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**TRUCK ROLL STABILITY  
DATA COLLECTION AND ANALYSIS**

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## ACRONYMS AND INITIALISMS

|       |  |
|-------|--|
| CD    | Compact Disk   |
| FARS  | Fatality Analysis Reporting System                       |
| FHWA  | Federal Highway Administration                           |
| FTP   | File Transfer Protocol                                   |
| GIS   | Geographic Information System                            |
| GPS   | Global Positioning Systems                               |
| LAN   | Local Area Network                                       |
| MPH   | Miles per Hour   |
| NHTSA | National Highway Traffic Safety Administration           |
| ORNL  | Oak Ridge National Laboratory                            |
| RFI   | Radio Frequency Interference                             |
| RPM   | Revolutions per Minute                                   |
| SA    | Selective Availability                                   |
| SDL   | Stability Data Logger                                    |
| TDOT  | Tennessee Department of Transportation                   |
| TTI   | Texas Transportation Institute                           |
| UMTRI | University of Michigan Transportation Research Institute |
| USGS  | U.S. Geological Survey                                   |
| UTC   | Coordinated Universal Time                               |
| UT    | The University of Tennessee                              |
| VMT   | Vehicle Miles Traveled                                   |



## ABSTRACT

The principal objective of this project was to collect and analyze vehicle and highway data that are relevant to the problem of truck rollover crashes, and in particular to the subset of rollover crashes that are caused by the driver error of entering a curve at a speed too great to allow safe completion of the turn. The data are of two sorts – vehicle dynamic performance data, and highway geometry data as revealed by vehicle behavior in normal driving. Vehicle dynamic performance data are relevant because the roll stability of a tractor trailer depends both on inherent physical characteristics of the vehicle and on the weight and distribution of the particular cargo that is being carried. Highway geometric data are relevant because the set of crashes of primary interest to this study are caused by lateral acceleration demand in a curve that exceeds the instantaneous roll stability of the vehicle.

An analysis of data quality requires an evaluation of the equipment used to collect the data because the reliability and accuracy of both the equipment and the data could profoundly affect the safety of the driver and other highway users. Therefore, a concomitant objective was an evaluation of the performance of the set of data-collection equipment on the truck and trailer.

The objective concerning evaluation of the equipment was accomplished, but the results were not entirely positive. Significant engineering apparently remains to be done before a reliable system can be fielded. Problems were identified with the trailer to tractor fiber optic connector used for this test. In an over-the-road environment, the communication between the trailer instrumentation and the tractor must be dependable. In addition, the computer in the truck must be able to withstand the rigors of the road.

The major objective – data collection and analysis – was also accomplished. Using data collected by instruments on the truck, a “bad-curve” database can be generated. Using this database, instrumented vehicles would not need roadside beacons. The speed, acceleration, and roll stability of the vehicle could be determined prior to entering a curve, and a warning issued, if appropriate, for curves that have been characterized in the database. Thus, the analysis indicates that the data can be effectively used to provide a timely warning of rollover risk.

# 1. INTRODUCTION

The trucking industry is a crucial part of the economic well-being of the United States. Since 1993, large trucks, defined as single-unit trucks and truck tractors with a gross vehicle weight rating of more than 10,000 pounds, have accounted for about 3% of all registered vehicles and about 7% of all vehicle miles traveled (VMT).<sup>1</sup>

In 1998, large trucks were involved in 8.7% of all fatal crashes, 2.4% of all injury crashes, and 4.2% of all property-damage-only crashes. Most of the heavy truck fatal crashes (72%) involved a truck tractor body type. In general, when a crash involves a large truck and another vehicle, about 80% of the fatalities are occupants of the other vehicle.

## 1.1 BACKGROUND

Rollover crashes are of particular concern to safety analysts because they result in fatalities at a greater frequency than other types of crashes. In fact, 18.9% of all vehicles involved in fatal crashes were rollovers in 1998. This percentage is almost five times as high as the proportion of rollovers in injury crashes (4.1%) and almost 16 times as high as property-damage-only crashes.

Table 1.1 compares the numbers and percentages of vehicles involved in rollover crashes in 1998 for various crash categories.

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<sup>1</sup>National Highway Traffic Safety Administration. Various years. "Traffic Safety Facts," <http://www.nhtsa.dot.gov/people/ncsa/factsheet.html> and <http://www.nhtsa.dot.gov/people/ncsa/factprev.html#1996>.

**Table 1.1. Vehicles involved in fatal crashes by vehicle type and rollover occurrence, 1998**

| Vehicle type                 | Rollovers | Non-rollovers | Percent rollover |
|------------------------------|-----------|---------------|------------------|
| Fatal crashes                |           |               |                  |
| Large truck                  | 683       | 4,252         | 13.8%            |
| All other vehicles           | 9,597     | 40,009        | 19.3%            |
| Total                        | 10,280    | 44,261        | 18.9%            |
| Injury crashes               |           |               |                  |
| Large truck                  | 10,000    | 79,000        | 11.4%            |
| All other vehicles           | 143,000   | 3,480,000     | 4.0%             |
| Total                        | 153,000   | 3,559,000     | 4.1%             |
| Property-damage only crashes |           |               |                  |
| Large truck                  | 8,000     | 310,000       | 2.4%             |
| All other vehicles           | 83,000    | 7,178,000     | 1.1%             |
| Total                        | 90,000    | 7,488,000     | 1.2%             |

Source: National Highway Traffic Safety Administration. October 1999. *Traffic Safety Facts 1998: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System*, <http://www.nhtsa.dot.gov/people/ncsa/tsf-1998.pdf> .

While Table 1.1 lists numbers of *vehicles* in fatal crashes, Table 1.2 shows numbers of *fatalities* in rollover accidents. The fatalities listed in this table are occupants of the vehicle type listed in the left column. Although trucks account for about 8-9% of all vehicles involved in fatal crashes, the truck occupants are fatalities only about 2% of the time. However, as noted in Table 1.2, 53.1% of all large-truck occupant fatalities occur when the truck is involved in a rollover crash.

**Table 1.2. Occupant fatalities for 1999, by rollover occurrence, for large trucks and all other vehicles**

| Vehicle type       | Total fatalities | Rollover fatalities | Percent rollovers |
|--------------------|------------------|---------------------|-------------------|
| Large trucks       | 763              | 405                 | 53.1%             |
| All other vehicles | 35,043           | 10,289              | 29.4%             |
| All types          | 35,806           | 10,694              | 29.9%             |

Source: National Highway Traffic Safety Administration. FARS (Fatality Analysis Reporting System) on-line query system, <http://www-fars.nhtsa.dot.gov/www/query.html> .

With these statistics in mind, it is easy to see why a study of truck roll stability is important. In August 2000, Cate documented research in the prioritization of sites in Tennessee that appear to be potential rollover hazards.<sup>2</sup> Cate's thesis examined the relationship between rollover crashes and geometric highway design with the purpose of developing a set of guidelines that highway officials could use to determine the placing of truck rollover warning systems.

This report examines data that can be produced by equipment installed on the vehicle itself.

## 1.2 PROJECT OBJECTIVES

The objective of this project was to test the concept that a combination of on-board equipment and cooperative infrastructure could provide the information needed to give a commercial vehicle driver warning of rollover risk in time for the driver to take corrective action. For timely warning, knowledge is required about the vehicle's roll stability as loaded, its location relative to an upcoming "bad curve," its projected speed as it enters and traverses the curve, and the lateral acceleration demand of the curve. On-board equipment was used to collect data about the weight of the loaded trailer and weight transfer when the vehicle was subjected to lateral acceleration in a curve. Satellite signals from the Global Positioning System (GPS) were used to determine vehicle location. Speed information was collected from the vehicle's internal data bus. In the original concept, the GPS location data about the vehicle and potential bad curves were to be supplemented by positional information and curve data derived from broadcasts from roadside beacons. The vehicle and curve data were to be analyzed in real time to determine a truck's approach to a curve at a speed that could result in rollover. Likely rollover would have invoked a computer-generated warning signal a few seconds in advance of the curve.

Significant changes in this approach occurred during the project. First, the data from roadside beacons were never available. Second, the frequent introduction of deliberate error in signals from GPS satellites, so-called Selective Availability, was discontinued, making GPS-derived location data an order of magnitude more accurate. More accurate GPS data make it potentially feasible to generate and/or use a database of locations and characteristics of bad curves, thus making roadside beacons less necessary.

The fundamental problem addressed by this project remained the same: determination of safe speed in a curve, which depends on information that a driver cannot easily obtain. Characteristics of the curve can in theory be known in advance, but this information is not normally published. In addition, knowledge is also required about the instantaneous roll stability of the vehicle, and that information can be obtained only from measurements on the loaded vehicle.

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<sup>2</sup>Cate, Matthew Alan. August 2000. "Development of a System to Prioritize Sites for the Installation of Automated Truck Rollover Warning Systems in Tennessee," a thesis prepared for the University of Tennessee, Knoxville, Tennessee.

