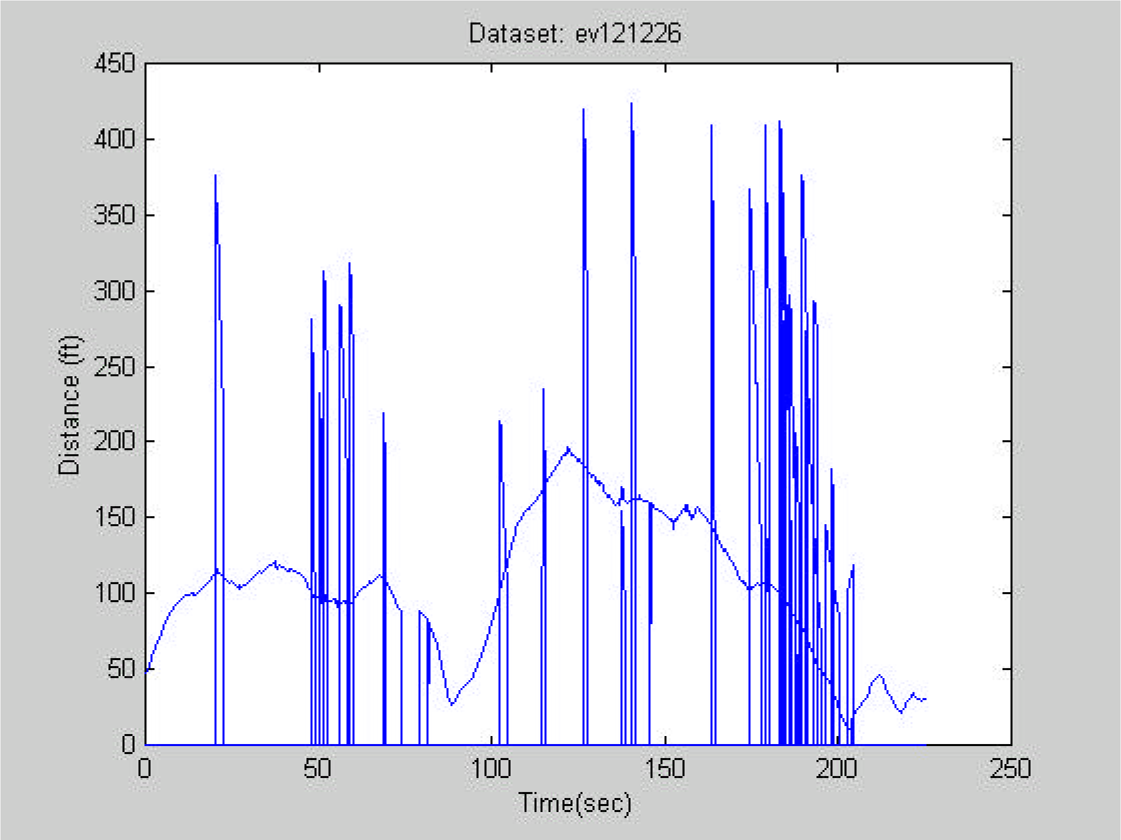
Dataset: ev114804
Distance (ft)
0
50
100
150
200
250
300
350
Time(sec)
0
50
100
150
200
250

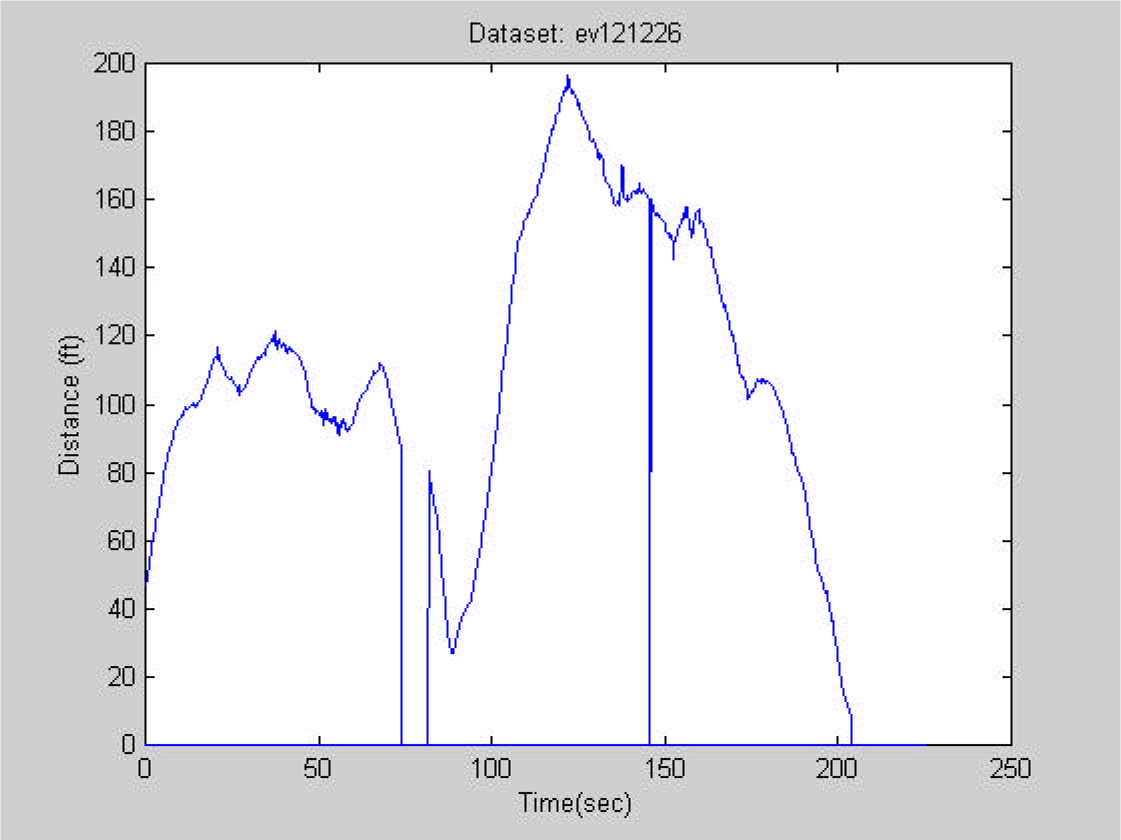

ev114804:Distance to Lead Car #1
Distance (ft)
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
5
0
-5
-10
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

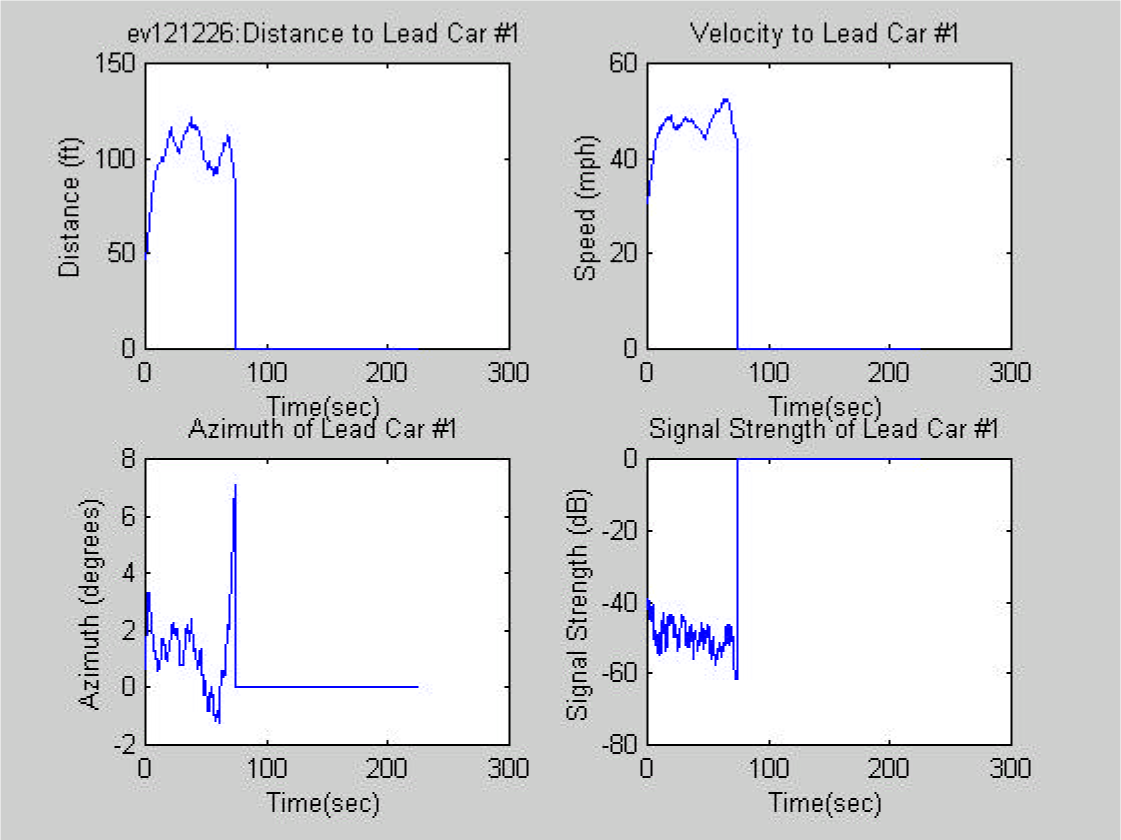

ev114804:Distance to Lead Car #2
Distance (ft)
100
80
60
40
20
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
60
40
20
0
-20
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
5
0
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

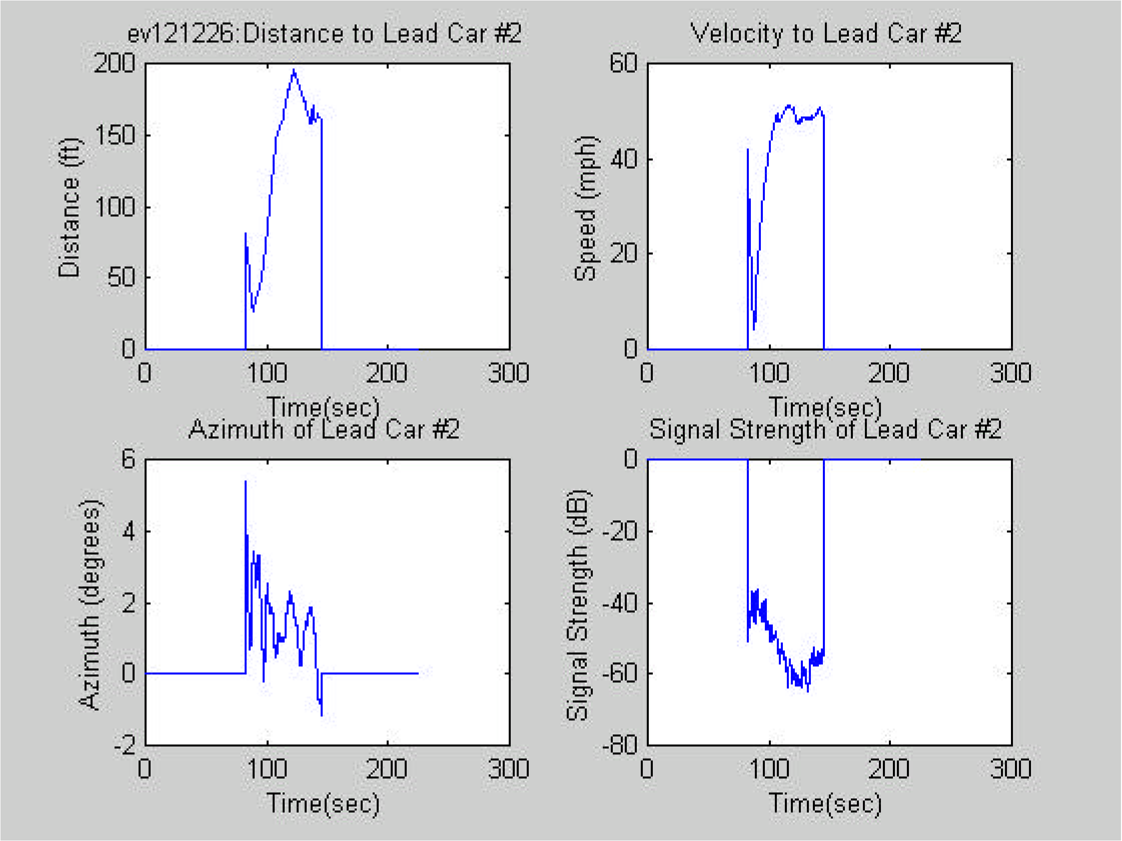

ev114804:Distance to Lead Car #3
Distance (ft)
0
50
100
150
200
Time(sec)
0
100
200
300
Velocity to Lead Car #3
Speed (mph)
0
20
40
60
80
100
Time(sec)
0
100
200
300
Azimuth of Lead Car #3
Azimuth (degrees)
0
1
2
3
4
5
Time(sec)
0
100
200
300
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
-80
Time(sec)
0
100
200
300

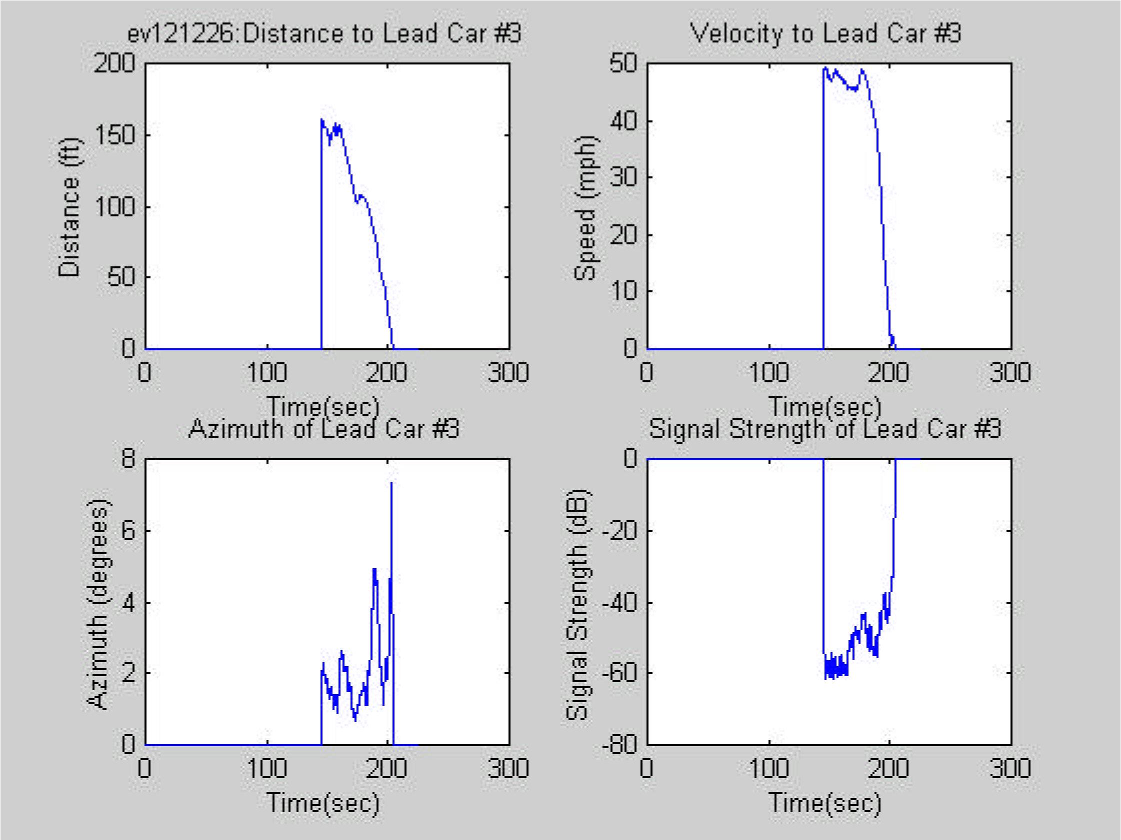

ev114804:Distance to Lead Car #4
Distance (ft)
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #4
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #4
Azimuth (degrees)
2
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #4
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)


Dataset: ev121226
Distance (ft)
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Time(sec)

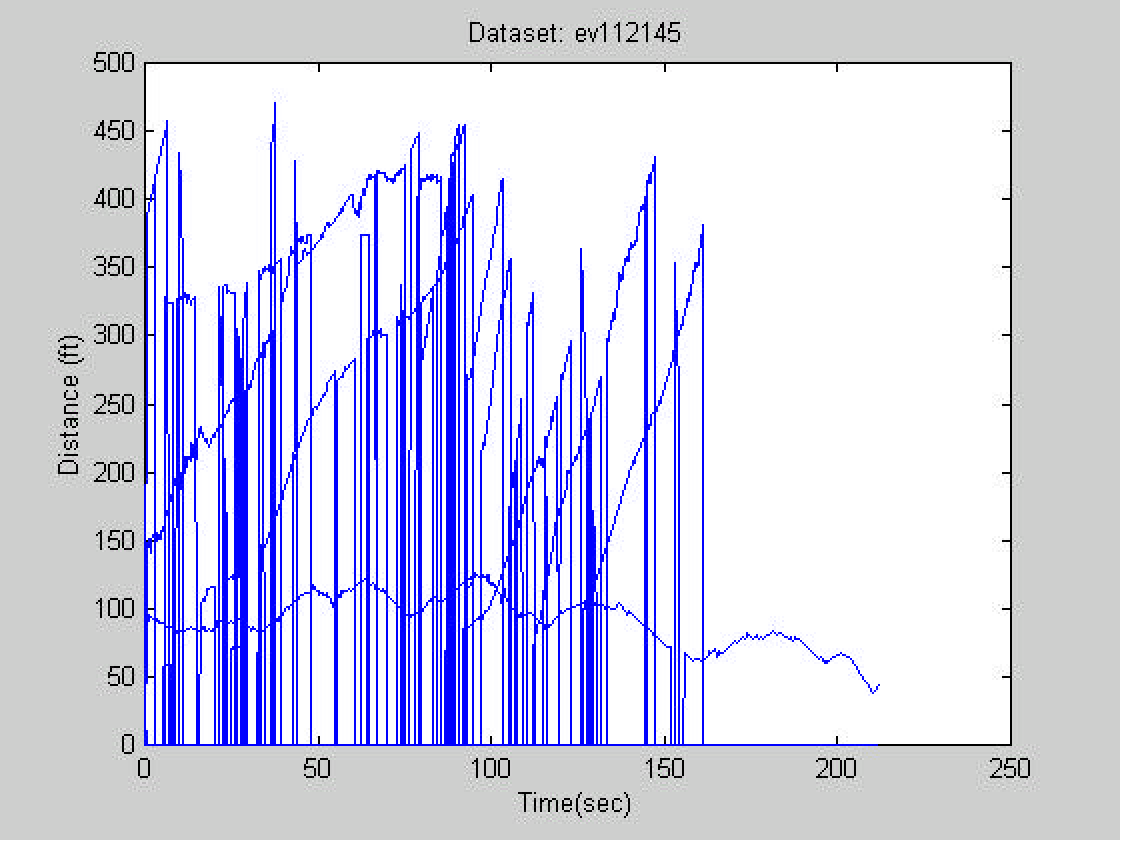

Dataset: ev121226
Distance (ft)
Time(sec)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250