Thus, the objective of the Federally-funded portion of this project, as stated above, is to determine if the prototype system under test could obtain the information required to give drivers timely and credible warning of rollover risk. This objective was accomplished through

- An evaluation of the suite of test equipment to determine its reliability, and
- An analysis of the data to determine its accuracy and timeliness as a predictor.

### **1.3 PROJECT PARTNERS AND THE EXPERIMENTAL SITUATION**

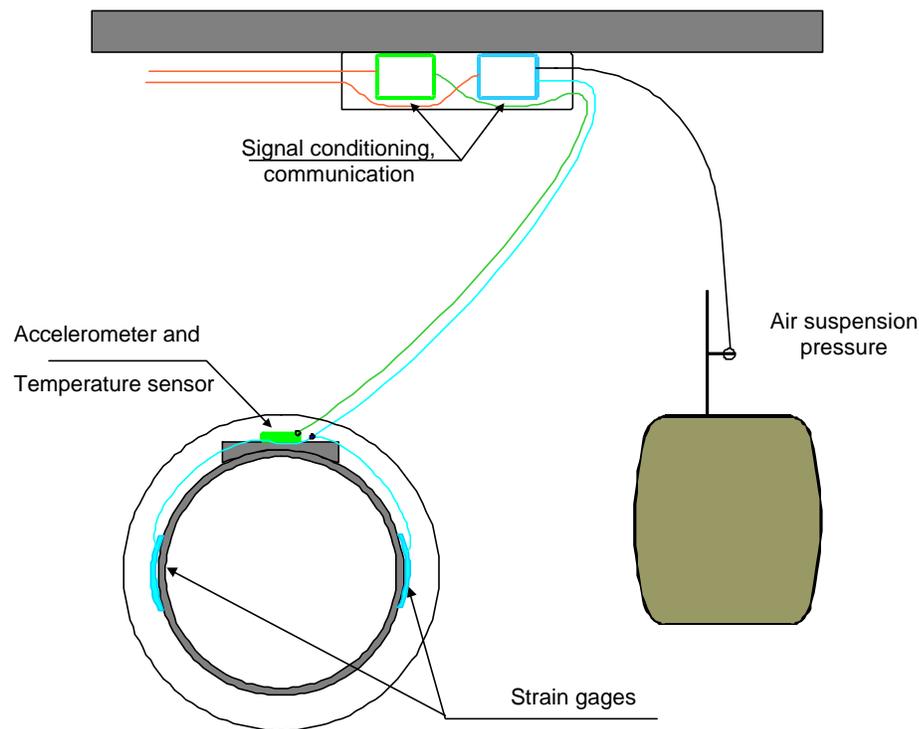
Contributing partners in the project originally included U.S. Xpress Enterprises, a major 48-state truckload hauler with headquarters in Chattanooga, Tennessee; Volvo Trucks North America; Wabash National Corporation, a major manufacturer of trailers; Control by Light Inc. (formerly a division of Raytheon Corporation); and the Operations Division of the Tennessee Department of Transportation (TDOT). Praxair, a hauler of cryogenic fluids, asked to join the project in mid-course. Significant subcontractors originally included the Texas Transportation Institute (TTI) and the University of Michigan Transportation Research Institute (UMTRI). The University of Tennessee (UT) Transportation Center, in a concurrent collaboration with TDOT, was to assist in the procurement of roadside equipment and will be responsible for some analysis of the data produced by our test-and-evaluation efforts.

The trucking firms, U.S. Xpress and Praxair, collected the data using trucks in revenue service and provided the data to ORNL for analysis. U.S. Xpress had three instrumented tractors and six instrumented trailers traveling primarily on Interstate-75 on a long-distance route between Atlanta, Georgia, and Wilmington, Ohio. Praxair, a company specializing in industrial gases, delivers cryogenics liquids to a number of customers in Pennsylvania, New Jersey, New York, and Connecticut. One instrumented tanker was used to collect Praxair data for this project.

## 2. CHARACTERISTICS OF THE ON-BOARD COMPONENTS

### 2.1 SYSTEM HARDWARE

Onboard instrumentation includes components on both the tractor and the trailer. Of particular interest is the trailer instrumentation, since in almost all cases it is the roll stability of the trailer that determines the stability of the entire rig. The instrumentation includes a strain gauge, a two-axis accelerometer, a pressure gauge, and a temperature sensor (Figure 2.1). The trailer instruments operate under the control of a programmable trailer-mounted module (embedded computer) that provides excitation for the strain gauges, analog-to-digital conversion, and protocol generation for digital transmission of the data to the tractor cab. Manufacturers of the data acquisition equipment and the model numbers are given in Table 2.1. A schematic of tractor-trailer equipment is shown in Figure 2.2.



**Figure 2.1. Axle sensors and signal conditioners.**

**Table 2.1. List of on-board equipment**

| F/N             | QTY | Part No./ID      | Spec or Vendor Name      | Title   |
|-----------------|-----|------------------|--------------------------|---|
| Tractor Segment |     |                  |                          |   |
| 0               | REF | G712977          | CBL Systems Corp*        | Truck Rollover Warning System - Tractor Segment |
| 1               | 1   | PT-6500          | DSE                      | Cab Mount, Rugged PC with Touch Display         |
| 2               | 1   | C-1075           | BICC Brand Rex           | Cab Mounted Fiber Cable Assembly                |
| 3               | 1   | C-1077           | BICC Brand Rex           | Cab To Trailer Umbilical Fiber Cable Assembly   |
| 4               | 1   | 73200            | Echelon                  | Network Interface Card (PCC-10)                 |
| 5               | 1   | 75005-1          | CBL Systems Corp         | Fiber Optic Pod for PCC-10 Interface            |
| Trailer Segment |     |                  |                          |   |
| 0               | REF | G712978          | CBL Systems Corp         | Truck Rollover Warning System – Trailer Segment |
| 1               | 1   | G712979          | CBL Systems Corp         | D4SIO Enclosure                                 |
| 2               | 1   | G733469-1        | CBL Systems Corp         | D4SIO   |
| 3               | 1   | G712981          | CBL Systems Corp         | Wire Harness                                    |
| 4               | 1   | C-1076           | BICC Brand Rex           | Trailer Mounted Fiber Cable Assembly            |
| 5               | 1   | 23203A           | Summit Instruments       | Two-Axis Accelerometer                          |
| 6               | 4   | CEA-06-187UV-350 | Measurements Group, Inc. | Strain Gage                                     |
| 7               | 1   | PK 80042         | Honeywell                | Pressure Sensor                                 |

\*Control by Light (CBL) is one of the project partners, as noted in Section 1.3.

A schematic of the original design showing locations of proposed components is given in Figure 2.2.

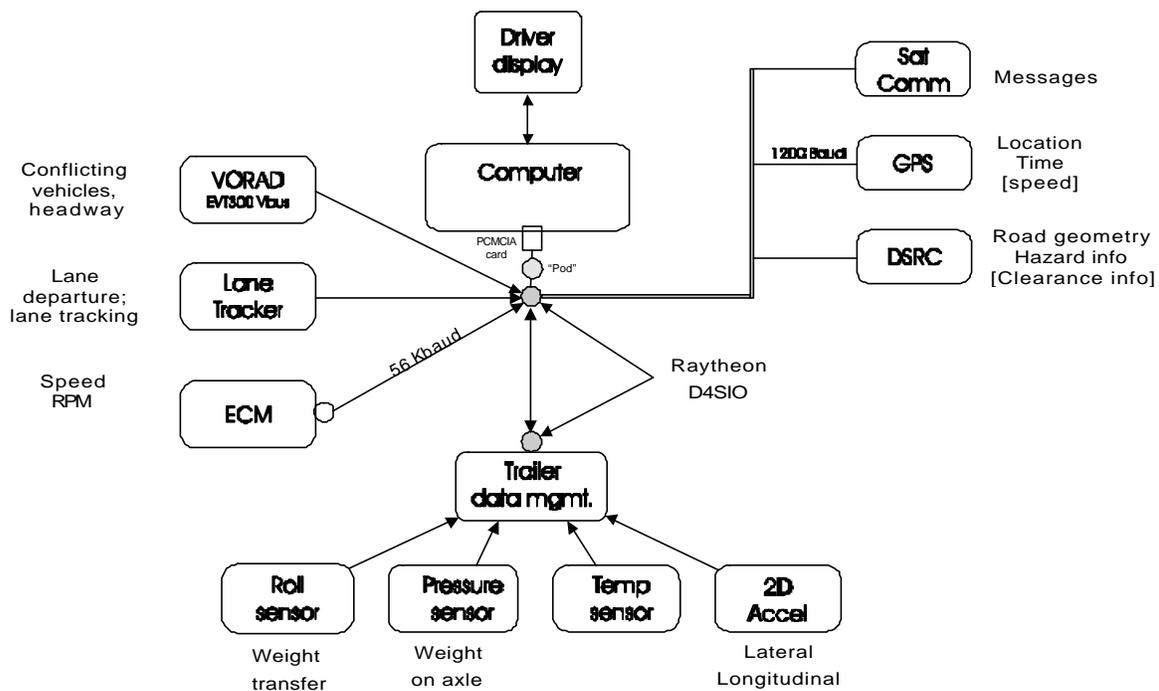


Figure 2.2. Truck-trailer schematic.