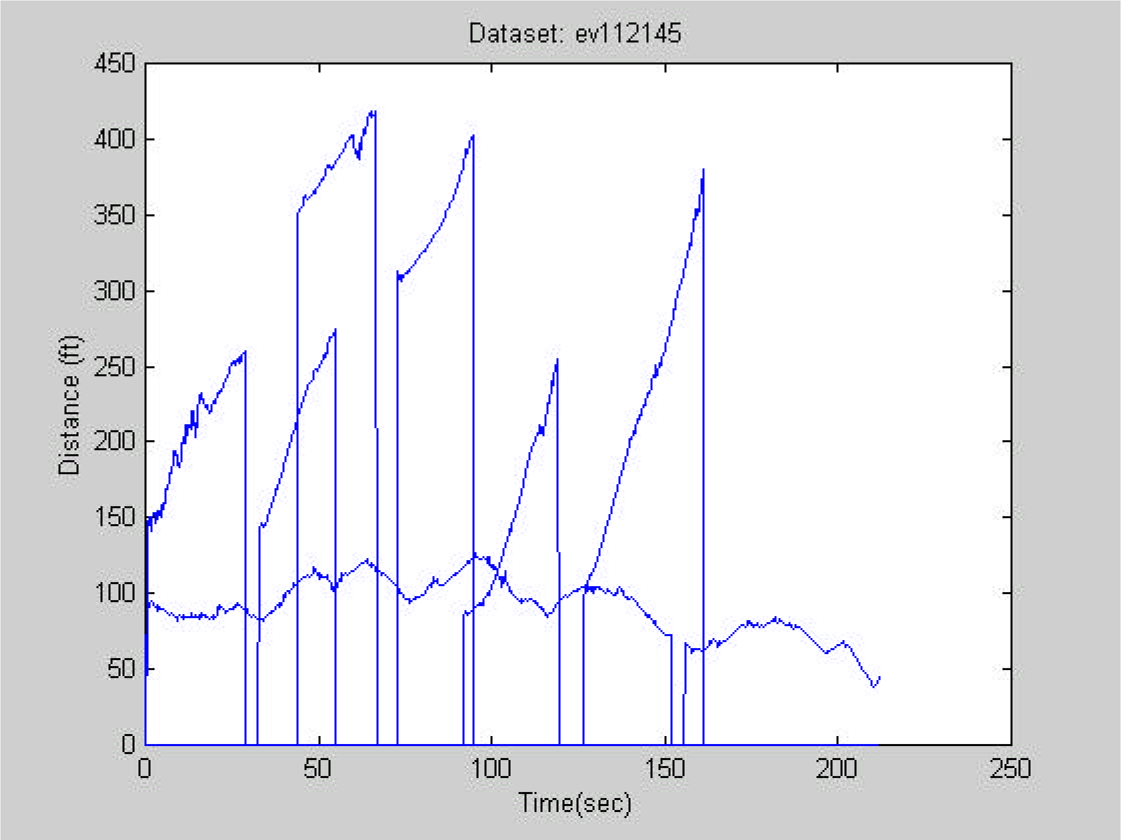

ev121226:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
8
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

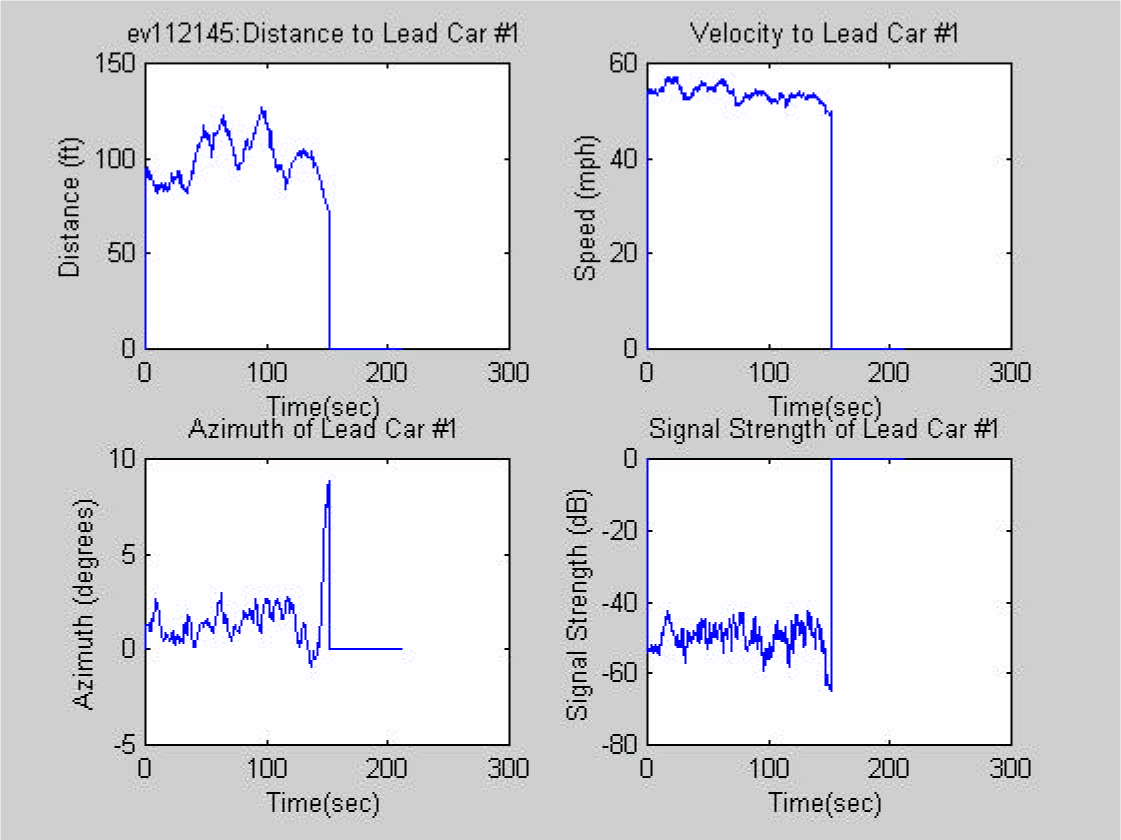

ev121226:Distance to Lead Car #2
Distance (ft)
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

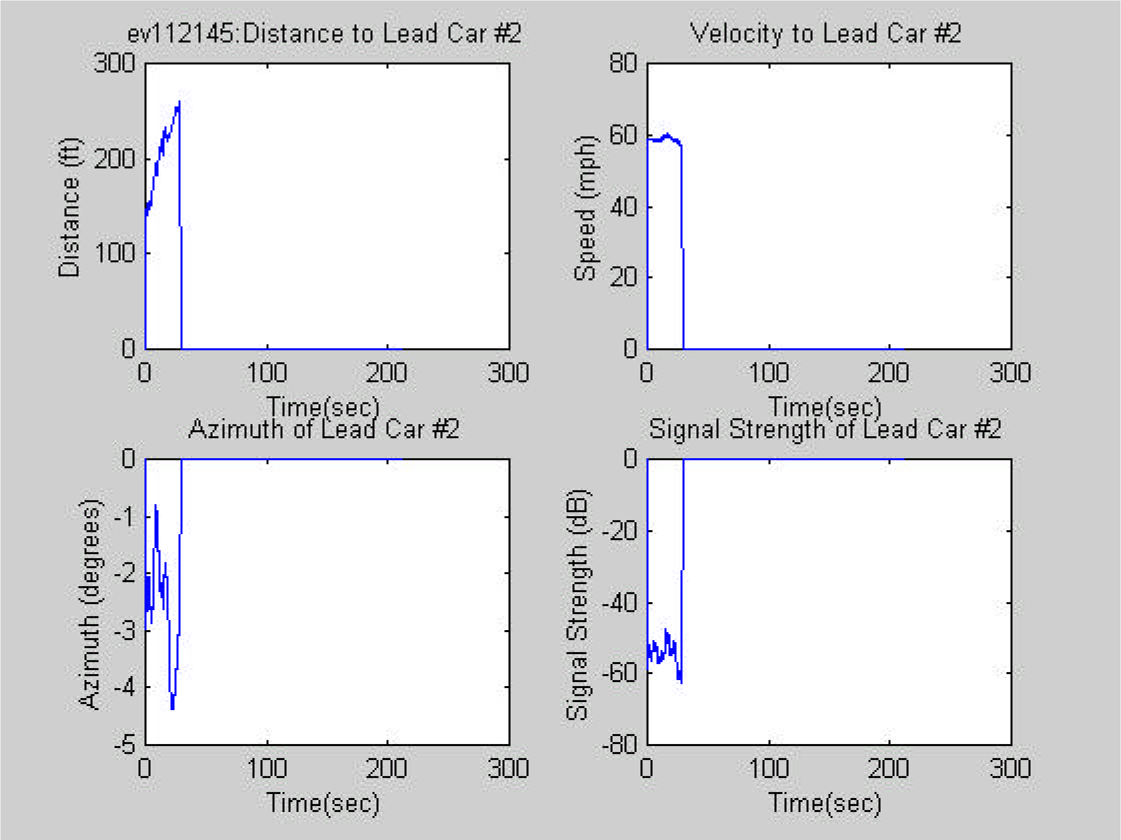


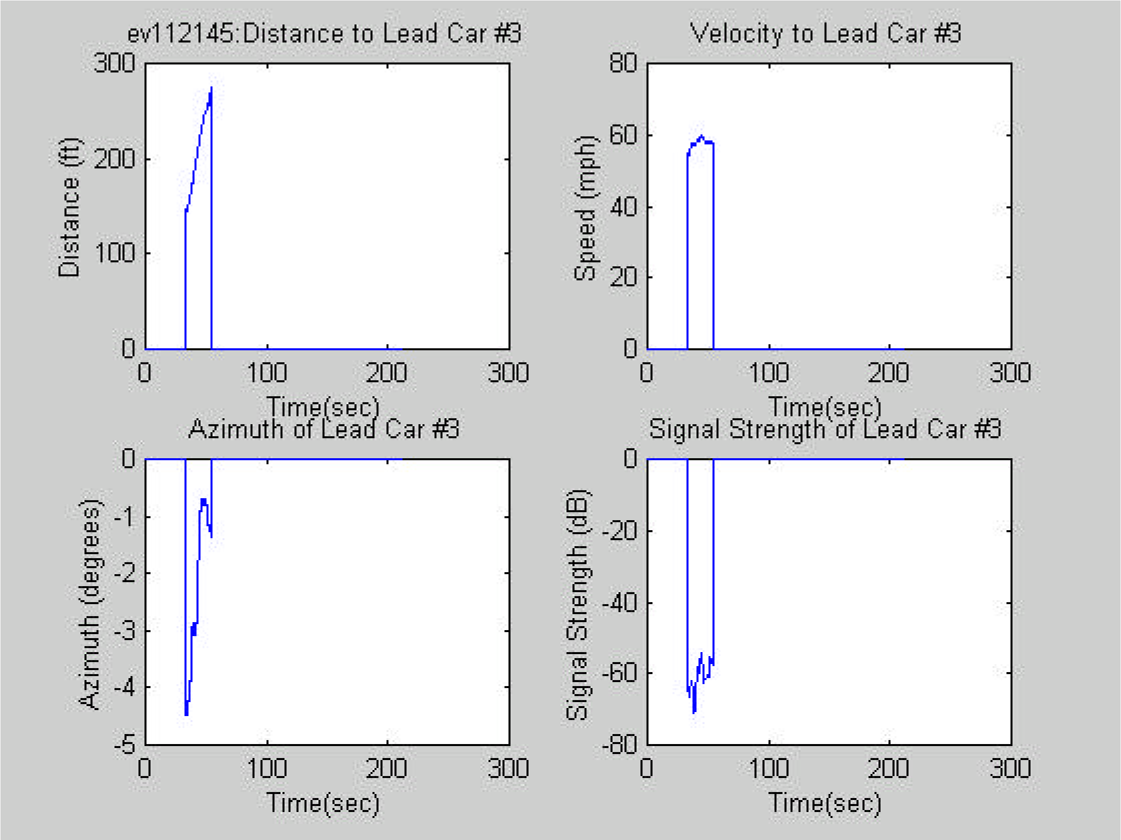
ev121226:Distance to Lead Car #3
Distance (ft)
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #3
Speed (mph)
50
40
30
20
10
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
8
6
4
2
0
0
100
200
300
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

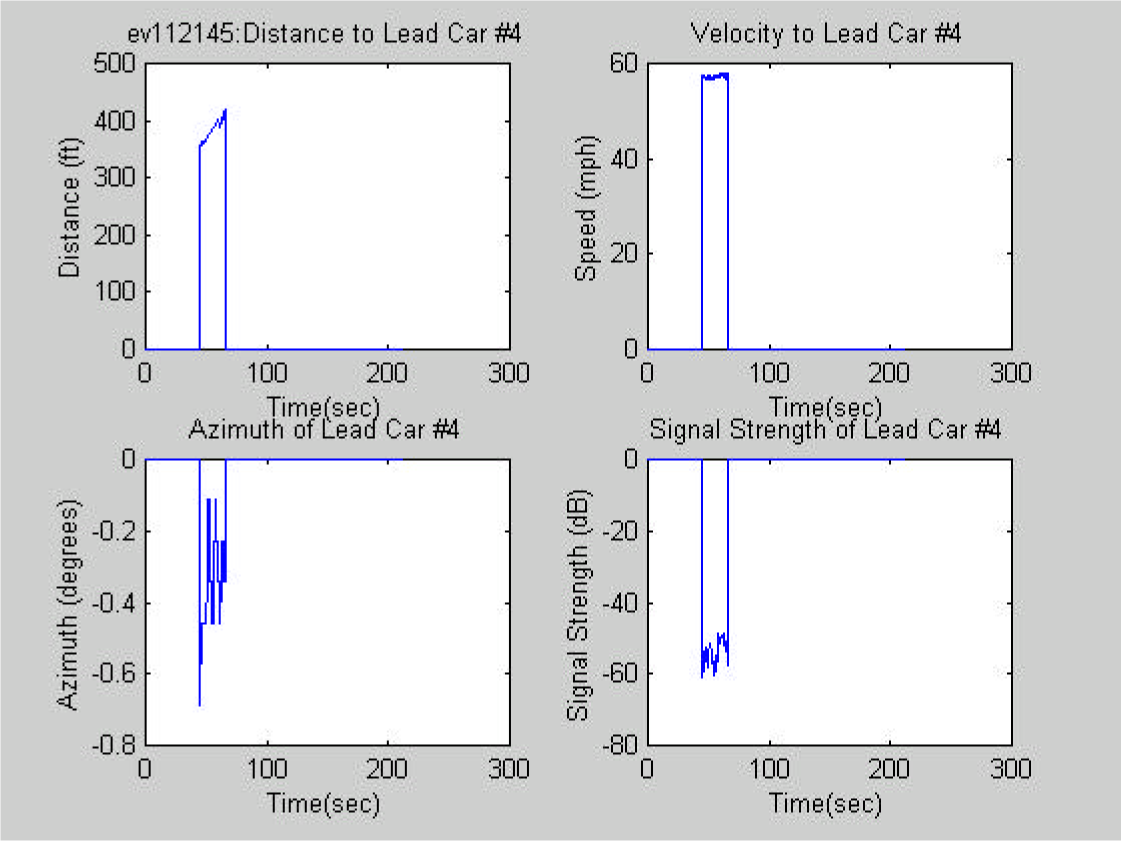

Dataset: ev112145
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250

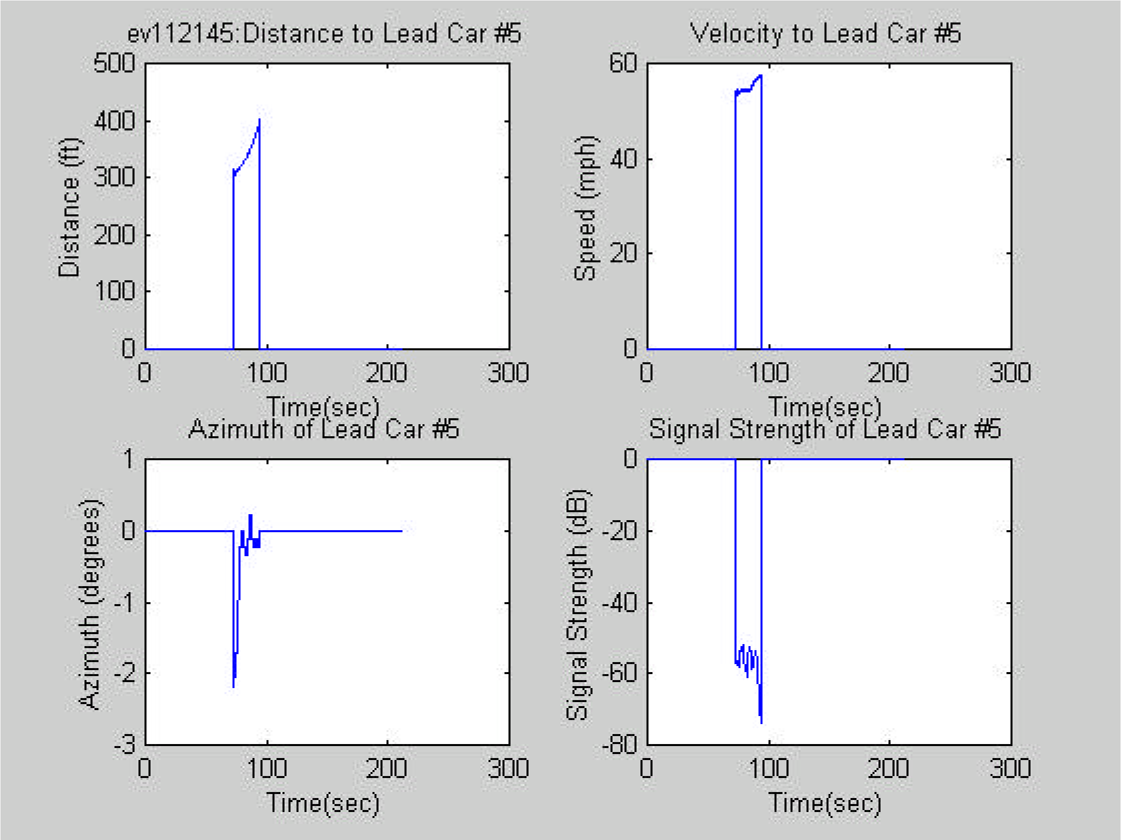

Dataset: ev112145
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
400
450
0
50
100
150
200
250

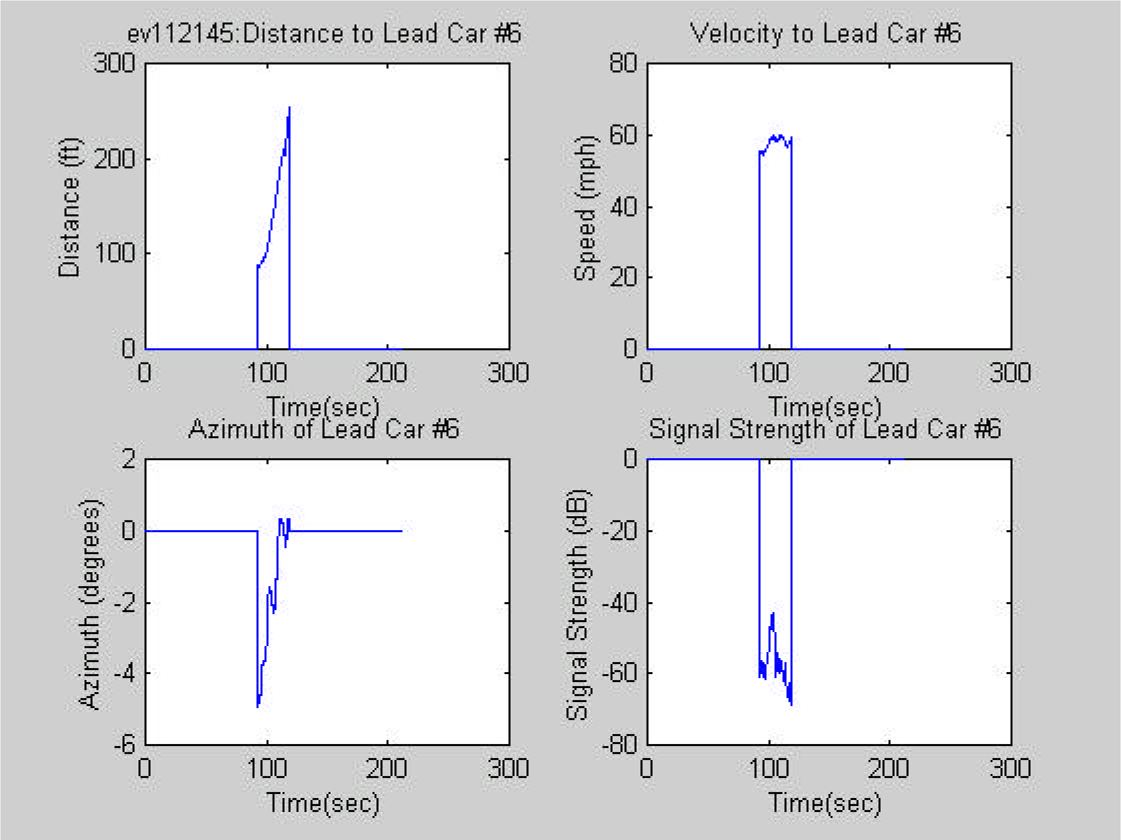

ev112145:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
10
5
0
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

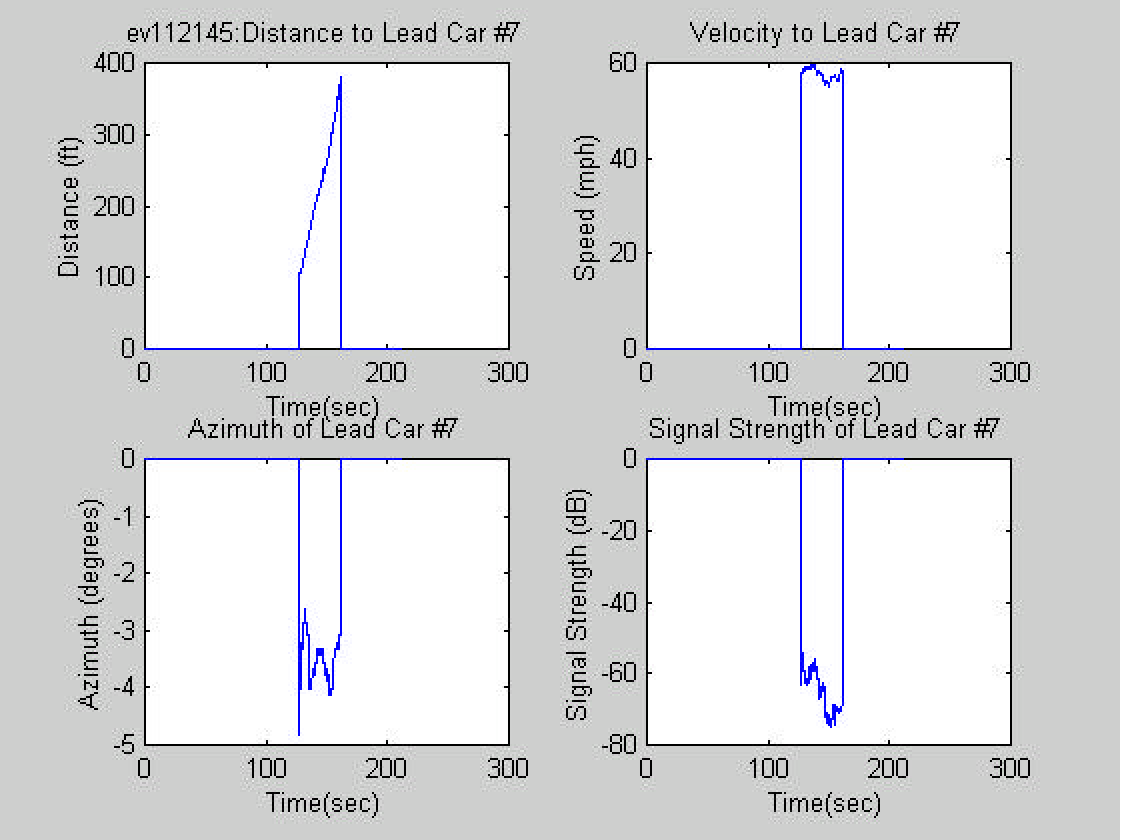

ev112145:Distance to Lead Car #2
Distance (ft)
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
0
-1
-2
-3
-4
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

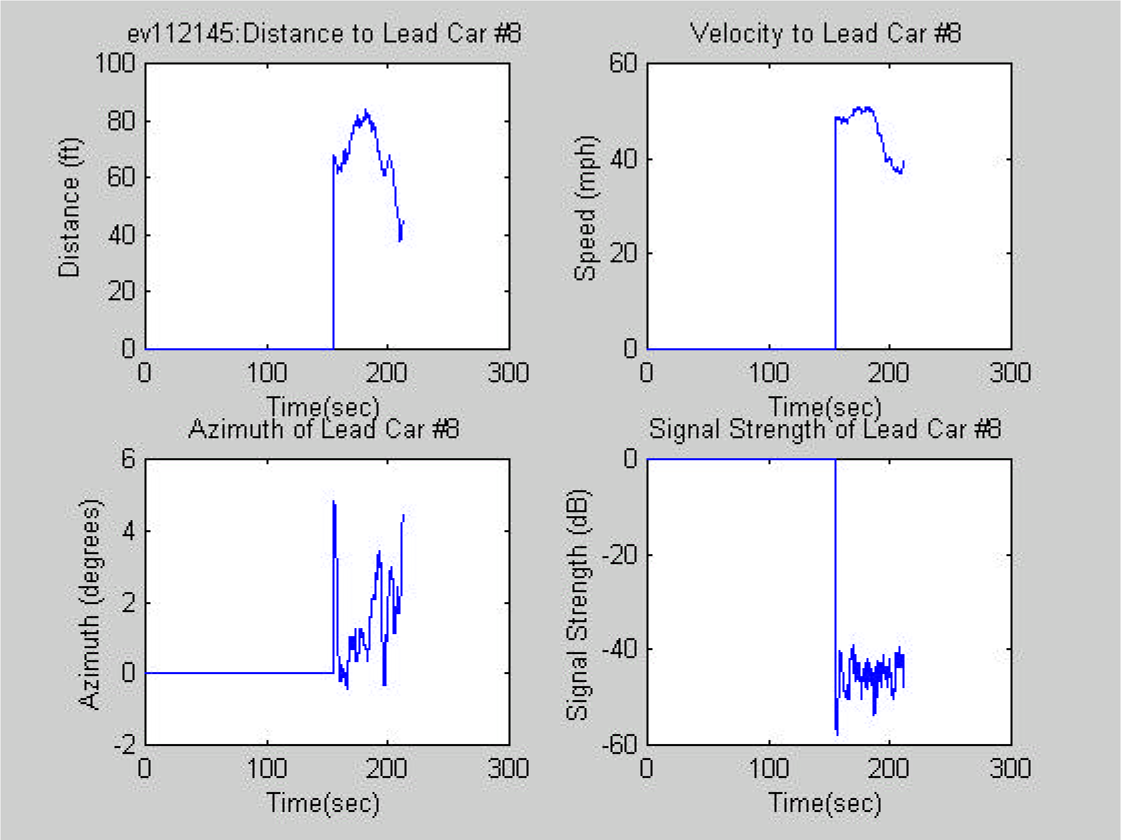

ev112145:Distance to Lead Car #3
Distance (ft)
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #3
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
0
-1
-2
-3
-4
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

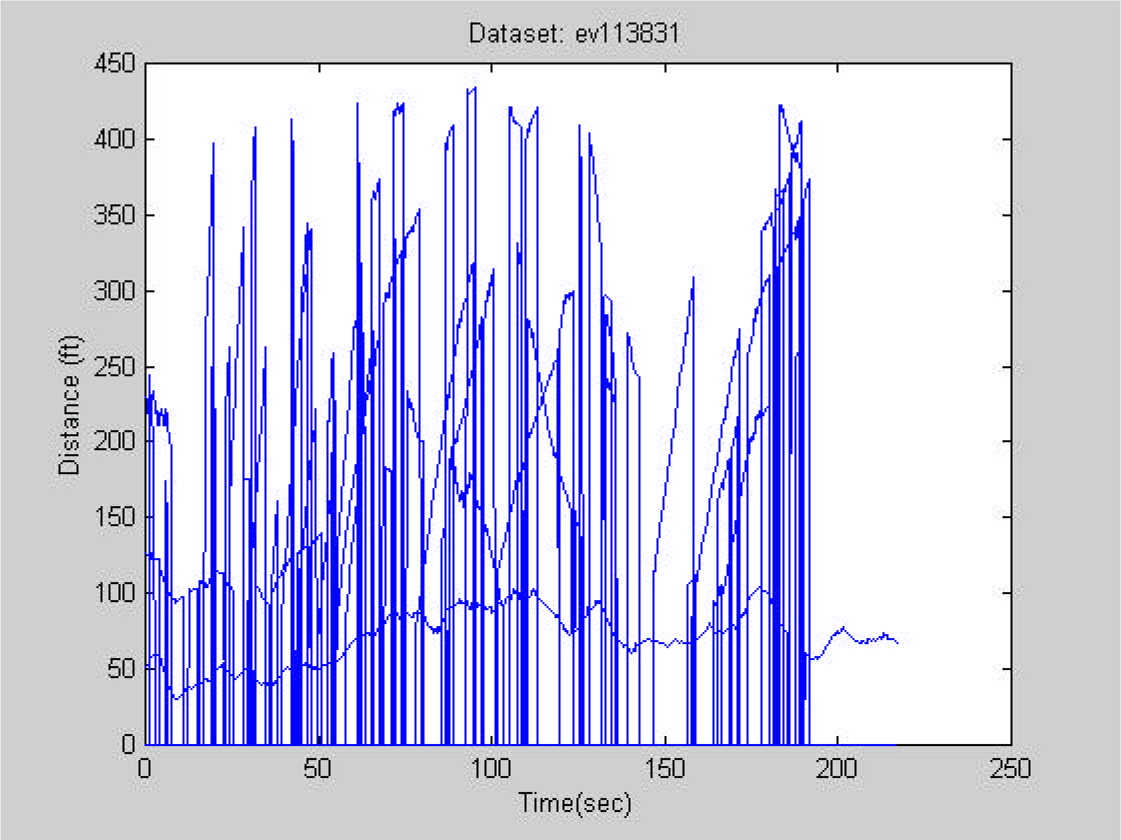

ev112145:Distance to Lead Car #4
Distance (ft)
500
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #4
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #4
Azimuth (degrees)
0
-0.2
-0.4
-0.6
-0.8
0
100
200
300
Time(sec)
Signal Strength of Lead Car #4
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

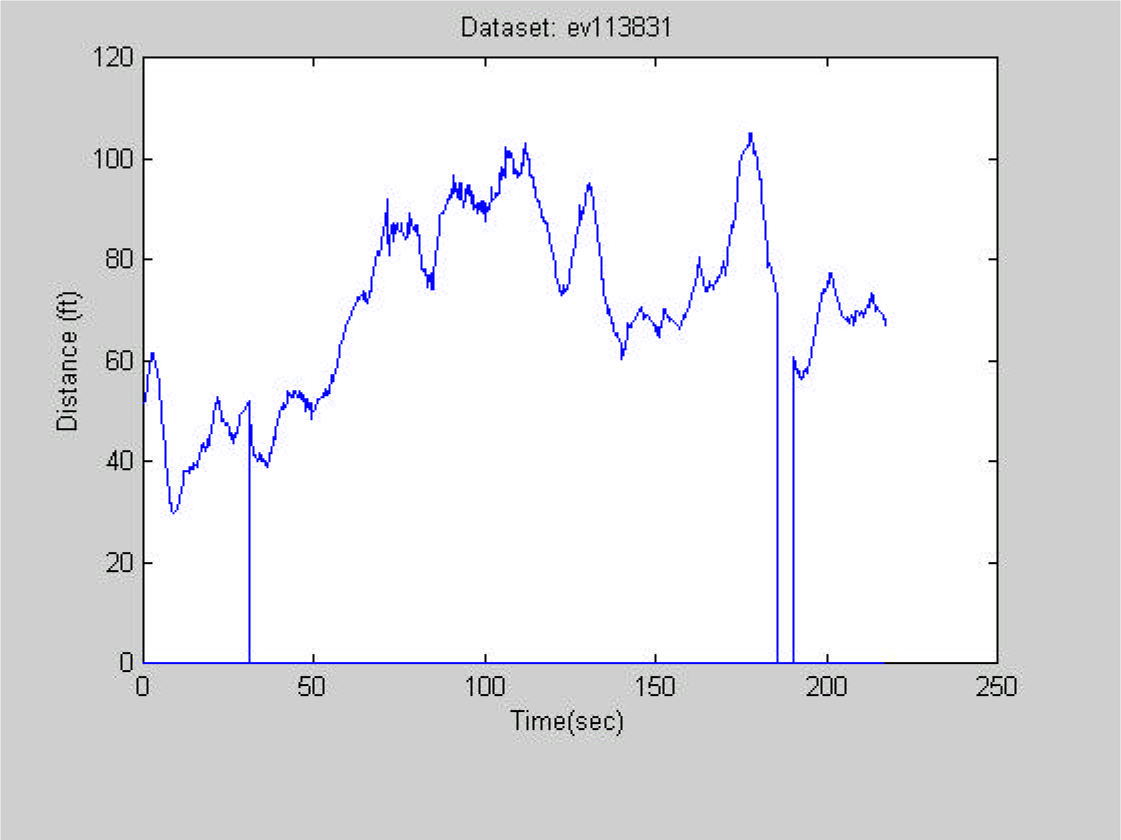

ev112145:Distance to Lead Car #5
Distance (ft)
500
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #5
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #5
Azimuth (degrees)
1
0
-1
-2
-3
0
100
200
300
Time(sec)
Signal Strength of Lead Car #5
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

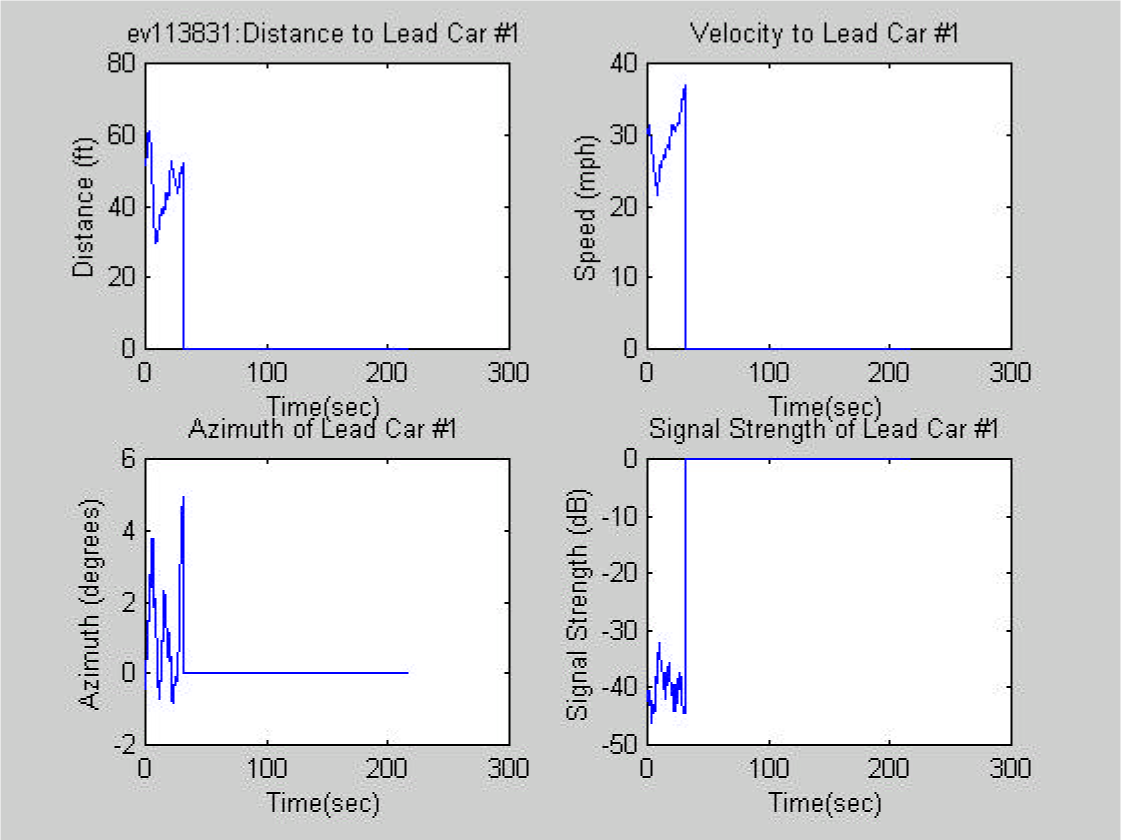

ev112145:Distance to Lead Car #6
Distance (ft)
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #6
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #6
Azimuth (degrees)
2
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #6
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