### 2.1.1 Trailer instrumentation

Trailers used in the project have air suspensions; such suspensions typically have leading or trailing arms on each side with air bags that support the load but provide little roll stiffness. The trailing arms are connected by torque tubes that provide the primary roll stiffness of the suspension. The assembly resists roll moment in a manner similar to that of an anti-sway bar in an automobile suspension. (For an excellent and more extensive discussion, see Winkler, et al.<sup>3</sup> Our trailer instrumentation closely follows the example provided by the successful UMTRI project.)

<sup>3</sup> Winkler, C. B., P. Fancher, R. Ervin. 1999. "Intelligent Systems for Aiding the Truck Driver in Vehicle Control." University of Michigan, Transportation Research Institute, Ann Arbor, Michigan. IV Vehicle Navigation Systems and Advanced Controls (SAE-SP-1428). Warrendale, SAE, 1999, pp. 165-178. Report No. SAE 1999-01-1301.

Sensing of the strain in the torque tube as the trailer sways from side to side provides a signal proportional to the side-to-side weight transfer. Similarly, measurement of the air pressure in the suspension's air bags provides an output proportional to the total load of trailer and cargo. In addition, a two-axis accelerometer on the axle is mounted so that it measures lateral and longitudinal acceleration as the vehicle travels on the highway. A temperature sensor is included in the instrumentation to allow compensation for the temperature dependencies of the measurements provided by the rest of the sensors.

### **2.1.2 Tractor instrumentation**

Instrumentation in the tractor includes a rugged computer with a VGA-capable liquid crystal touch screen display, a receiver for signals from GPS satellites, an interface to the vehicle's internal (J1708) data bus, and other features that could be used to assist the driver.

### **2.1.3 On-board data communication**

The embedded data acquisition computer on the trailer and the main computer in the tractor are connected by a dedicated fiber optic cable. At the time that hardware was being specified for this project, there were competing systems for multiplexing data onto the trailer power leads, and hardware was not readily available for either multiplexing system. A fiber optic cable was proposed, and its superior bandwidth and immunity to radio frequency interference (RFI) were cited as advantages. With some expressed misgivings about the survivability of such components in the over-the-road environment, we selected the fiberoptic system.

## **2.2 SYSTEM SOFTWARE**

### **2.2.1 Data collection and transmission**

Software installed on the trailer's embedded computer manages the collection of data from the trailer's sensors. In normal operation, air pressure, torque tube strain, and acceleration data are collected ten times a second; the embedded computer can be programmed to change that rate if a situation warrants a different collection rate. The software for the embedded computer was furnished by Control by Light, one of the corporate partners in the project.

The main on-board computer, mounted in the cab, accepts messages from all of the installed equipment and stores the data in a log file according to specific conditions. Data management programs in Visual Basic 6.0 for the main computer were written by John Bate of Volvo and furnished by Volvo Trucks North America. Documentation for the data collection programs is included as Appendix A.<sup>4</sup> The programs were originally intended to serve only as an interim

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<sup>4</sup>Bate, John. May 8, 2000. *SDL: Stability Data Logger*, Version 1.1.20.

capability, until “final” programs were written by a contractor; they have served far beyond the original intent.

Additional information about the data logs is provided in Section 3.3.

### **2.2.2 Download procedure**

In keeping with the spirit of the ad hoc data collection program, Bate’s “data download” procedure, though not complicated, still is more suitable for computer-knowledgeable persons than for the computer-illiterate. This procedure copies the data from the tractor’s on-board computer to removable media. The download procedure involves removing a cover that protects the in-dash computer, inserting a memory card, and performing a manual file transfer operation. After the data transfer, the log file is reset, and data collection is re-enabled. For the complete set of instructions, see Appendix A.



## **3. DATA MANAGEMENT**

### **3.1 DATA TRANSFER TO ORNL**

After downloading data from their trucks, U.S. Xpress and Praxair staff sent the data to Oak Ridge National Laboratory (ORNL) electronically. Transfer over the Internet using File Transfer Protocol (FTP) was the method selected for transferring information. The procedures that were developed allow users to schedule their uploads at their convenience and will work with virtually any size file. In addition, they do not require disks or memory cards to be exchanged with ORNL and work from within current versions of Netscape Communicator and Internet Explorer browsers. Instructions for use of the transfer procedure are included as Appendix B.

### **3.2 FTP SERVER**

A Windows NT Server machine at ORNL was selected to host the FTP service. Three separate directories were set up underneath the primary FTP directory – one for PraxAir, one for U.S. Xpress, and the third for ORNL project use. Praxair and U.S. Xpress user accounts were established on the NT Server operating system; these users were given limited privileges and allowed logon access only to their own areas. External users were not allowed to delete or rename files once they were uploaded as a security precaution in case the password was compromised.

Files transferred to the FTP server from the trucking companies were maintained in duplicate. A copy of each file was placed into a separate directory on the FTP server accessible only by the project team via a shared directory on the ORNL local area network (LAN). Internet access to any ORNL LAN shared directories is blocked by a proxy server making this a secure means of project file access.

Data files were copied by the team members as the need arose. The files on the FTP server were considered originals, were not edited or replaced, and were archived onto writeable compact disks (CDs).

### **3.3 DATA LOG FILE**

As noted in Section 2.2.1, data captured from the truck on-board system were written to a log file in a pre-defined format by the Stability Data Logger (SDL) programs (see Appendix A).

Trucks for U.S. Xpress and Praxair were equipped with several on-board instrument sources including a GPS receiver, a DPA II J1708 adapter manufactured by Dearborn Group, and trailer instrumentation as discussed above and tabulated in Table 2.1. The GPS data included information such as time (as measured by Coordinated Universal Time – UTC, which is the same as Greenwich Meridian Time), and geographic locations of the trucks (longitude and latitude). The J1708 adapter provided speed, revolutions per minute (RPM), and odometer readings, while

the gauges attached to the trailer recorded measurements on lateral and longitudinal accelerations, torque tube strain, temperature, and weight on the rear axles.

It is important to note that the frequency of readings varied by instrument and data type. Generally, GPS readings were recorded once per second, while lateral and longitudinal accelerations were captured up to ten times per second. Because these data were written to a text file, certain conventions were used to identify data types. They are described as follows.

- C All GPS readings were identified by a line that began with the letter “G” or characters “\$G” followed by a UTC code that included time and, in some cases, date, latitude and longitude of the truck’s location, and an indication of GPS data quality. Each data item was separated by commas. For example, a line representing readings from the GPS might read

G,142326,3604.788390,N,07958.179359,W,1

In this example, G identifies the line as containing GPS data, 142326 is the UTC (14 hours, 23 minutes, and 26 seconds), 3604.788390 is latitude in degrees, N is the latitudinal compass direction (i.e., North), 07958.179359 is longitude in degrees, W is longitudinal compass direction (i.e., West), and 1 is GPS quality code (i.e., by definition, 0 = invalid; 1 = GPS fix; and 2 = Diff. GPS fix).

It should be noted that various message formats can be output from GPS receivers, and the U.S. Xpress and Praxair receivers were not set to provide exactly the same messages. Variations in GPS readings between data captured by U.S. Xpress and Praxair trucks are discussed in Section 3.4.

- C Every other data item was identified by a line that began with a letter followed by a comma and then a single reading. For example, lines for the log file might read  
S,33 which indicates a speed of 33 MPH, or  
R,1583 which indicates 1583 RPM.

Table 3.1 shows the letter codes used to identify a particular data element, as well as the typical frequency of recording and their instrument source.

**Table 3.1. Codes indicating the type of data for lines in the log file**

| <b>Identification Letter</b> | <b>Data Type</b>          | <b>Frequency</b> | <b>Instrument</b> |
|------------------------------|---------------------------|------------------|-------------------|
| G or \$G                     | GPS Data                  | 1 per second     | GPS               |
| S                            | Speed                     | 1 per second     | J1708             |
| R                            | RPM                       | 1 per second     | J1708             |
| O                            | Odometer                  | 10 per second    | J1708             |
| X                            | Lateral Acceleration      | 10 per second    | Trailer Gauges    |
| Y                            | Longitudinal Acceleration | 10 per second    | Trailer Gauges    |
| Q                            | Strain                    | 10 per second    | Trailer Gauges    |
| C                            | Ambient Air Temperature   | 1 per second     | Trailer Gauges    |
| W                            | Weight at Rear Axle       | 10 per second    | Trailer Gauges    |

To reduce the amount of storage space needed for the output data file, the SDL program applied certain rules for writing data to the log file. No data captured from the J1708 adaptor was written to the log file unless a GPS data point was recorded. Unless a problem occurred, such as inadequate reception of transmissions from satellites, GPS data was always to be written to the log file whenever data logging was enabled (see Appendix A for additional explanation about the user interface) and the minimum speed limit was greater than or equal to the minimum logging speed entered in the user interface (usually 5 to 10 MPH). To minimize the size of the log file, additional constraints were applied to the speed and RPM records. Speed was logged only if the current reading was 2 MPH different from the last reading; RPM was logged when the current reading was 50 RPM different from the last reading.