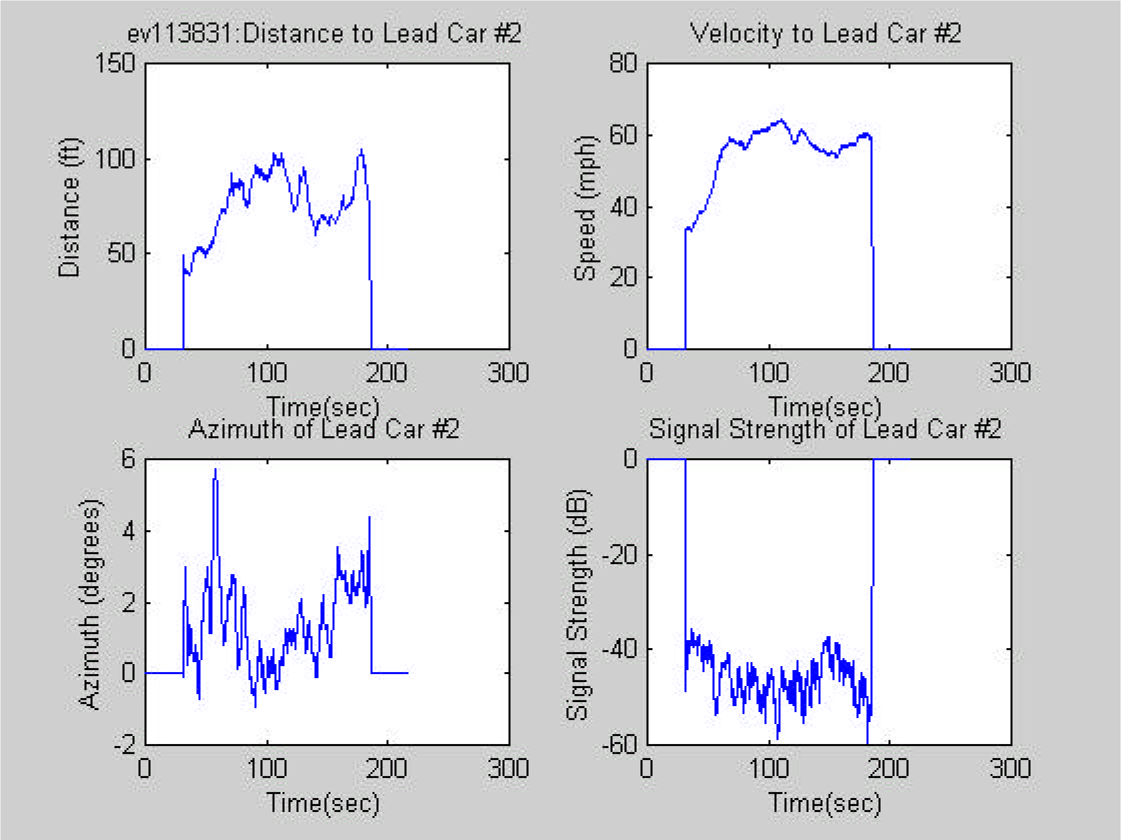

ev112145:Distance to Lead Car #7
Distance (ft)
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #7
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #7
Azimuth (degrees)
0
-1
-2
-3
-4
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #7
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

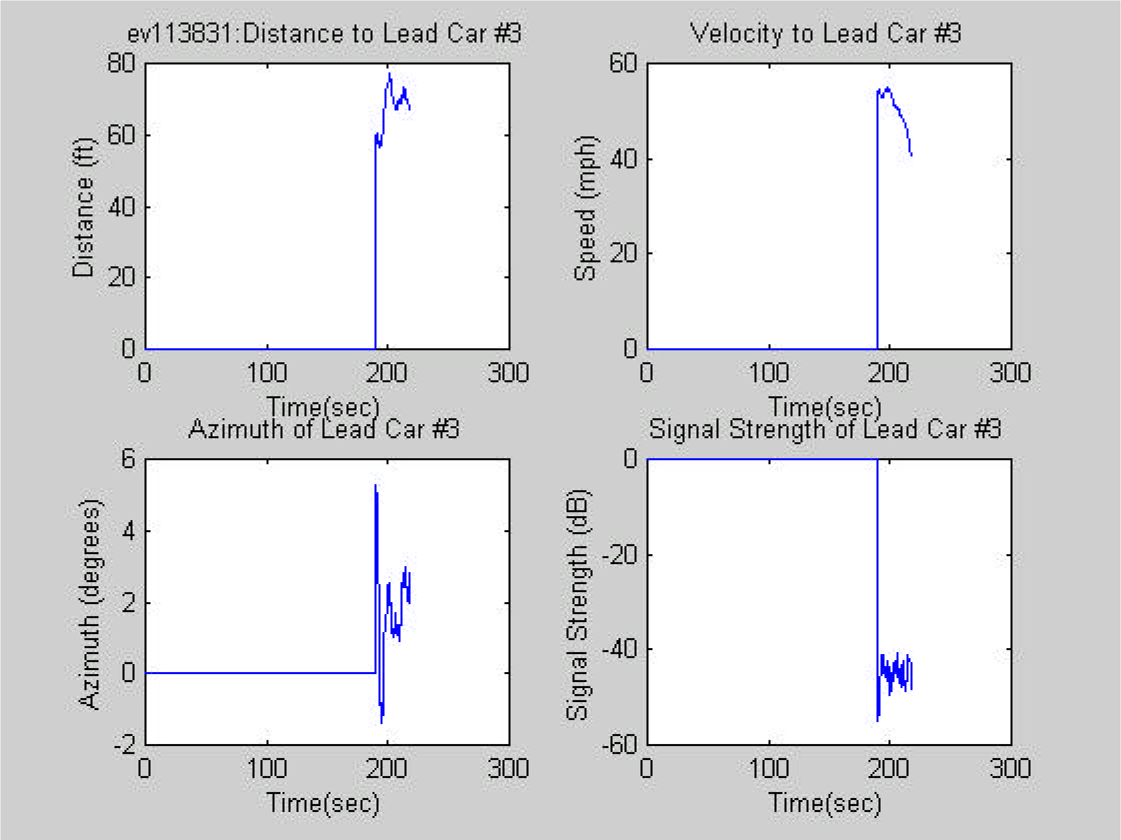

ev112145:Distance to Lead Car #8
Distance (ft)
100
80
60
40
20
0
0
100
200
300
Time(sec)
Velocity to Lead Car #8
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #8
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #8
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

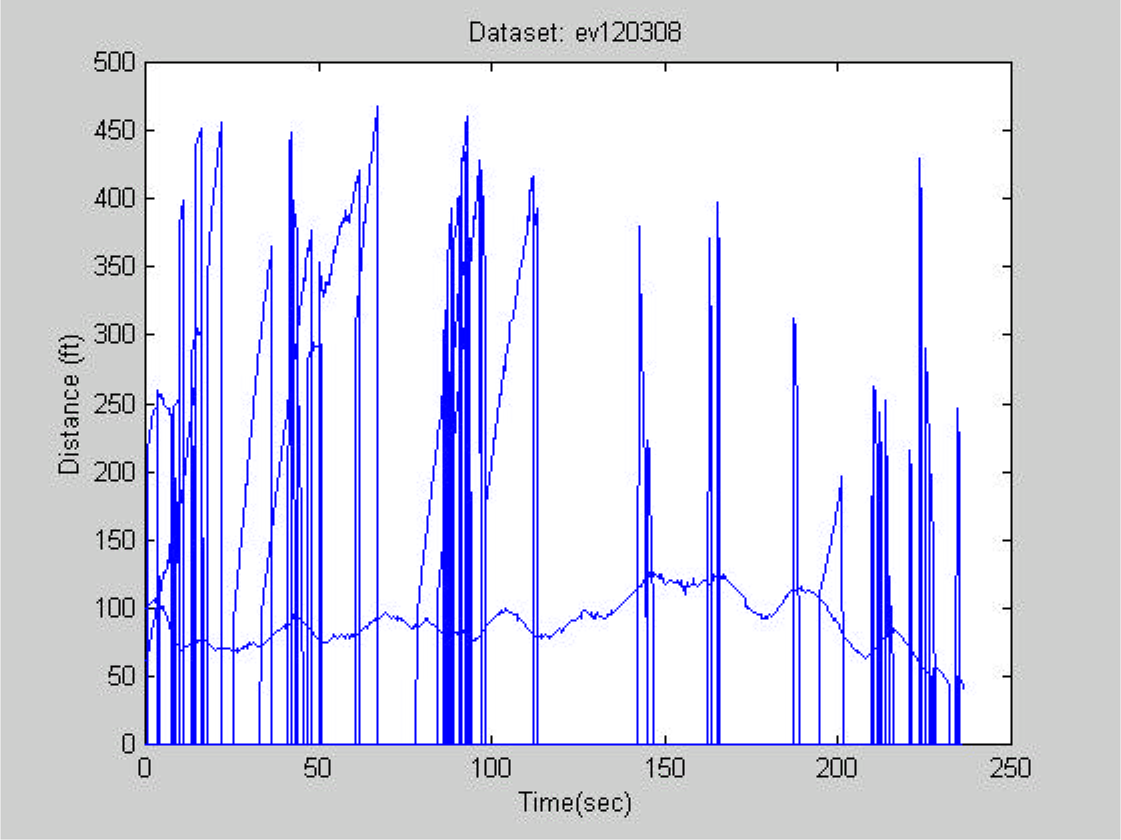

Dataset: ev113831
Distance (ft)
0
50
100
150
200
250
300
350
400
450
Time(sec)
0
50
100
150
200
250

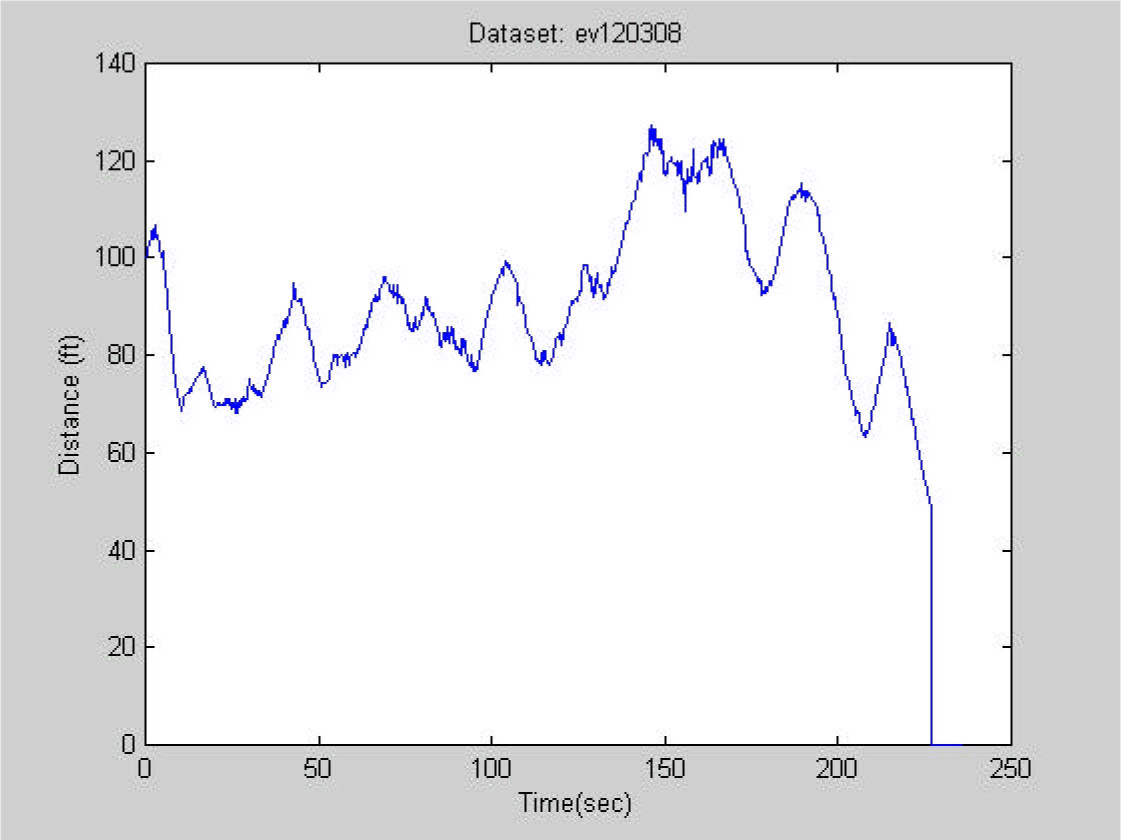

Dataset: ev113831
120
100
80
60
40
20
0
Distance (ft)
0
50
100
150
200
250
Time(sec)

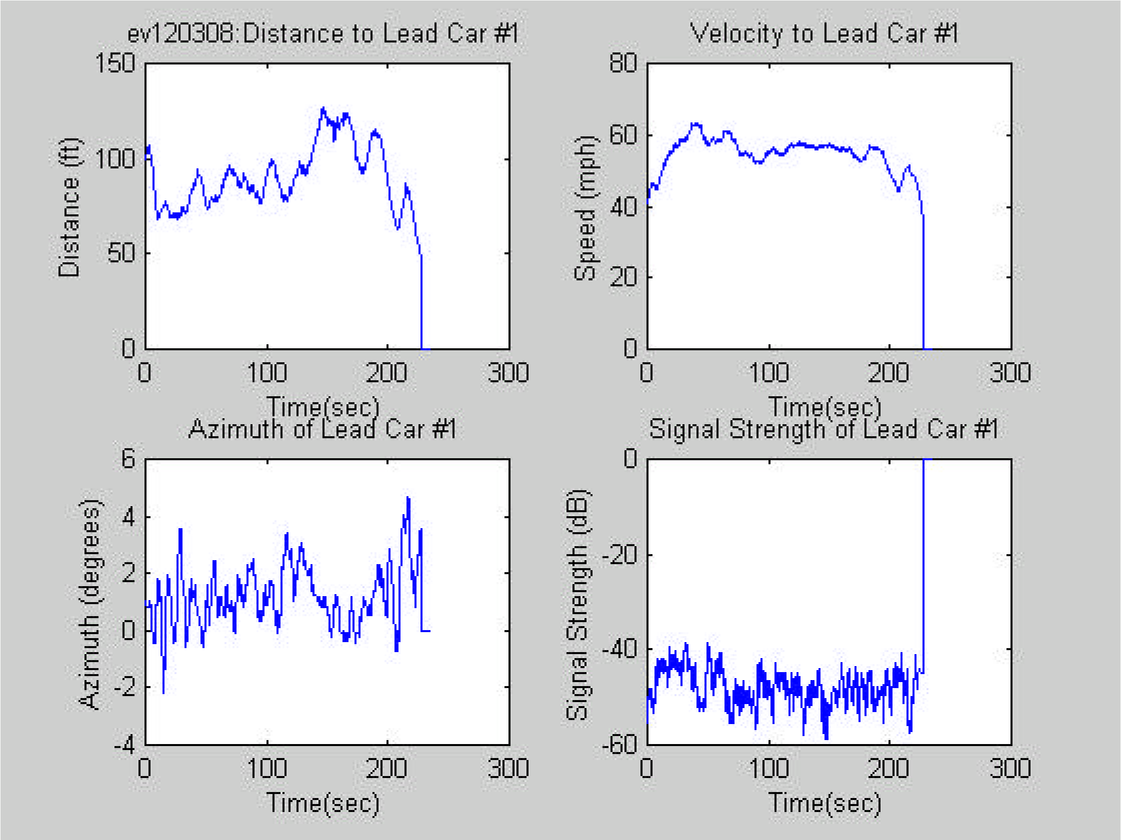

ev113831:Distance to Lead Car #1
Distance (ft)
80
60
40
20
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
40
30
20
10
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-10
-20
-30
-40
-50
0
100
200
300
Time(sec)