Between June 2000 and late January 2001 (to date), ORNL received four data files from U.S. Xpress and five data files from Praxair. Table 3.2 shows the files ORNL received from each company.

**Table 3.2. Data files received from the participating truck companies**

| Date up-loaded | Company     | File name        | File size (in KB) | Number of records (i.e., lines) | Number of GPS readings | With acceleration measurements |
|----------------|-------------|------------------|-------------------|---------------------------------|------------------------|--------------------------------|
| 6/6/00         | U.S. Xpress | log.txt          | 160,407           | 6,753,703                       | 2,783,350              | Yes                            |
| 6/6/00         | Praxair     | ornl_june.txt    | 5,161             | 338,844                         | 33,040                 | Yes                            |
| 7/24/00        | Praxair     | ornljuly.txt     | 1,378             | 117,788                         | 4,047                  | Yes                            |
| 8/22/00        | U.S. Xpress | 2000_05_27.txt   | 760               | 19,799                          | 16,592                 | No                             |
| 8/29/00        | Praxair     | augdata.txt      | 5,857             | 482,801                         | 20,114                 | Yes                            |
| 8/30/00        | U.S. Xpress | 2000_aug_29.txt  | 52,070            | 1,843,715                       | 1,004,730              | Yes (very few)                 |
| 9/25/00        | U.S. Xpress | 2000_sept_24.txt | 2,032             | 53,316                          | 44,333                 | No                             |
| 10/11/00       | Praxair     | prax10_09.txt    | 499               | 34,085                          | 2,682                  | Yes                            |
| 11/16/00       | Praxair     | ornl_nov.txt     | 37,228            | 3,324,634                       | 92,121                 | Yes                            |
| 1/25/01        | Praxair     | jan-01-a.txt     | 71,666            | 6,232,861                       | 206,094                | Yes                            |

As ORNL began to receive log files from both U.S. Xpress and Praxair, it became apparent that there were differences between sets of GPS data from the two companies. The major differences in the GPS data were that (1) the Praxair file contained UTC date as well as time, while the U.S. Xpress file contained time only, and (2) the GPS data line was identified by the literal expression **\$GPRMC** in Praxair files and **G** in U.S. Xpress files. In addition, more data items were recorded in Praxair's GPS data line. Because of these differences, two slightly different database structures and programs were designed.

### 3.4 DATABASE DESIGN

During the summer of 2000, ORNL's effort on this project was refocused on data collection and analysis. To that end, an initial quick database design was implemented to allow immediate analysis of the data. The initial design of the database was very simple and constructed quickly so that data from the log files could be quickly put into tables in preparation for data analysis. Visual FoxPro 6.0 was chosen as the database to be used for two reasons: (1) project team members had the software readily available and (2) the programs to load the database could be written without investing time and effort in building an unnecessary event-driven user interface (required by Visual Basic 6.0).

A decision was made to extract, for analysis purposes, only the last reading for data elements that were captured more often than once every second. Because of the differences in the log file line containing GPS data, two slightly different tables were constructed, one for the U.S. Xpress data and one for Praxair data. The Praxair table contained one additional column to account for the date, which was not contained in the U.S. Xpress files. Table 3.3 shows the database structure for the database tables.

**Table 3.3 Database structure**

| <b>Data Name</b>  | <b>Type</b> | <b>Width</b> | <b>Decimal Places</b> | <b>Description</b>                               |
|-------------------|-------------|--------------|-----------------------|--|
| Time              | Numeric     | 6            |                       | Time signal from GPS                             |
| Date <sup>a</sup> | Numeric     | 6            |                       | Date signal from GPS                             |
| Longitude         | Float       | 15           | 6                     | GPS position reading                             |
| Latitude          | Float       | 15           | 6                     | GPS position reading                             |
| Speed             | Float       | 5            | 1                     | MPH from J1708                                   |
| RPM               | Integer     | 4            |                       | RPM from J1708                                   |
| Lateralacc        | Float       | 10           | 6                     | Trailer lateral acceleration                     |
| Longitacc         | Float       | 10           | 6                     | Trailer longitudinal acceleration                |
| Strain            | Float       | 10           | 6                     | Strain in trailer suspension torque tube         |
| Temp              | Float       | 6            | 2                     | Trailer accelerometer temperature sensor reading |
| Weight            | Float       | 10           |                       | Weight measured from pressure in air bag         |

<sup>a</sup>The Date field only existed in the table receiving Praxair data.

### 3.5 DATABASE LOADING

A utility program was written in Visual FoxPro to parse the text log files and load data items into the appropriate U.S. Xpress or Praxair tables. If a data element was not captured for a particular GPS reading, then the program inserted a null value (indicating missing data) into this field. A program listing is included in Appendix C.

Two versions of the program were written to accommodate the differences in the log file for the GPS line for U.S. Xpress and Praxair (see Section 3.3). The following shows how the GPS line was written for U.S. Xpress and Praxair, with the differences highlighted in bold.

U.S. Xpress: **G**,020331,3448.4154,N,08500.9751,W,**1**

Praxair: **\$GPRMC**,195003,,4112.1325,N,07956,W,**110500**,,,A\***67**

where **G** and **\$GPRMC** identified lines of GPS readings, the **110500** in the Praxair line indicated the UTC date (no date available for the U.S. Xpress data), and the **1** and **A\*67** indicated the GPS quality or checksum, respectively.

### 3.6 DATA VALIDATION

Validation procedures were applied to scan and to check the validity of the data after they were loaded into the appropriate tables. Some data problems were identified.

1. **Run-delimiting data elements were not present.** The input fields on the user interface screen that could be helpful in identifying a run – driver ID, vehicle ID, trailer ID, and load ID – were optional fields that the driver usually did not enter. Furthermore, U.S. Xpress data files did not contain a date element in their GPS data line, though Praxair files did. It was decided to attempt to separate Praxair runs by using the date field for analysis purposes, while U.S. Xpress runs were separated by using latitude/longitude location information and time-stamps recorded by the GPS.
2. **Trailer data was missing from the majority of the U.S. Xpress files.** Early in the project, U. S. Xpress dispatchers were seldom able to assure that the instrumented trailers were available to connect to the instrumented tractors. In addition, one fiber-optic cable had incorrect connectors installed and soon failed. As the project progressed and the tractor-trailer pairs were more often mated properly, the remaining fiber-optic connectors began to wear and fail. The net result was that most runs for U.S. Xpress had only tractor data (primarily GPS locations).
3. **Early Praxair data was fragmented.** Praxair data that were collected at the beginning of their participation in the project showed brief segments of reasonable data separated by significant time gaps within a day. There were only occasional episodes of contiguous data that could be analyzed.

The following data validation checks were run on data from both Praxair and U.S. Xpress. In general, all the data that were available looked valid.

|    |                           |                 |
|----|---------------------------|-----------------|
| 1. | Longitude                 | NA <sup>5</sup> |
| 2. | Latitude                  | NA              |
| 3. | Speed                     | 0.0 to 100.0    |
| 4. | RPM                       | 0 to 3500       |
| 5. | Temperature               | -20.0 to +120.0 |
| 6. | Weight                    | 0.0 to 30000    |
| 7. | Lateral acceleration      | -1.0 to +1.0    |
| 8. | Longitudinal acceleration | -1.0 to +1.0    |
| 9. | Strain                    | -1.0 to +1.0    |

---

<sup>5</sup>Plotted using a Geographic Information System (GIS) tool and checked against U.S. Geological Survey data.

## 4. DATA ANALYSIS

The following sections describe the processes of analyzing the data to determine its accuracy and usability as a predictor of rollover potential.

### 4.1 MAPPING OF GEOGRAPHIC DATA

The on-board GPS receiver collected geographic location data (i.e., longitude and latitude) of the truck approximately once every second. Such geographic reference information enabled ORNL to track truck routes with a GIS tool. GIS is a computer system capable of assembling, storing, manipulating, and displaying geographically referenced information.

The *Maptitude*<sup>®</sup> *Geographic Information System for Windows*, a computer software system developed by the Caliper Corporation, was used to evaluate and display the data. *Maptitude*, a personal-computer-based mapping tool, allowed the project team members to perform geographic mapping and to conduct spatial data analyses.

As described previously, the on-board GPS provided geographic reference information, in terms of longitude and latitude, for a truck's current position. This geographic referencing information is point-based data. To track a truck route, these point-based data were converted to polyline-based data. For this study, ORNL developed a simple algorithm to interpolate a polyline between two GPS data points. This algorithm is briefly explained here.

For any three consecutive geographic data points,  $P_{n-1}$ ,  $P_n$ , and  $P_{n+1}$  collected by the GPS unit, the interpolated polyline for  $P_n$  (including two line segments, one on each side of  $P_n$ ) is defined by the following three new data points:

$$\begin{aligned} Q_{n-1} &= (P_{n-1} + P_n)/2, \text{ which is the mid-point between } P_{n-1} \text{ and } P_n; \\ Q_n &= P_n, \text{ and} \\ Q_{n+1} &= (P_n + P_{n+1})/2, \text{ which is the mid-point between } P_n \text{ and } P_{n+1}. \end{aligned}$$

In other words, discrete data points (e.g.,  $P_{n-1}$ ,  $P_n$ , and  $P_{n+1}$ ) are replaced with a polyline consisting of two line segments (e.g., one line segment connecting  $Q_{n-1}$   $Q_n$  and the other connecting  $Q_n$   $Q_{n+1}$ ). It should be noted that available maps of interstate highways are based on geographic location information collected – in some cases, many years ago – by the U.S. Geological Survey (USGS). It is common for geographic information collected by different agencies, at different times, using different equipment, to result in minor discrepancies in displays, especially when viewed at high spatial resolution.

## 4.2 COMPARISON OF U.S. XPRESS AND PRAXAIR DATA ANALYSES

Most of the data analysis efforts performed under this study were conducted using U.S. Xpress data sets. The early data sets received from Praxair contained fragmented data, and the problem causing the fragmentation was difficult to diagnose. Although the Praxair data sets contained a date field, which eliminated the problem inherent in the U.S. Xpress data sets of determining the beginning and ending of a “trip” (see Section 4.3), the fragmentation problem caused most of the Praxair data sets to be unusable for our purposes. Sections 4.3-4.4 provide information and analyses on U.S. Xpress truck trips, and Section 4.5 discusses Praxair data.

## 4.3 IDENTIFICATION OF INDIVIDUAL U.S. XPRESS TRUCK TRIPS

With the exception of a few locally oriented short trips, the U.S. Xpress trucks participating in this study traveled a long-distance route between Atlanta, Georgia, and Wilmington, Ohio (see Figure 4.1). These long-distance truck trips were almost entirely on I-75. Since U.S. Xpress data did not typically contain information on travel date nor truck/trailer identification, data transmitted from the trucks were received as a long continuous stream of records. Additional effort was, therefore, required to separate these data into meaningful northbound or southbound truck-trips.

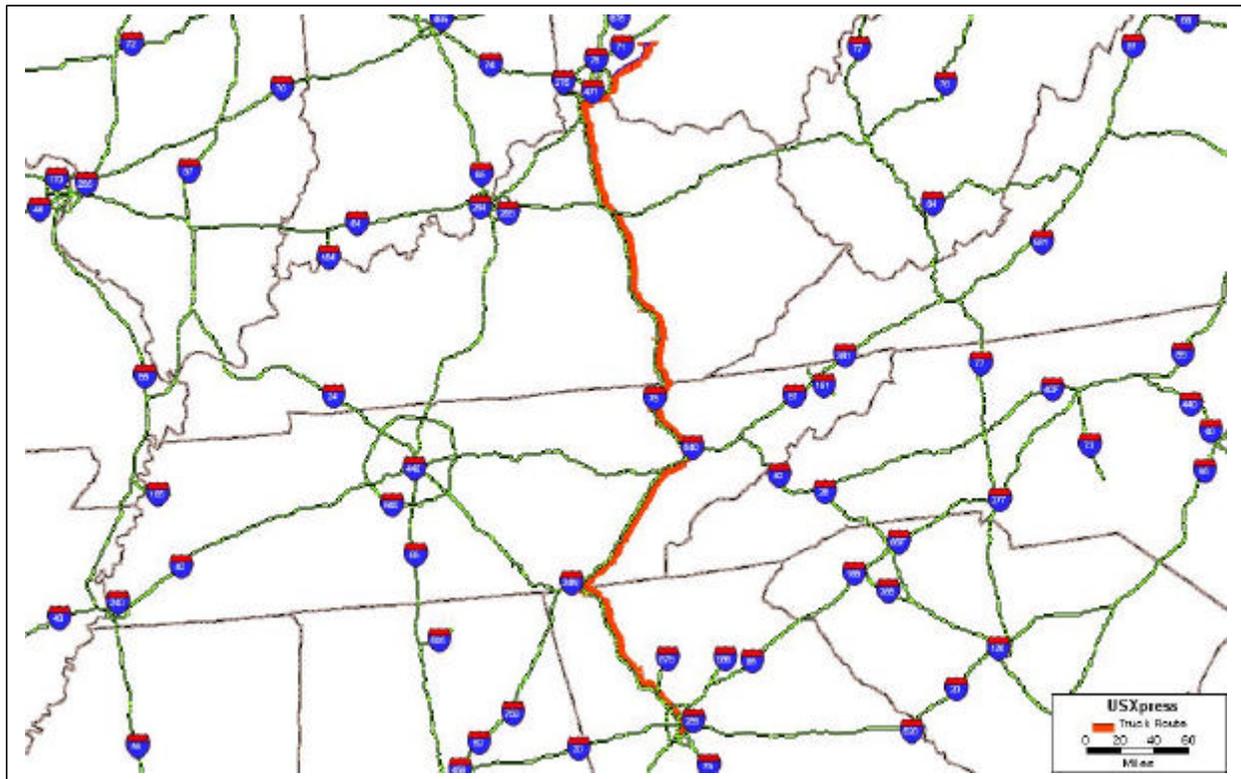


Figure 4.1. U.S. Xpress truck travel path.

To identify and separate individual truck trips, the project team developed a fairly simple algorithm that takes into consideration both spacial and temporal data gaps in the data stream. The algorithm allows one to set criteria to define the beginning of a truck trip. These criteria include (1) setting a temporal gap limitation (e.g., 30 minutes) or a spacial gap limitation (e.g., 2 miles); (2) setting a temporal gap limitation and a spacial gap limitation; (3) setting a temporal gap limitation or a fixed distance from a fixed point; and (4) setting a temporal gap limitation and a fixed distance from a fixed point. It should be noted that this algorithm would not necessarily generate “perfect” results. Some manual modification of the preliminary results might be needed.

Data from Praxair trucks did not require this trip-identification process because the Praxair data contained date information.

#### **4.4 ANALYSIS OF U.S. XPRESS TRUCK DATA**

The largest U.S. Xpress data file received (i.e., log.txt, June 2000) was processed using the method described above. Over 80 long-distance one-way truck trips were identified from this process. These trucks traveled, either northbound or southbound, between Atlanta, Georgia, and Wilmington, Ohio, and, generally, made a stop at a location near Corbin, Kentucky, to switch drivers. Only three of over 80 truck trips contained a significant amount of trailer data (i.e., measurements on lateral and longitudinal accelerations). These three routes are referred to as the “complete” trips in this report. Detailed analyses were conducted using data from these “complete” runs to evaluate the characteristics of, and relationships among, measurements collected from the on-board instruments. The following presents a summary of these results.

The U.S. Xpress truck trip data set described in this section contained a northbound trip, which began at Atlanta, Georgia, and ended at Wilmington, Ohio (Figure 4.1). Time series plots for several on-board-system-recorded data items were generated to evaluate possible changes in driving behavior or patterns along the travel path. Spatial displays of these measurements were reviewed using the GIS tool as described previously. This type of analysis is especially useful in visualizing measurement variations due to changes in roadway curves or types (e.g., urban streets or rural interstates).