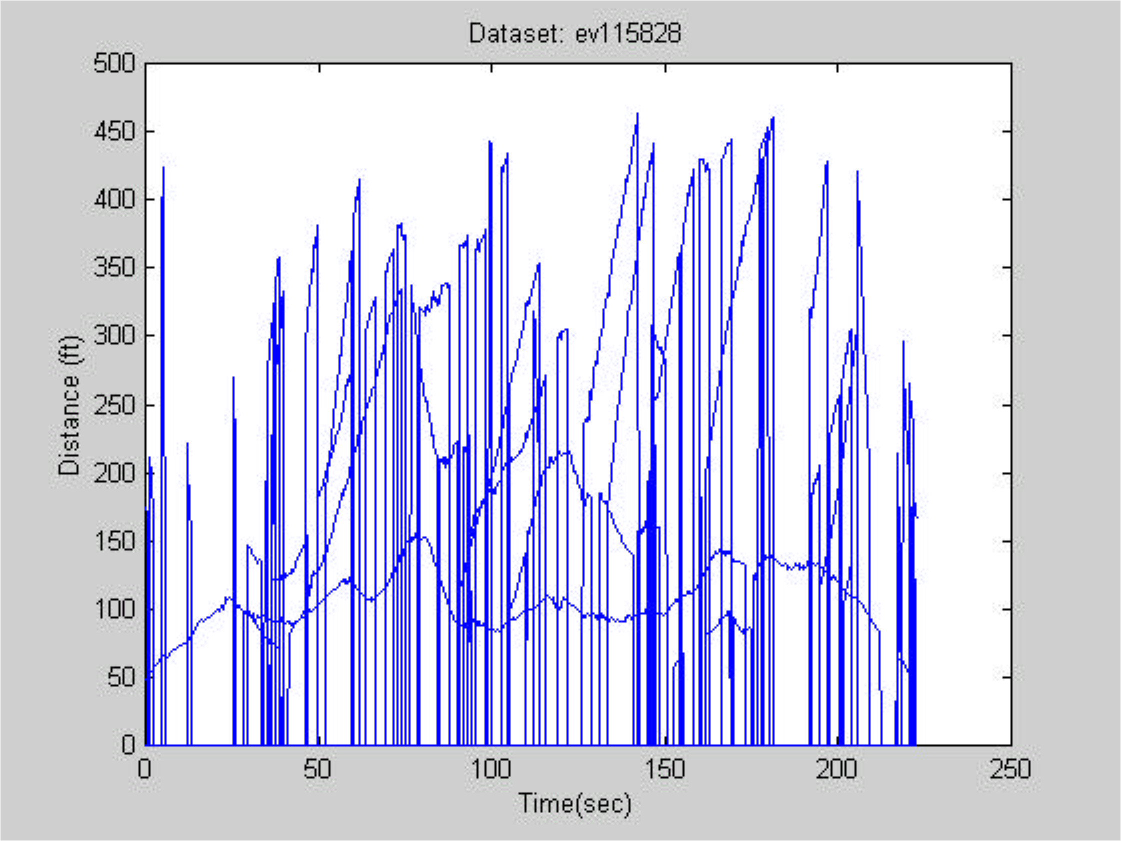

ev113831:Distance to Lead Car #2
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

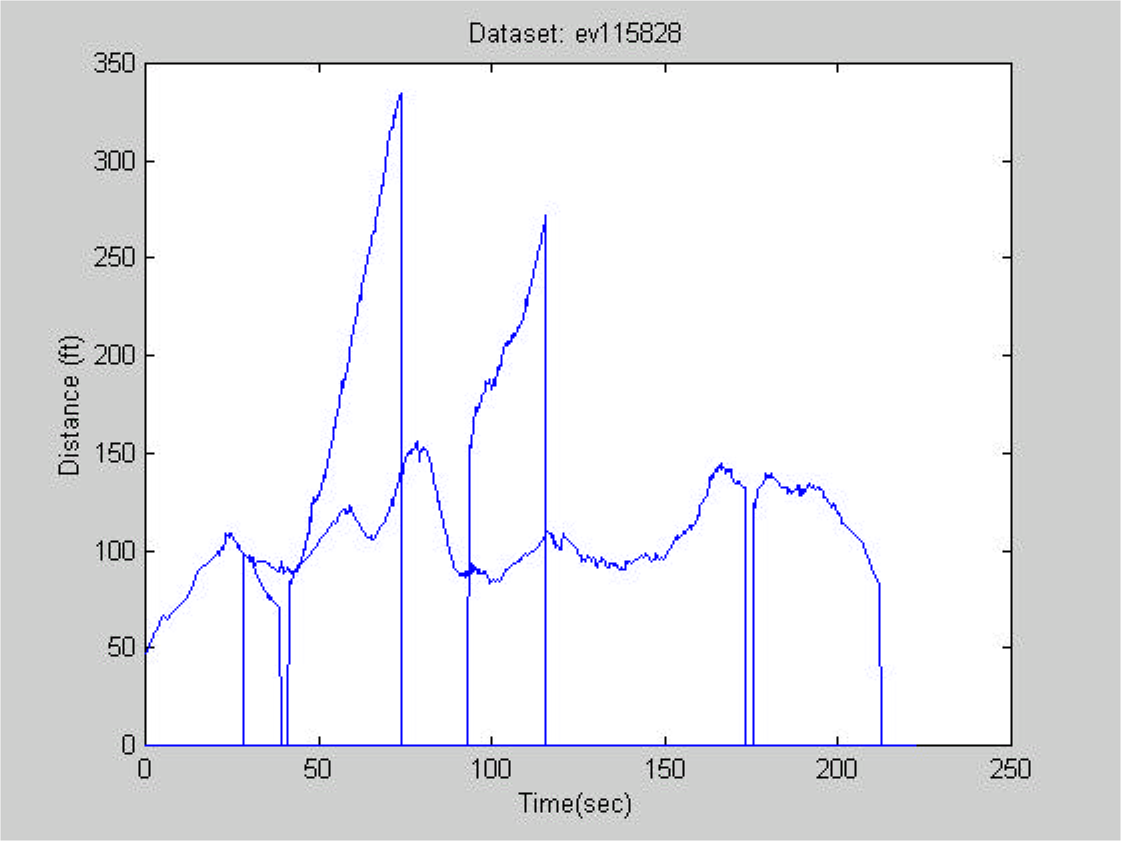

ev113831:Distance to Lead Car #3
Distance (ft)
80
60
40
20
0
0
100
200
300
Time(sec)
Velocity to Lead Car #3
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

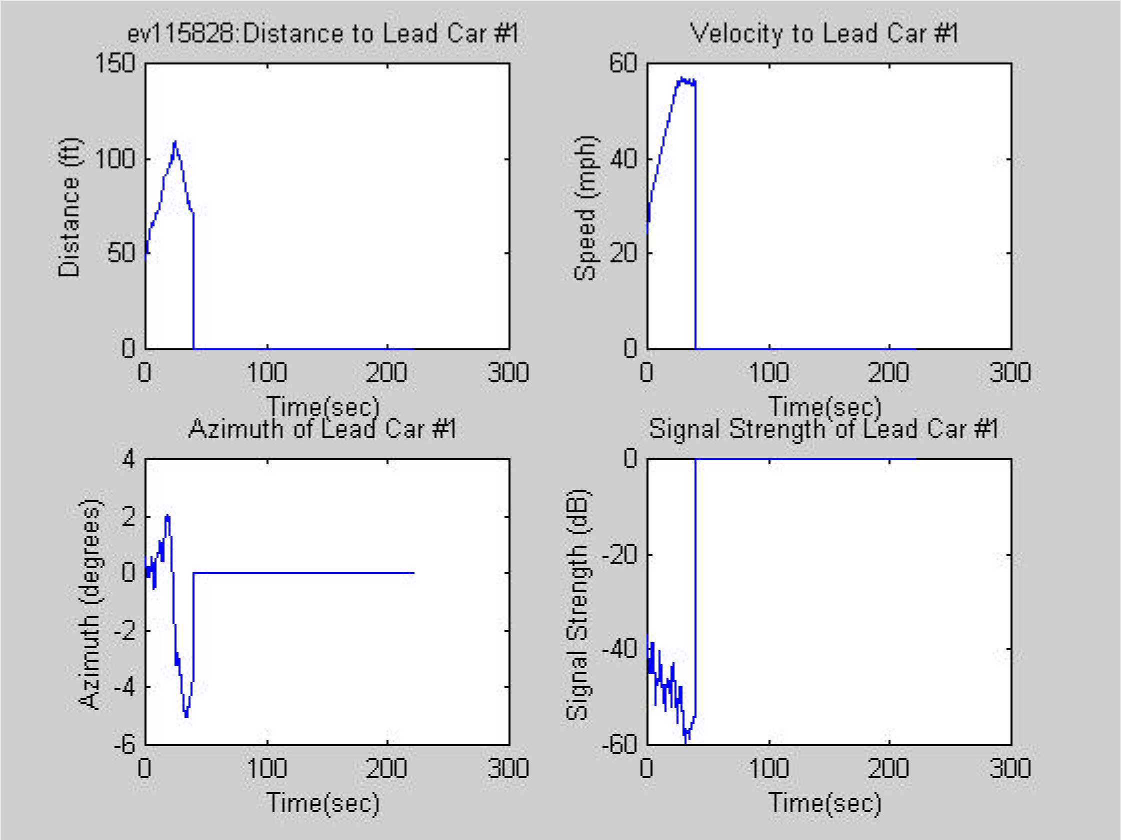

Dataset: ev120308
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250

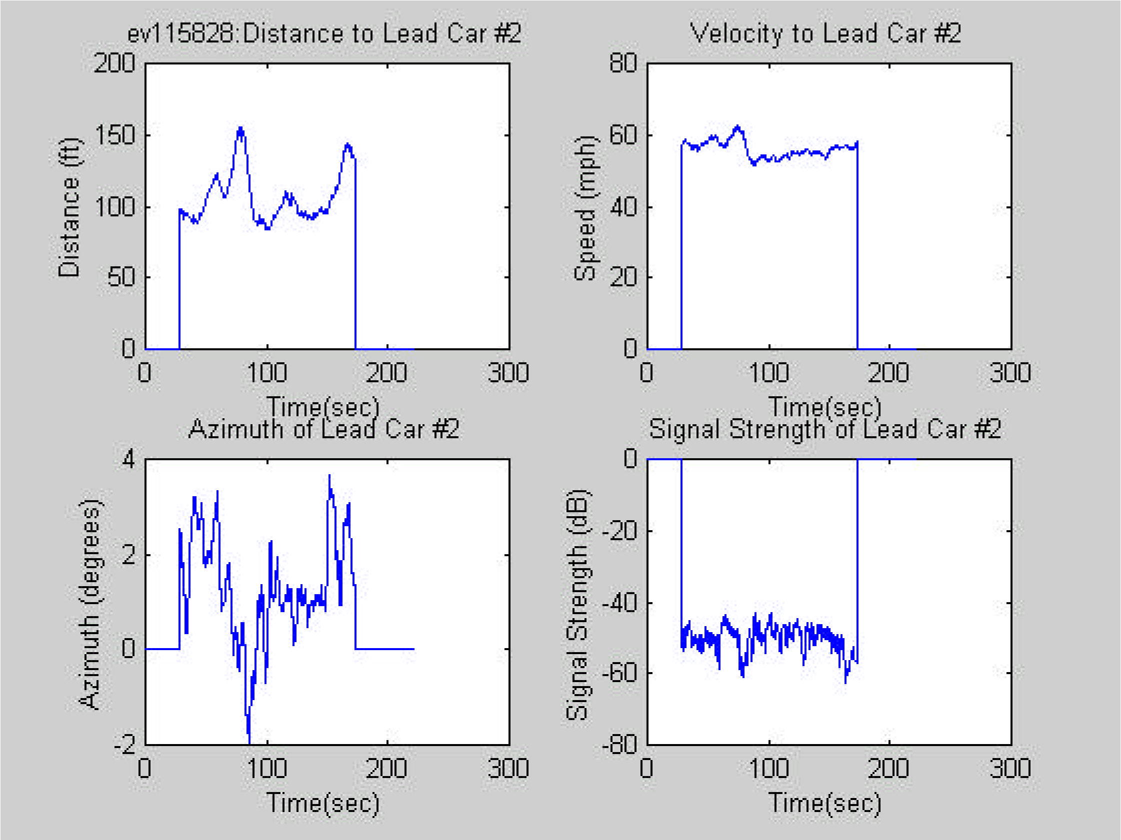

Dataset: ev120308
Distance (ft)
Time(sec)
0
20
40
60
80
100
120
140
0
50
100
150
200
250

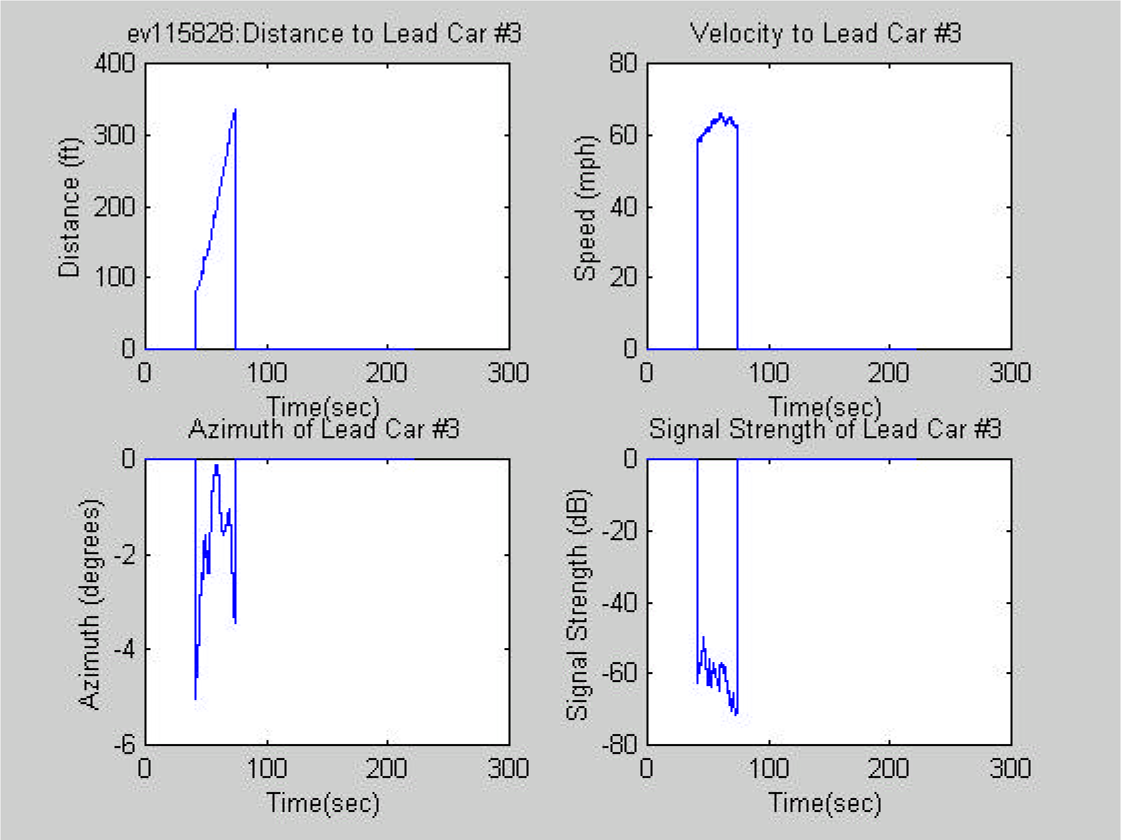

ev120308:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
6
4
2
0
-2
-4
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)


Dataset: ev115828
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250

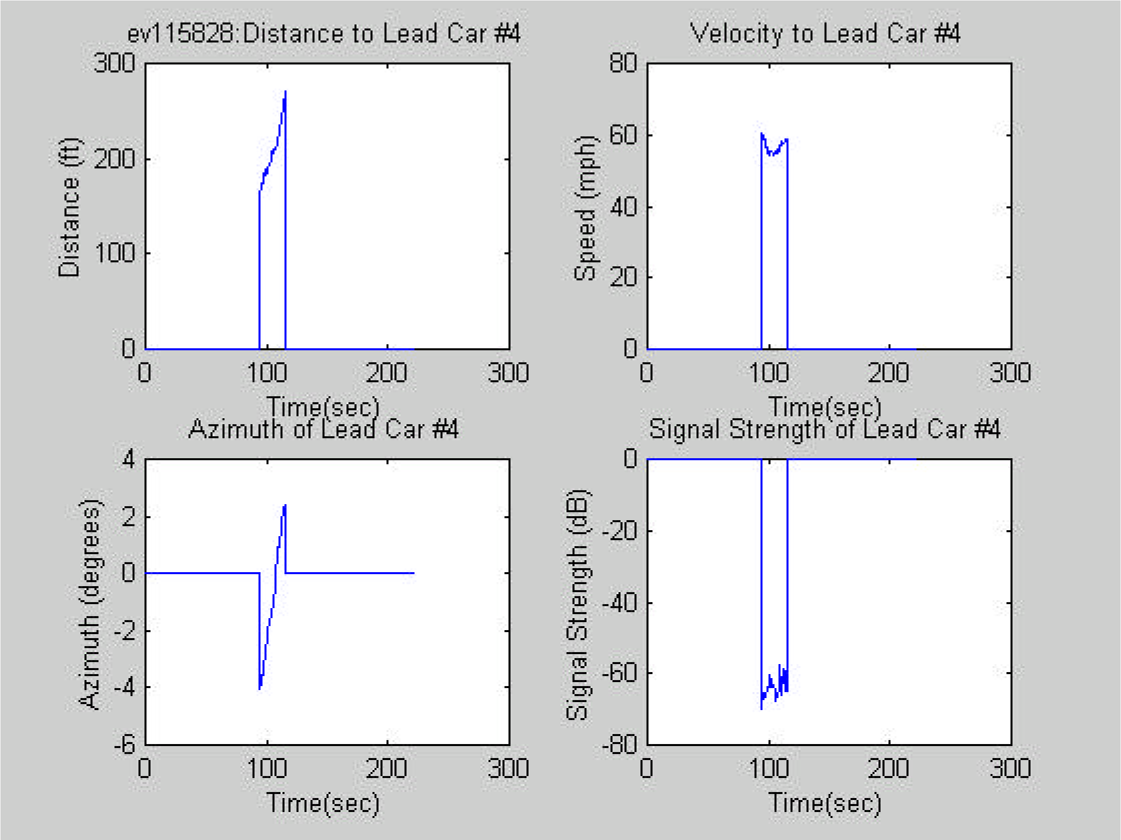

Dataset: ev115828
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
0
50
100
150
200
250