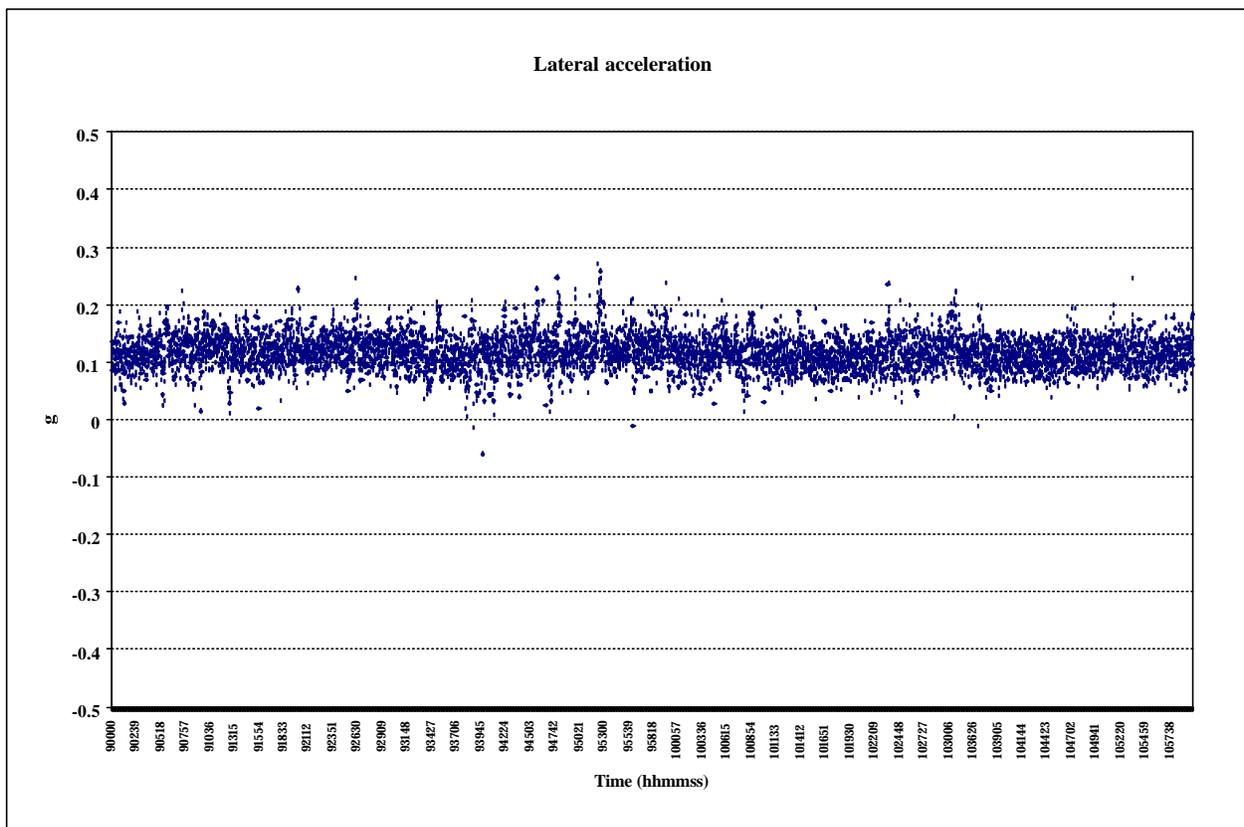
##### **4.4.1 Measurements over time**

###### Lateral acceleration

Lateral acceleration is an important measurement in studying the relationship between truck-roll stability and the roadway design of a location. Generally, lateral acceleration is a positive or negative value between -1.0 g and +1.0 g. The unit “g” represents the acceleration of one unit of the earth gravity which is  $9.8 \text{ meter/sec}^2$ , or equivalently  $32 \text{ feet/sec}^2$ . The sign of this value

depends on the direction of a turn that the truck makes at a roadway curve. When traveling on a straight and level roadway, the average lateral acceleration is expected to be zero.

A set of lateral acceleration measurements recorded by the trailer-mounted instrument, for a selected period of approximately two hours, is presented in Figure 4.2. This specific time period was chosen because it included data collected from the location where I-24 and I-75 merge. This I-24/I-75 junction, located near Chattanooga, Tennessee, has a relatively sharp turning curve (see Figure 4.3). It was expected that measurements of lateral acceleration at this location would be higher than those measured at other straighter stretch of the I-75.



**Figure 4.2. Lateral acceleration measured during the selected 2-hour period.**



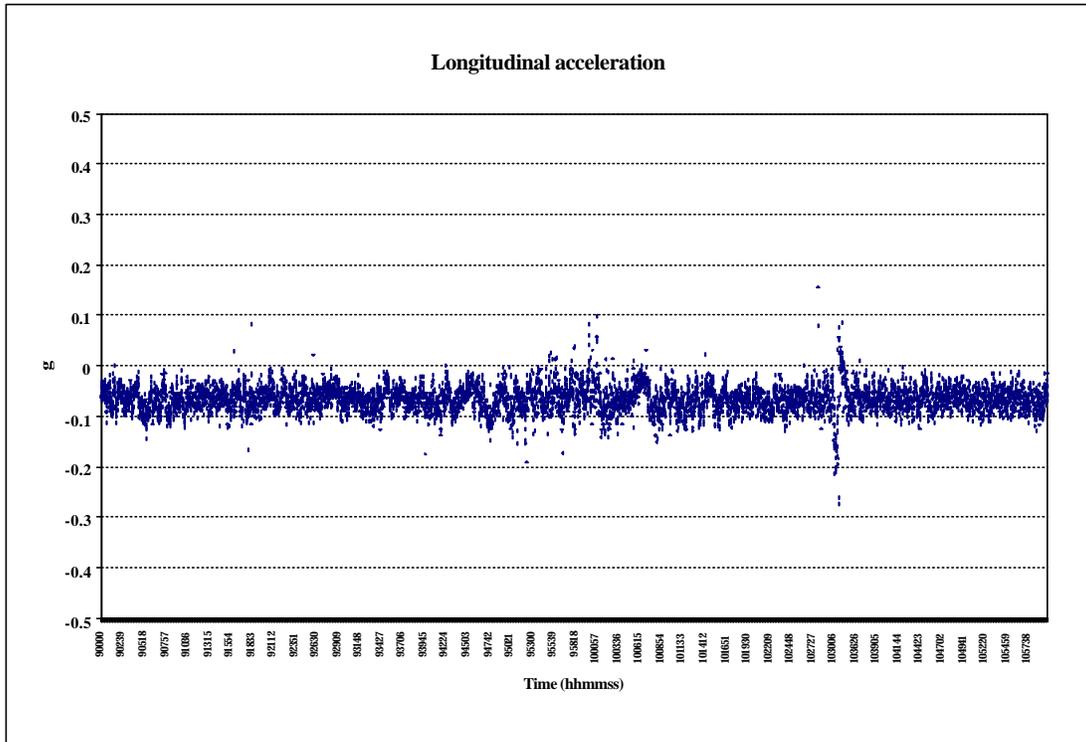
**Figure 4.3. Truck trajectory on curve at junction of I-24/I-75 near Chattanooga, Tennessee.**

From Figure 4.2, it appears that the average lateral acceleration is located approximately at +0.12 g. Further review of lateral accelerations collected for the entire travel path revealed that similar positive values were measured from all locations. Review of another data set from a different U.S. Xpress truck-trip confirmed the existence of this positive bias. The sensors on the trailer have known temperature coefficients, and some instrument drift probably occurred. Refined analysis of the data should allow separation of these two causes of biased readings, but a simple adjustment as discussed later in this report was used by the project team for this analysis. A simple calibration check (described in Appendix D) would resolve any ambiguities and assure valid data.

### Longitudinal acceleration

Longitudinal acceleration measurements for the same data set are presented in Figure 4.4. Longitudinal acceleration measurements represent either actual forward acceleration, braking, or the effect on a vehicle traveling either downhill or uphill at a location. When traveling at constant speed on a “flat” roadway with a properly calibrated instrument, readings from this measurement should be on or near zero. It can be easily seen from Figure 4.4 that an unusual change of pattern occurred at approximately 10:30 Universal Time. Further examination of associated geographic location information with the *Maptitude* GIS tool pointed to a four-lane,

steep uphill stretch on northbound I-75 near the town of Ooltewah at the north of Chattanooga in Tennessee, followed by a three-lane downhill section. Trucks were required to travel on the two right-most lanes while ascending the hill.



**Figure 4.4. Longitudinal acceleration measured during the selected 2-hour time period.**

### Recorded speed

Figure 4.5 is a time-series plot of the truck speed as recorded by the on-board instrument for the same data set. The data capturing utility program (see Appendix A) was designed to log vehicle speeds only when the speed changed by 2 MPH and the GPS data was logged. A minimum speed of 10 MPH was set for the data logger on U.S. Xpress trucks. The GPS data were logged only when this minimum speed was met. Data for recorded speeds, as shown in Figure 4.5, were rather spotty, which indicated that the truck traveled mostly around steady speeds. Speed was recorded more frequently at the area of the I-24/I-75 junction. Moreover, a rapid decline of speed followed by a rapid gain of speed can also be clearly seen at the location where the steep hill is located.

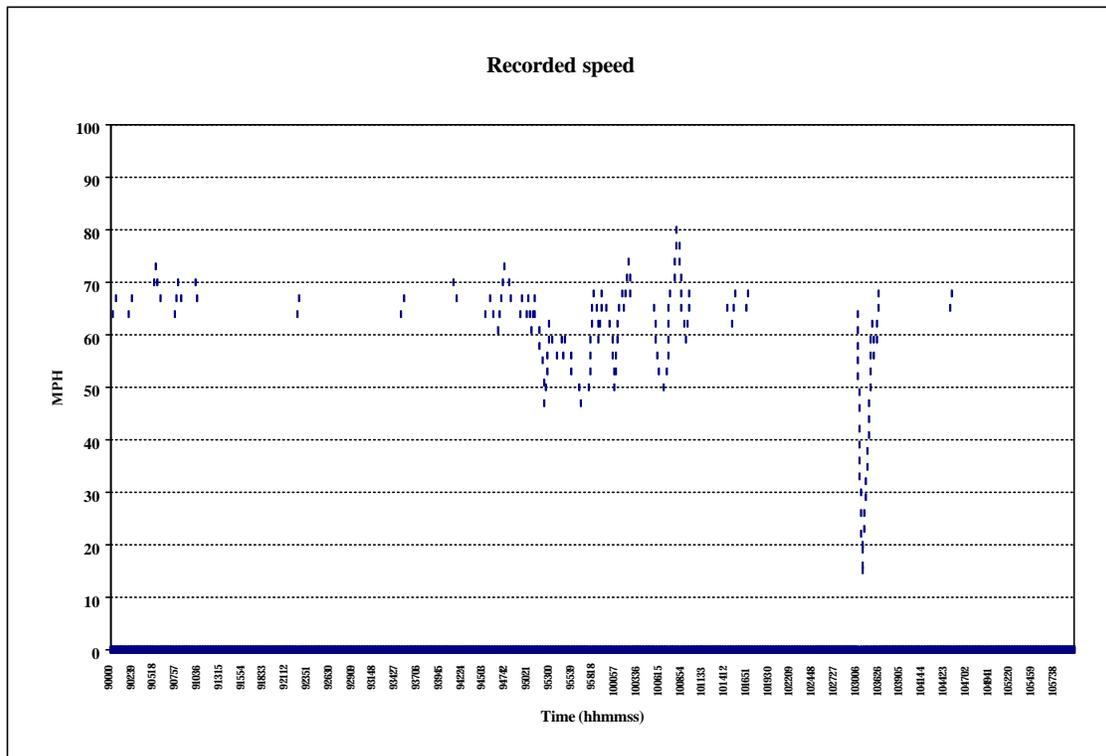
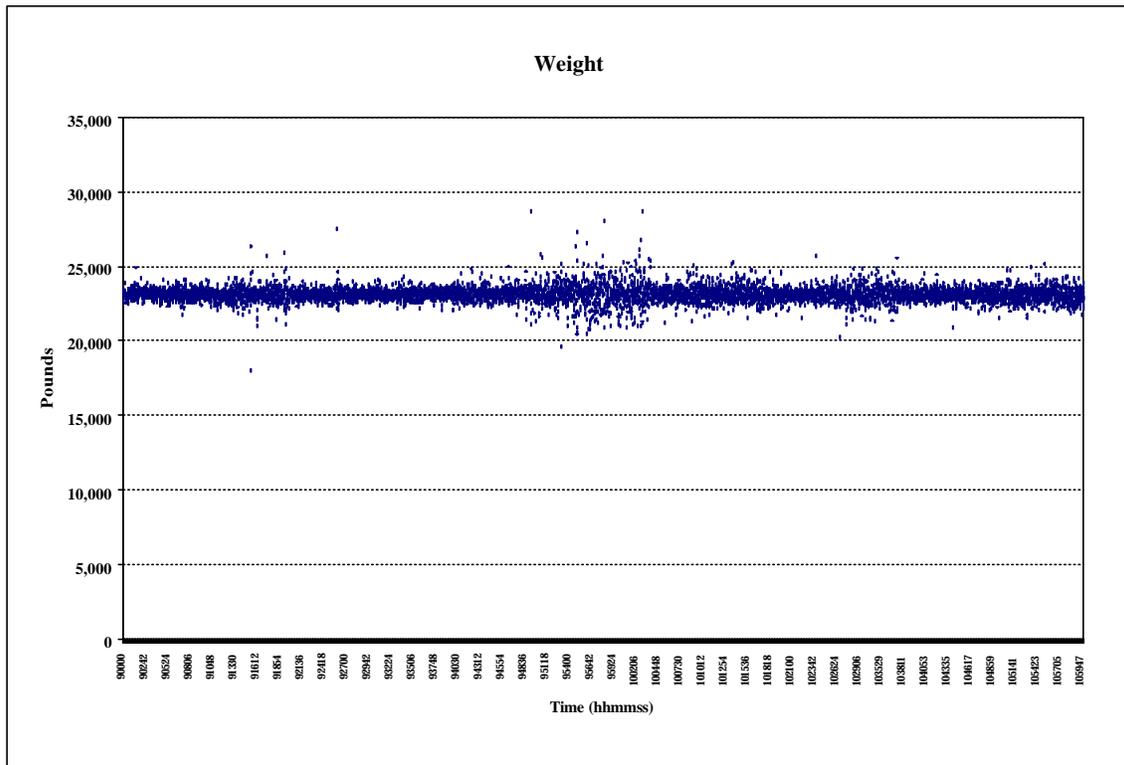


Figure 4.5. Speed (MPH) recorded by the on-board instrument for the selected time period.

### Rear-axle weight

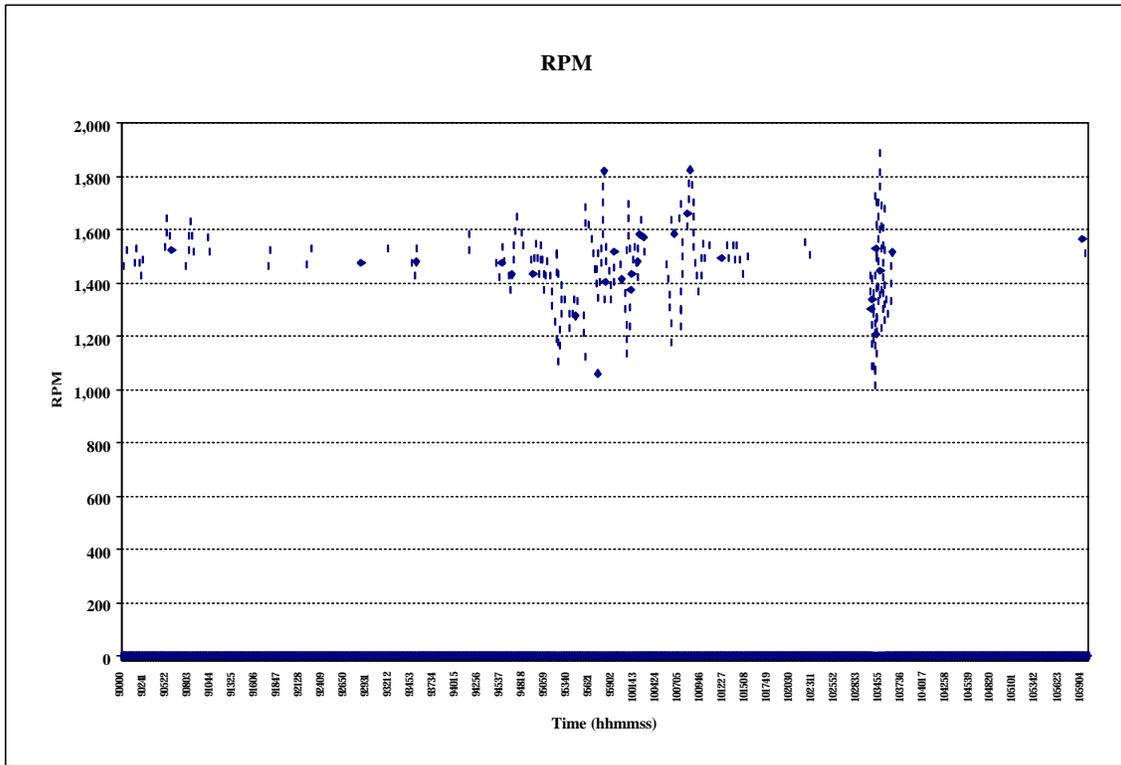
The instrument mounted on the trailer also records the weight of truck and load (in pounds) at its back axle. Measurement of load from the same data set (as used in previous figures) is displayed in Figure 4.6. When traveling on a “flat” and straight roadway, the rear-axle weight of a truck should stay at a relatively constant level. Geographic impacts to the weights measured around the two specific locations (i.e., I-24/I-75 curve and the steep hill) can be seen from the graph shown in Figure 4.6.