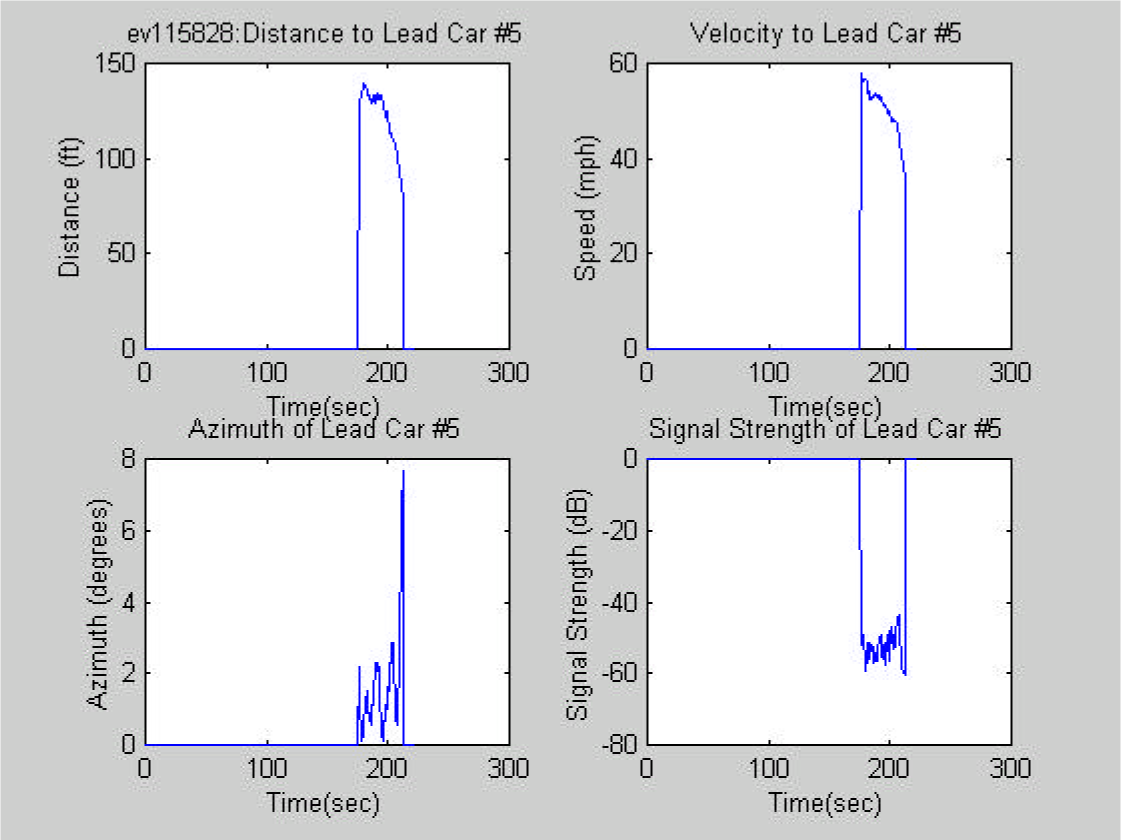

ev115828:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
4
2
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

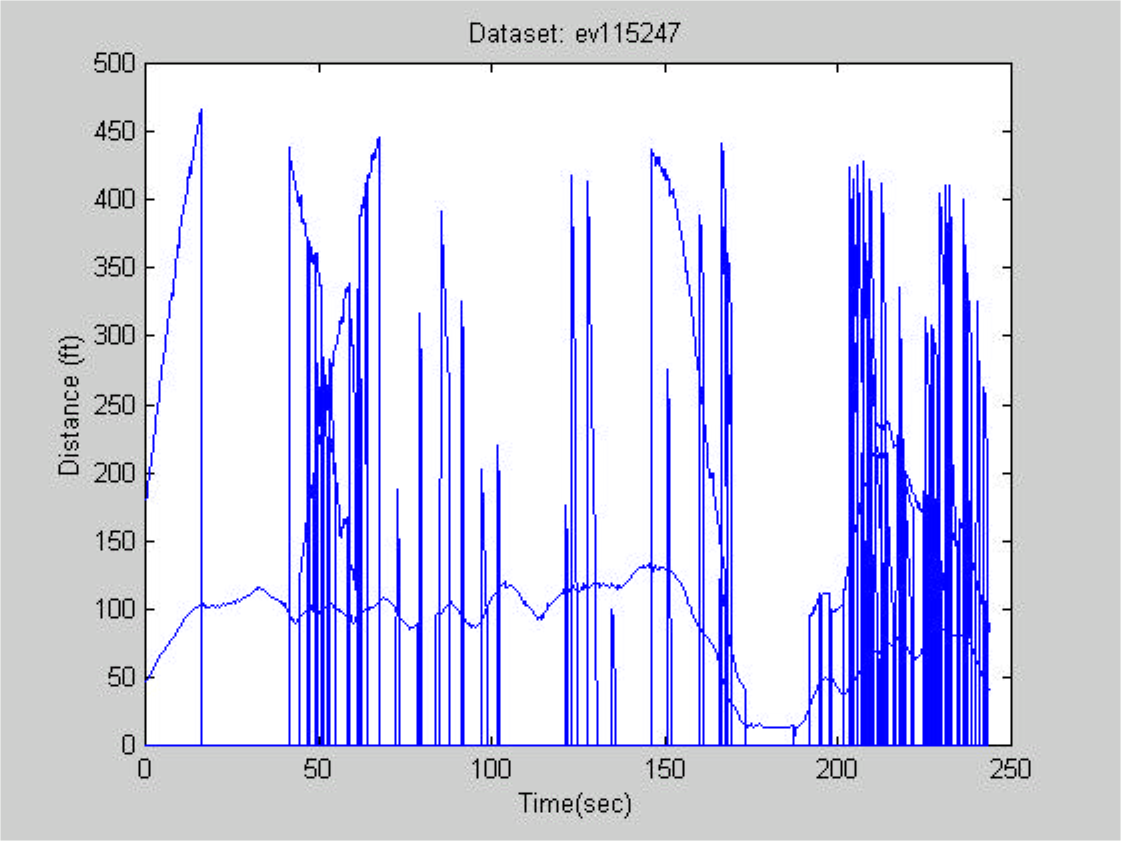

ev115828:Distance to Lead Car #2
Distance (ft)
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

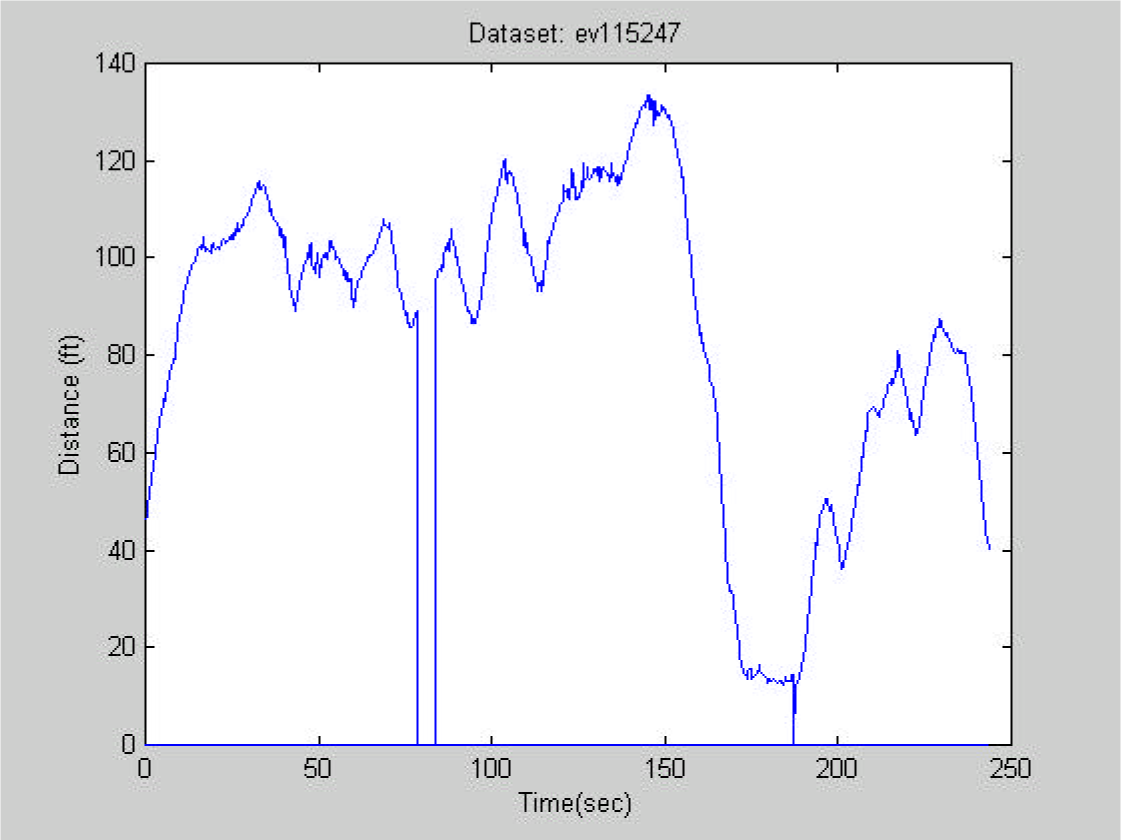


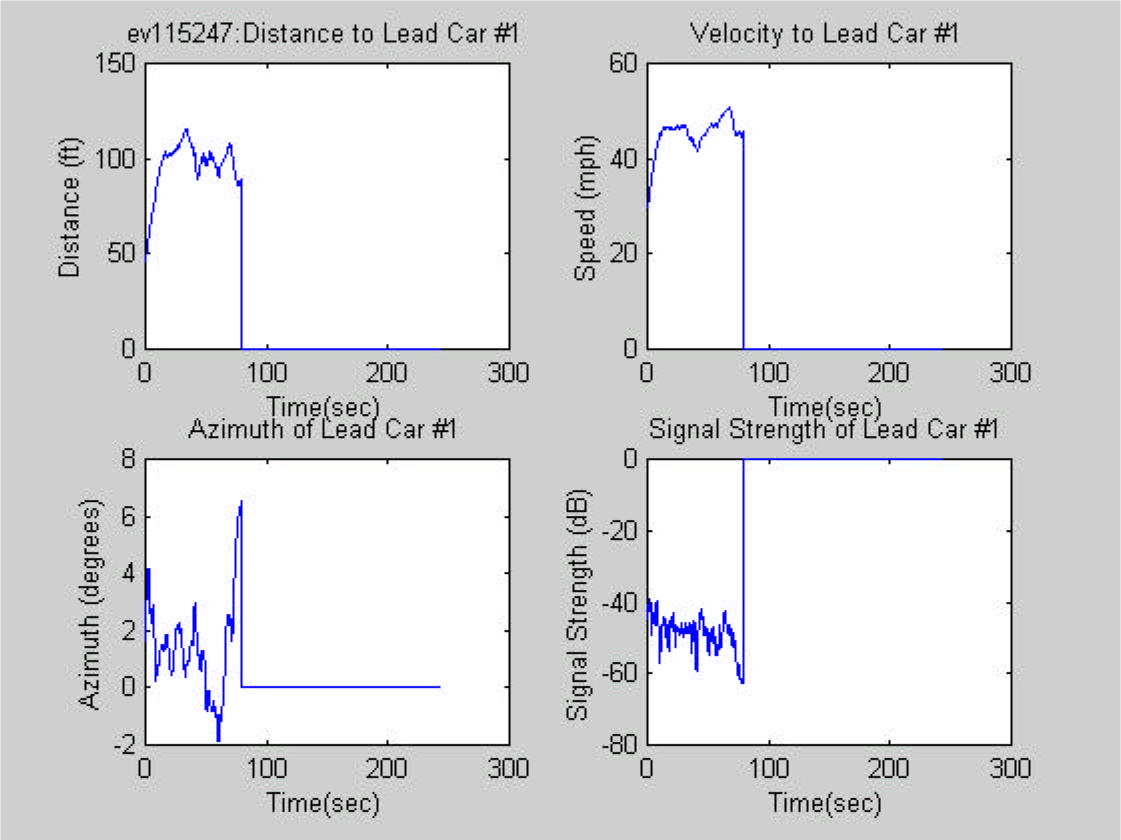
ev115828:Distance to Lead Car #3
Distance (ft)
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #3
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

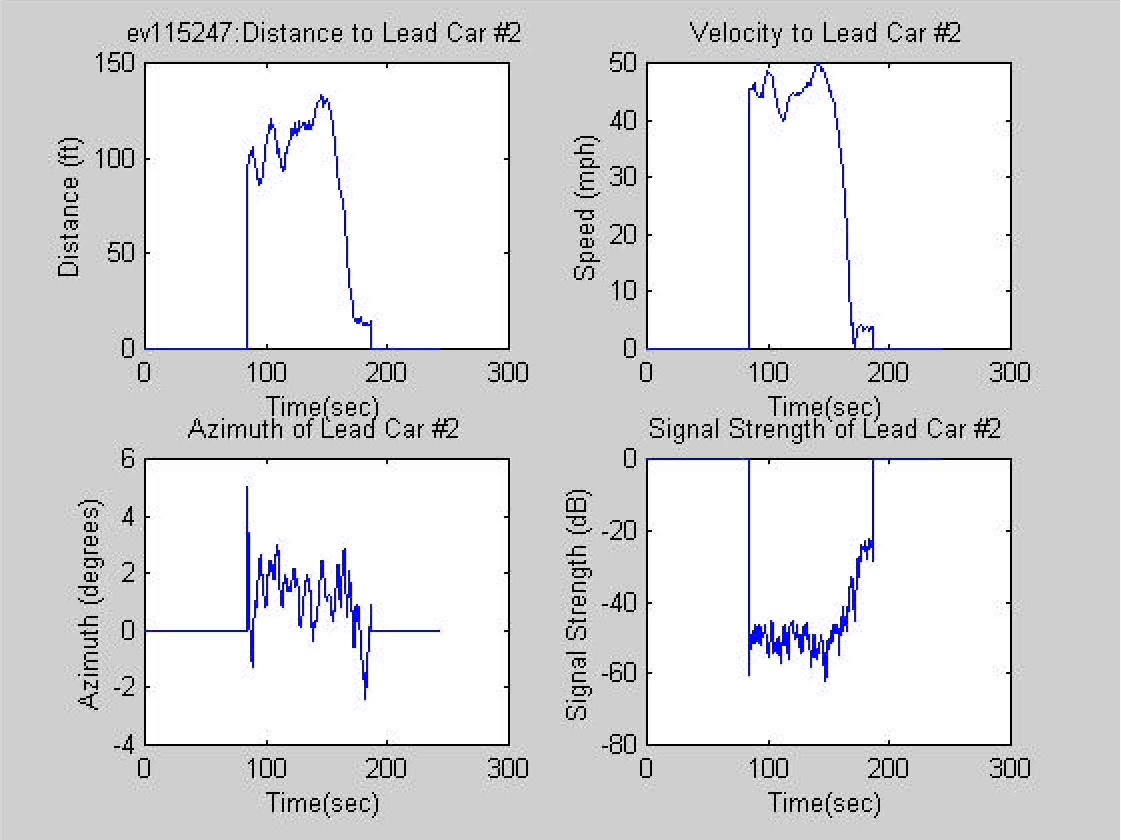

ev115828:Distance to Lead Car #4
Distance (ft)
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #4
Speed (mph)
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #4
Azimuth (degrees)
4
2
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #4
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

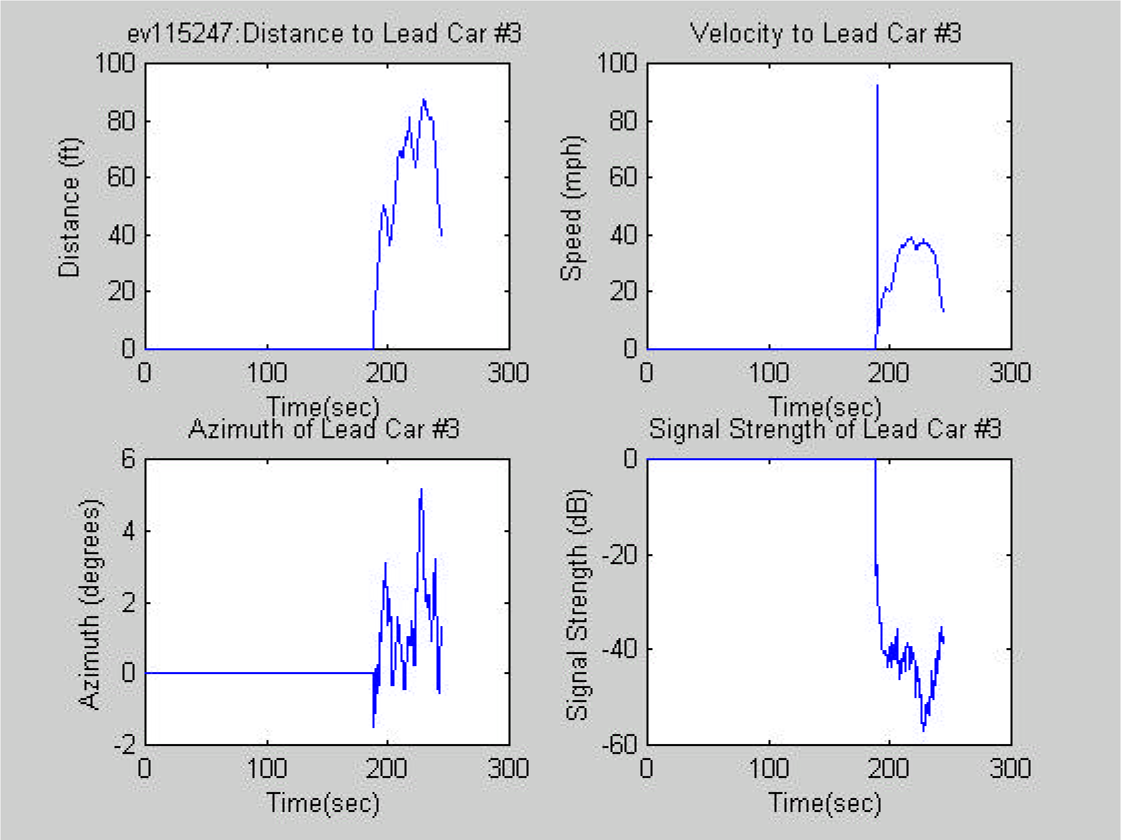

ev115828:Distance to Lead Car #5
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #5
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #5
Azimuth (degrees)
8
6
4
2
0
0
100
200
300
Time(sec)
Signal Strength of Lead Car #5
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

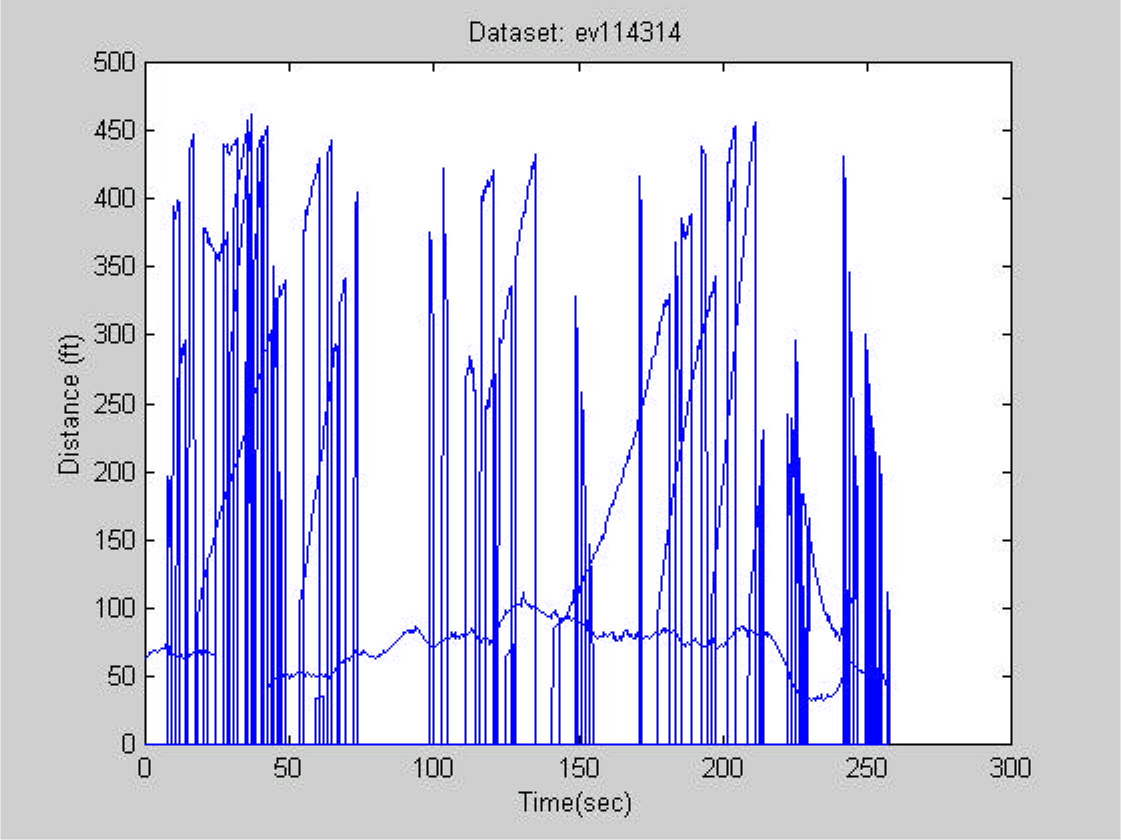

Dataset: ev115247
Distance (ft)
Time(sec)
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
200
250

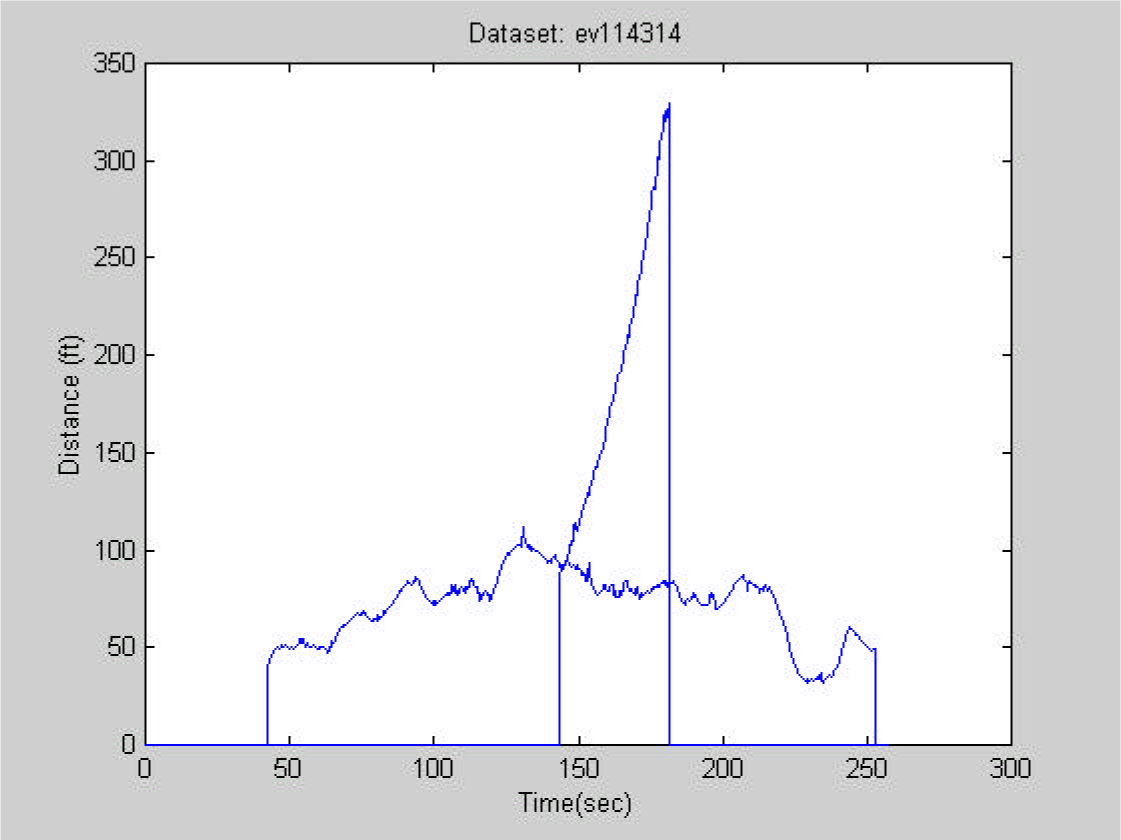

Dataset: ev115247
Distance (ft)
0
20
40
60
80
100
120
140
Time(sec)
0
50
100
150
200
250

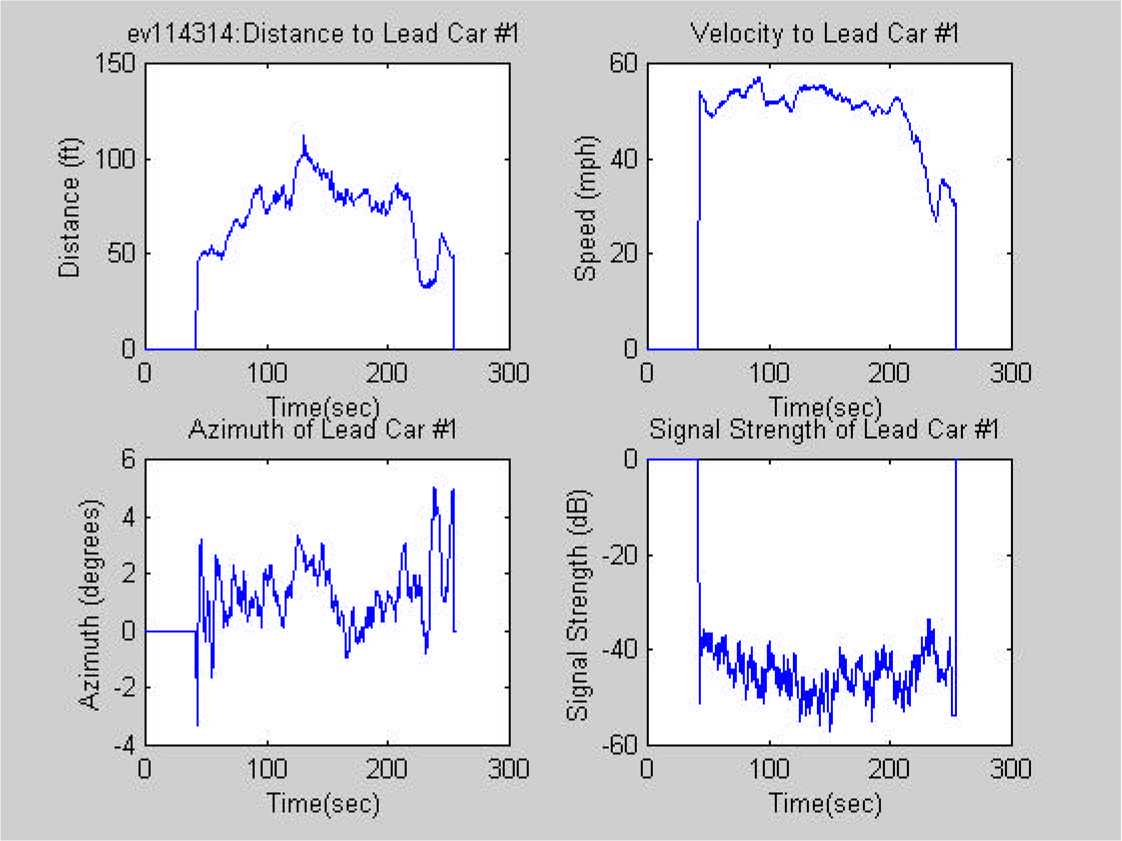

ev115247:Distance to Lead Car #1
150
100
50
0
Distance (ft)
0
100
200
300
Time(sec)
Velocity to Lead Car #1
60
40
20
0
Speed (mph)
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
8
6
4
2
0
-2
Azimuth (degrees)
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
0
-20
-40
-60
-80
Signal Strength (dB)
0
100
200
300
Time(sec)

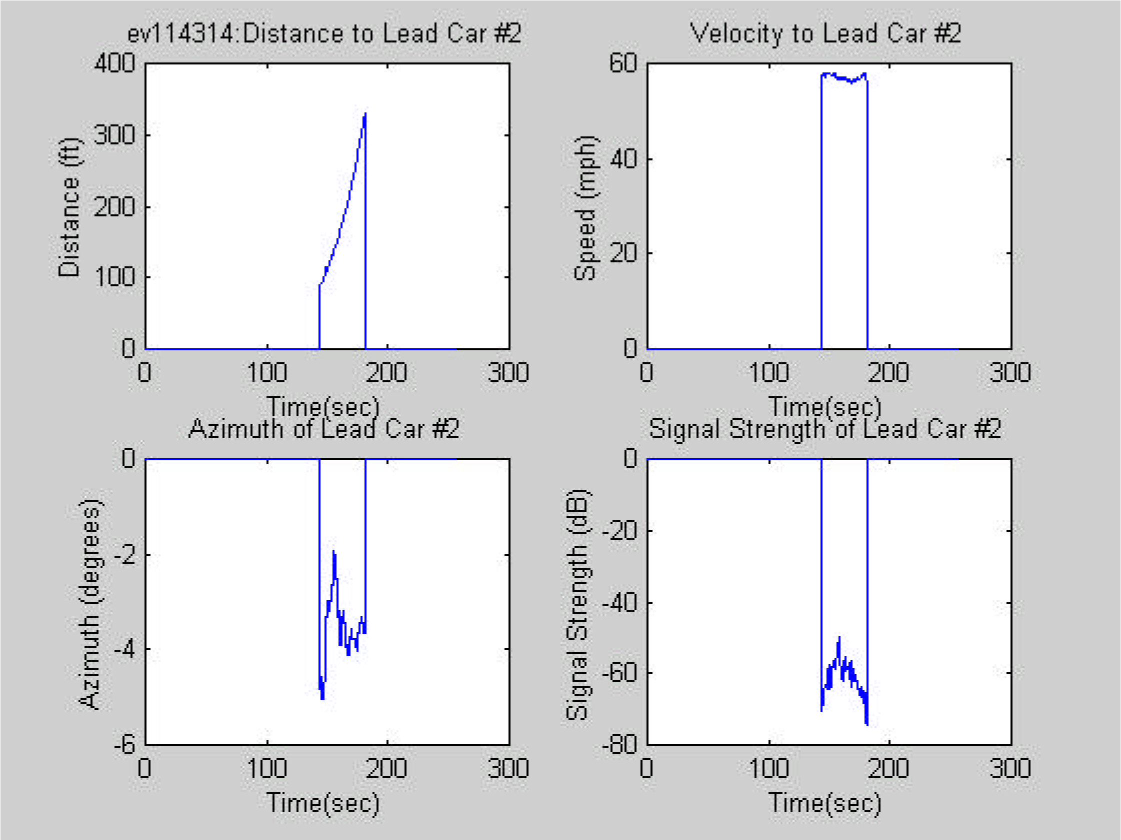

ev115247:Distance to Lead Car #2
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
50
40
30
20
10
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
6
4
2
0
-2
-4
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

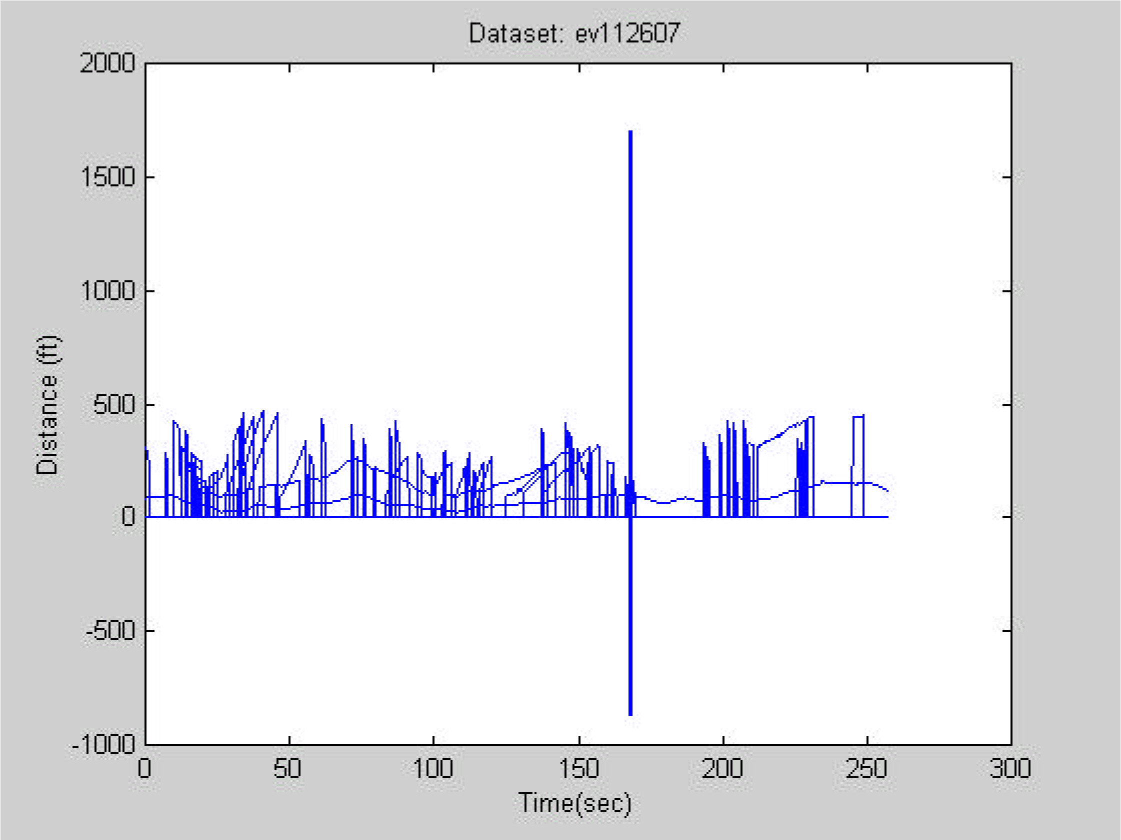

ev115247:Distance to Lead Car #3
Distance (ft)
100
80
60
40
20
0
0
100
200
300
Time(sec)
Velocity to Lead Car #3
Speed (mph)
100
80
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
6
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

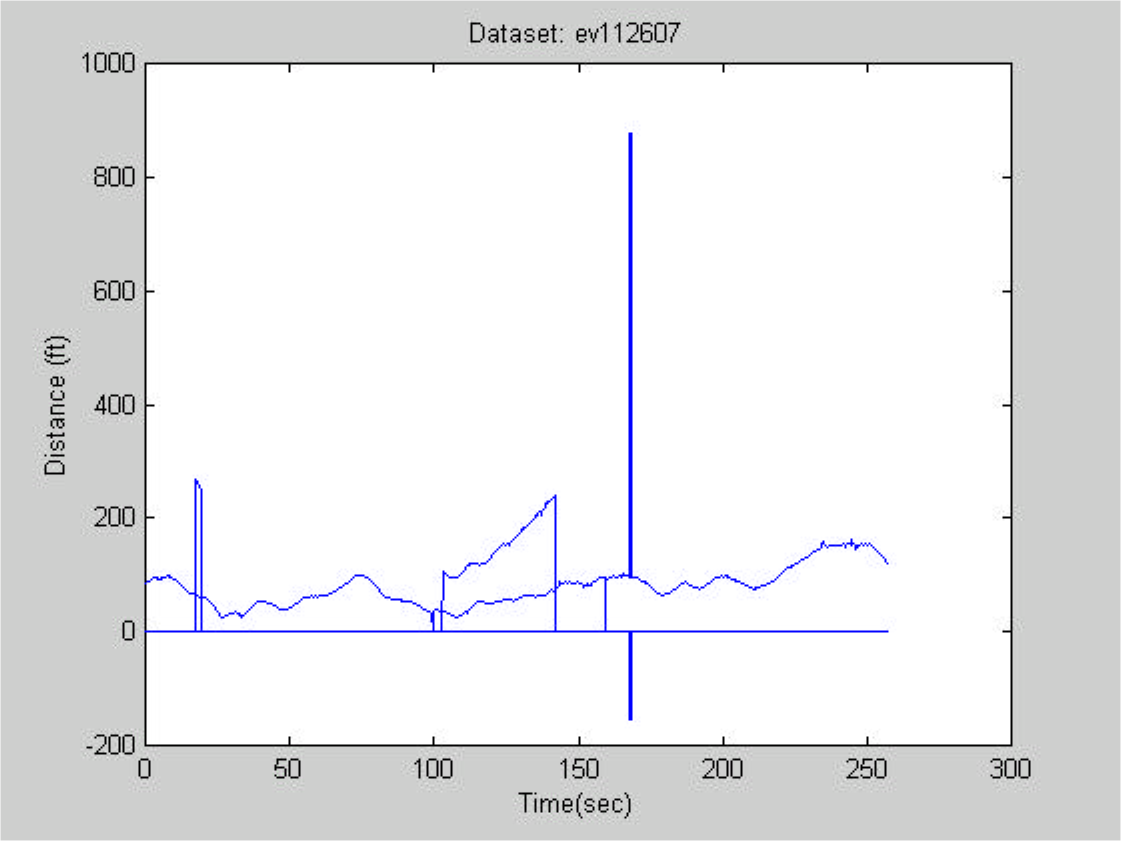

Dataset: ev114314
Distance (ft)
0
50
100
150
200
250
300
350
400
450
500
Time(sec)
0
50
100
150
200
250
300

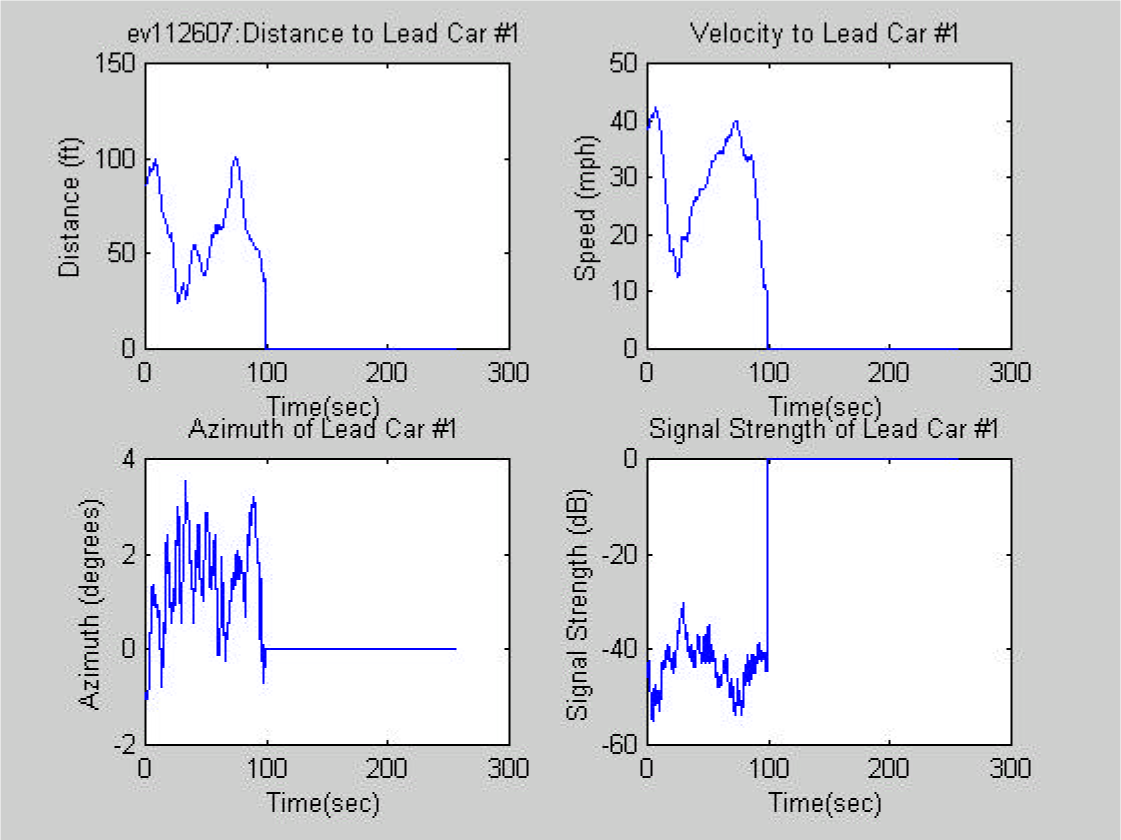

Dataset: ev114314
Distance (ft)
0
50
100
150
200
250
300
350
Time(sec)
0
50
100
150
200
250
300

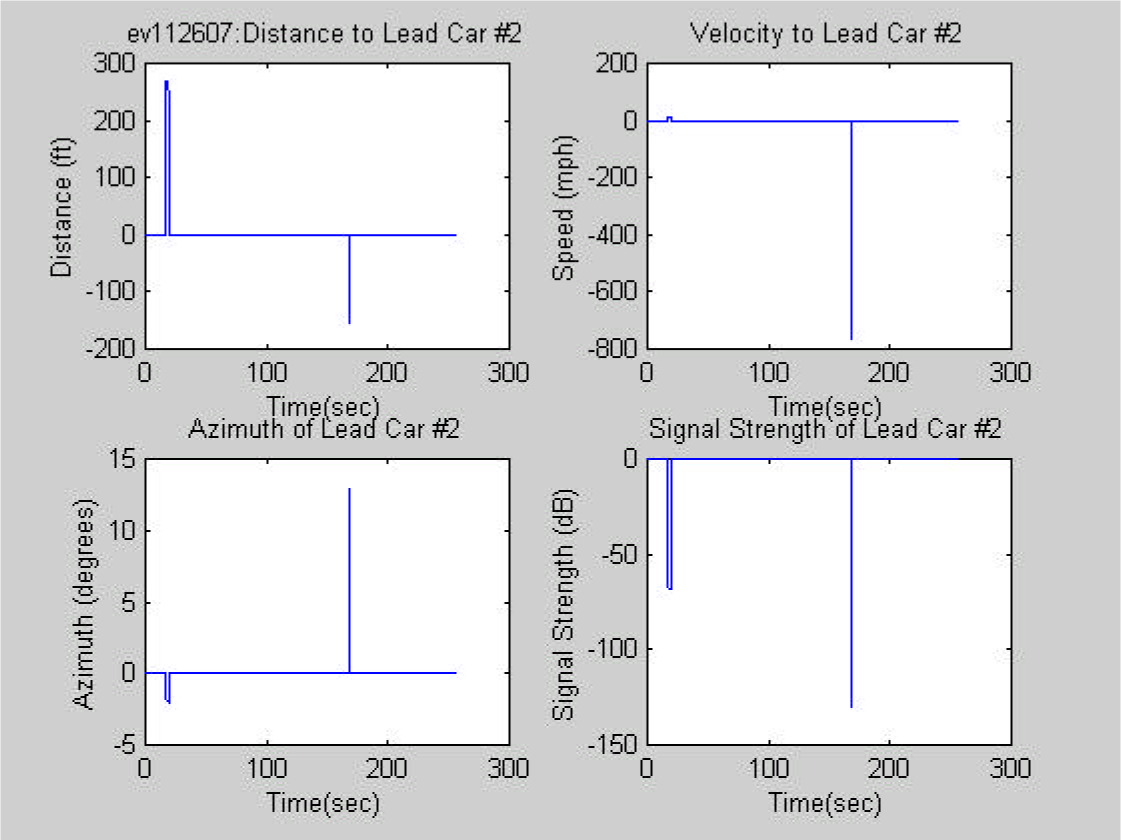

ev114314:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
6
4
2
0
-2
-4
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)

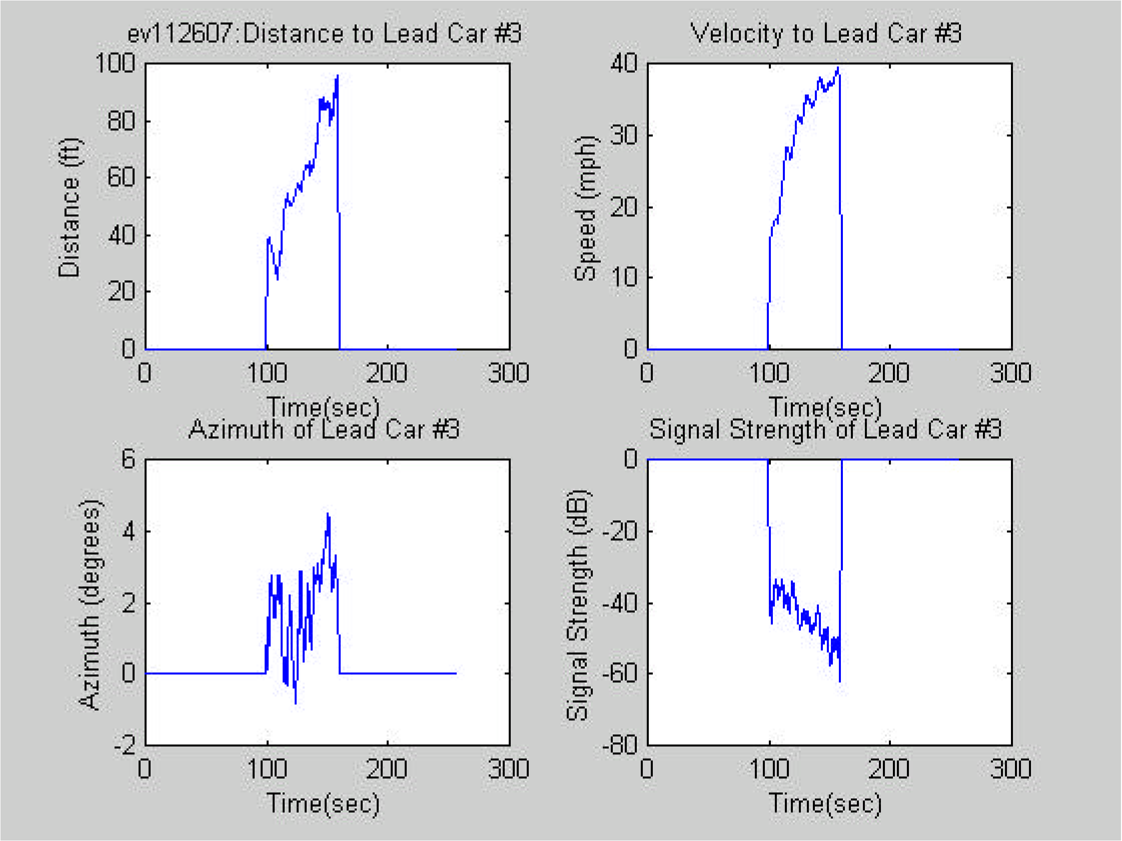

ev114314:Distance to Lead Car #2
Distance (ft)
400
300
200
100
0
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
60
40
20
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
0
-2
-4
-6
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)

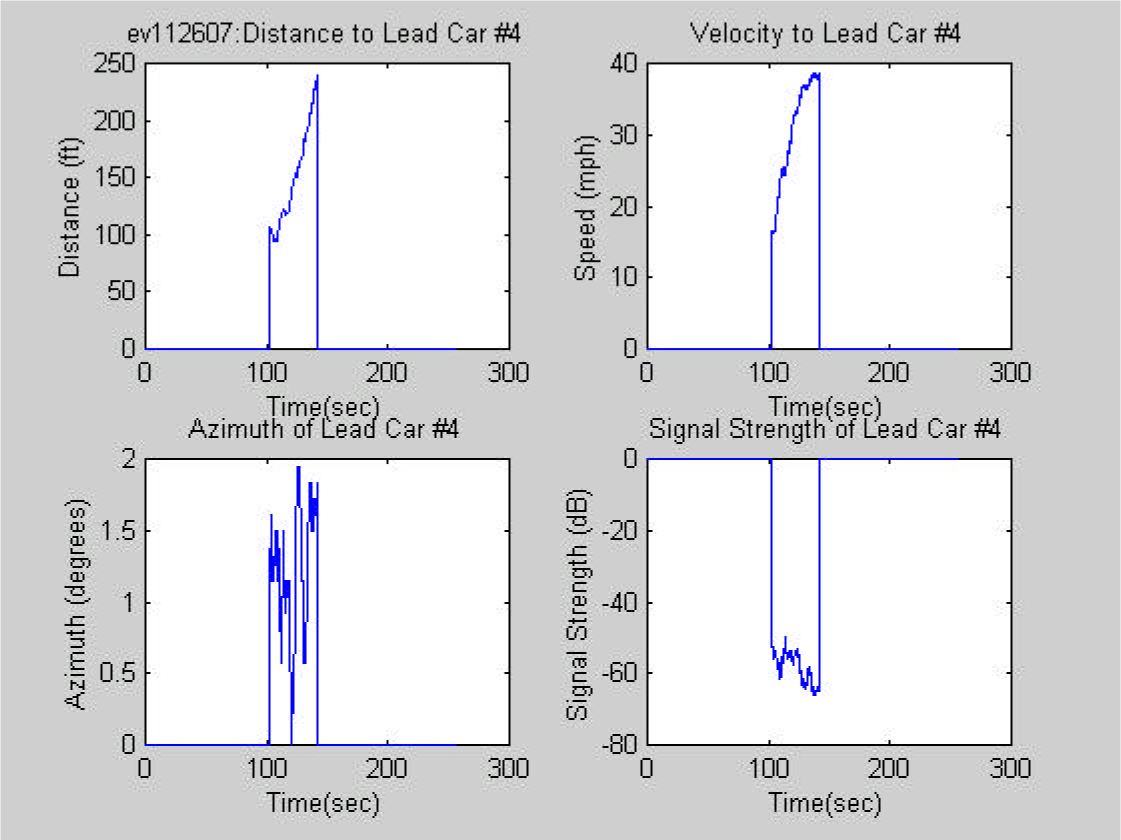

Dataset: ev112607
2000
1500
1000
500
0
-500
-1000
Distance (ft)
0
50
100
150
200
250
300
Time(sec)

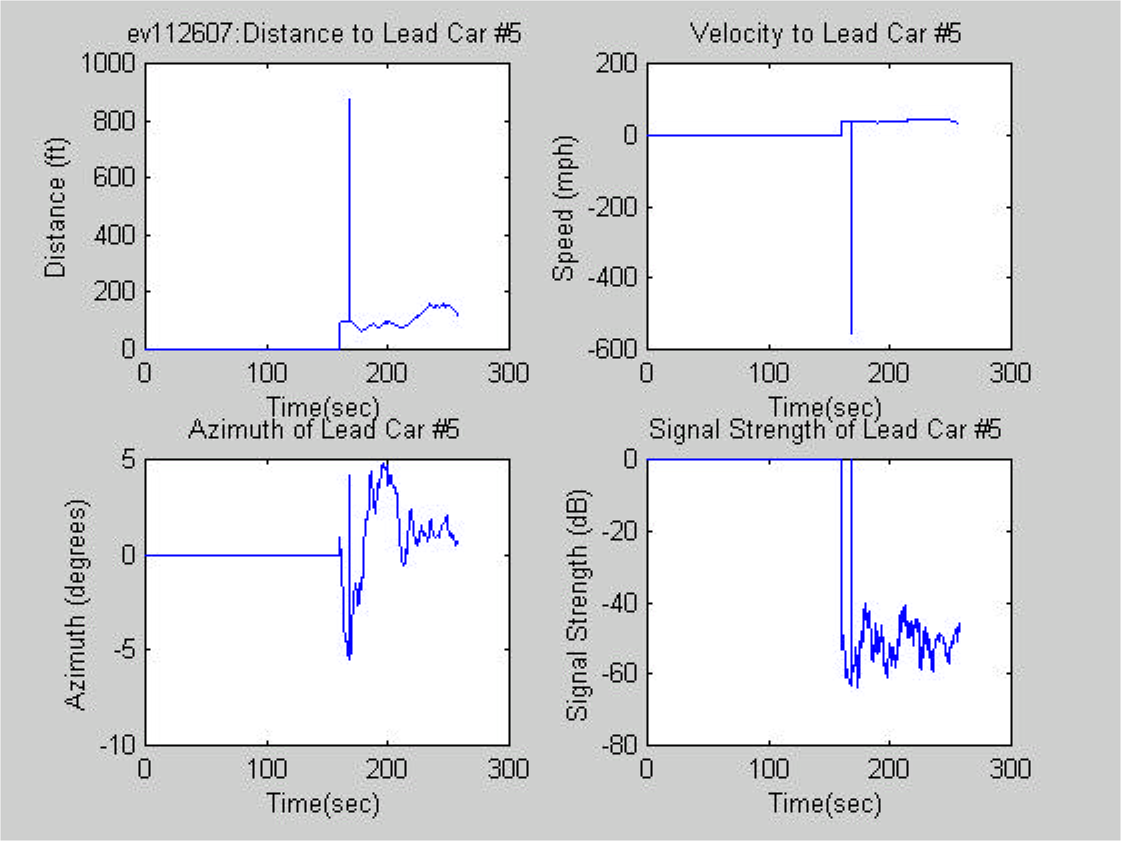

Dataset: ev112607
Distance (ft)
Time(sec)
1000
800
600
400
200
0
-200
0
50
100
150
200
250
300


ev112607:Distance to Lead Car #1
Distance (ft)
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #1
Speed (mph)
50
40
30
20
10
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #1
Azimuth (degrees)
4
2
0
-2
0
100
200
300
Time(sec)
Signal Strength of Lead Car #1
Signal Strength (dB)
0
-20
-40
-60
0
100
200
300
Time(sec)


ev112607:Distance to Lead Car #2
Distance (ft)
300
200
100
0
-100
-200
0
100
200
300
Time(sec)
Velocity to Lead Car #2
Speed (mph)
200
0
-200
-400
-600
-800
0
100
200
300
Time(sec)
Azimuth of Lead Car #2
Azimuth (degrees)
15
10
5
0
-5
0
100
200
300
Time(sec)
Signal Strength of Lead Car #2
Signal Strength (dB)
0
-50
-100
-150
0
100
200
300
Time(sec)


ev112607:Distance to Lead Car #3
Distance (ft)
Time(sec)
Velocity to Lead Car #3
Speed (mph)
Time(sec)
Azimuth of Lead Car #3
Azimuth (degrees)
Time(sec)
Signal Strength of Lead Car #3
Signal Strength (dB)
Time(sec)
0
100
200
300
0
20
40
60
80
100
0
10
20
30
40
-2
0
2
4
6
-80
-60
-40
-20
0


ev112607:Distance to Lead Car #4
Distance (ft)
250
200
150
100
50
0
0
100
200
300
Time(sec)
Velocity to Lead Car #4
Speed (mph)
40
30
20
10
0
0
100
200
300
Time(sec)
Azimuth of Lead Car #4
Azimuth (degrees)
2
1.5
1
0.5
0
0
100
200
300
Time(sec)
Signal Strength of Lead Car #4
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)


ev112607:Distance to Lead Car #5
Distance (ft)
1000
800
600
400
200
0
0
100
200
300
Time(sec)
Velocity to Lead Car #5
Speed (mph)
200
0
-200
-400
-600
0
100
200
300
Time(sec)
Azimuth of Lead Car #5
Azimuth (degrees)
5
0
-5
-10
0
100
200
300
Time(sec)
Signal Strength of Lead Car #5
Signal Strength (dB)
0
-20
-40
-60
-80
0
100
200
300
Time(sec)