**Figure 4.6. Rear axle weight measured during the selected 2-hour time period.**

### Engine speed

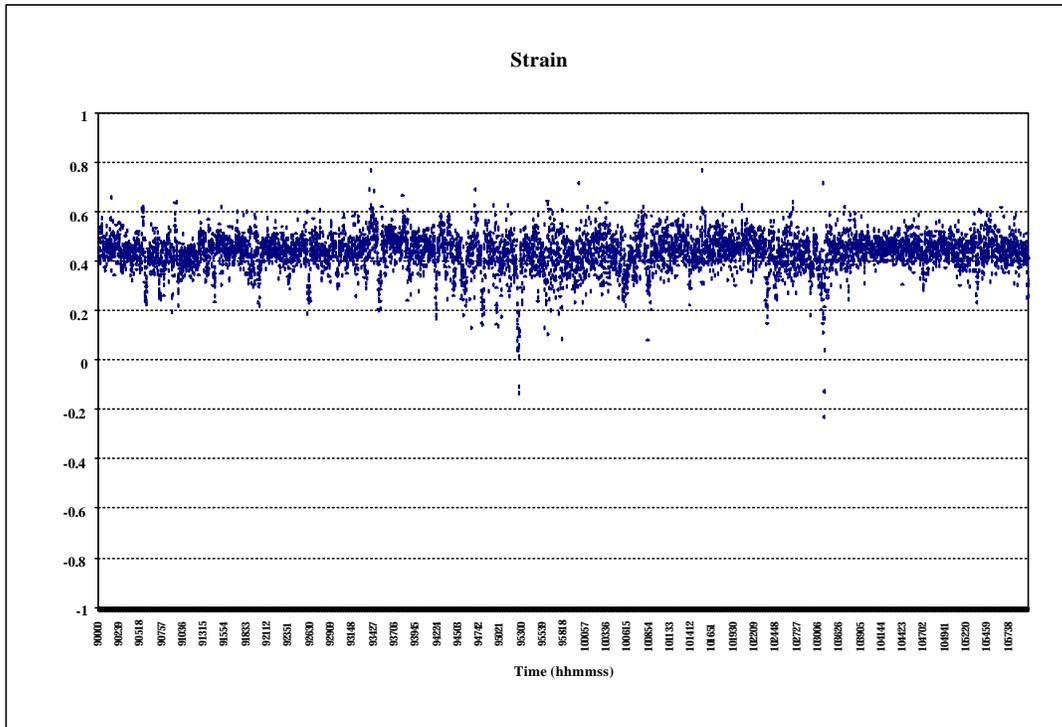
Vehicle engine rotational speed, i.e., RPM, was also logged by the on-board computers on these trucks. To minimize the data storage requirement of the output file, the data logger recorded the RPM measurement only if it changed by 50 RPM. It was anticipated that these RPM measurements could provide insight into driver behavior as well as the driving situation at a given location. Figure 4.7 shows values of RPM from the same data set as those used in earlier discussions. Changes in RPM measurements can be seen at I-24/I-75 junction as well as at the location of the steep hill.



**Figure 4.7. RPM measurements for the selected 2-hour time period.**

### Strain

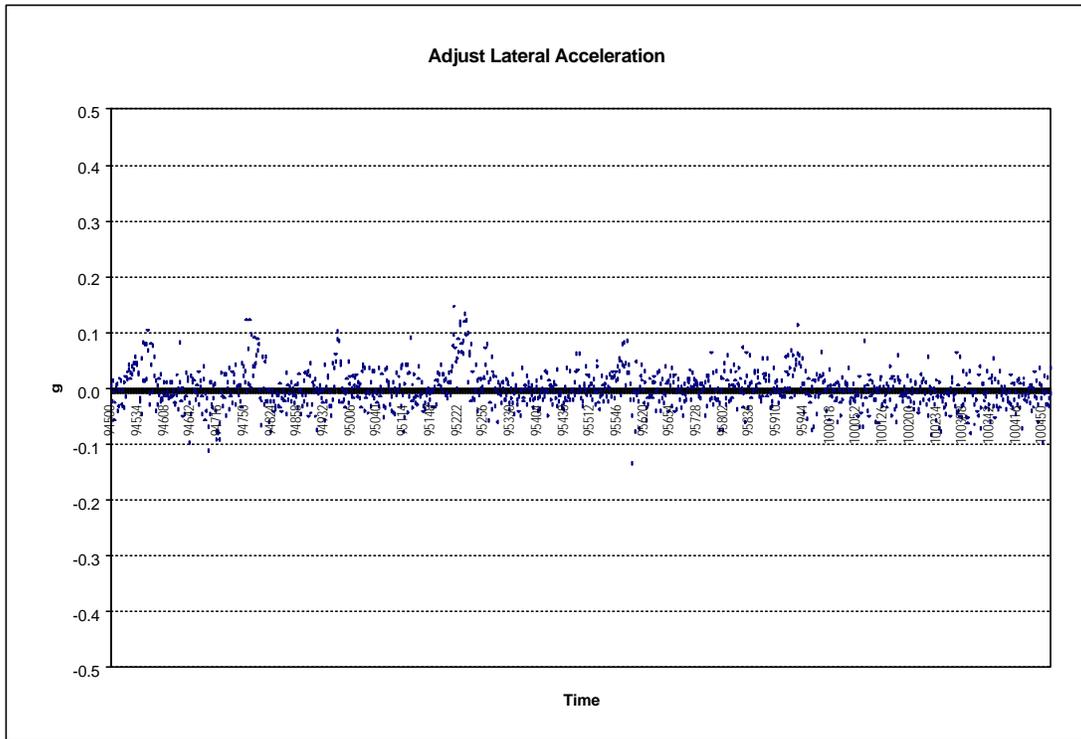
Another measurement collected from the on-board system was the vehicle torque-tube strain. These data were used to determine truck roll response to lateral acceleration. Figure 4.8 displays the strain measured for the same trip as those used in earlier figures.



**Figure 4.8. Measurements of strain for the selected 2-hour time period.**

#### **4.4.2 Adjustment to correct instrument bias**

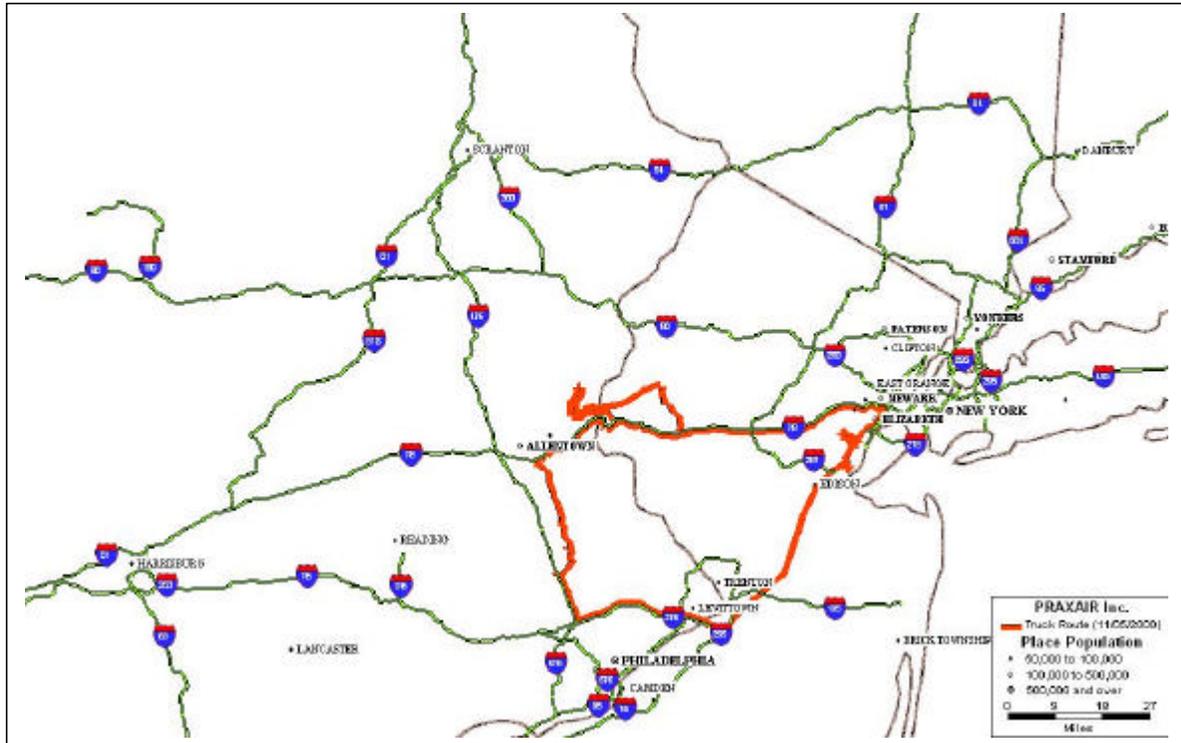
As discussed before, lateral acceleration measured at a straight stretch of roadway should be approximately zero. Review of lateral accelerations collected from U.S. Xpress trucks revealed a positive value “band” at about +0.12 g for the entire travel path. A simple adjustment was used to correct this positive bias. Values of lateral acceleration were adjusted downward by subtracting the average value calculated from measurements collected from all locations on the travel route. These adjusted lateral acceleration measurements are presented in Figure 4.9.



**Figure 4.9. Adjusted lateral acceleration measurements for the selected 2-hour time period.**

#### **4.5 ANALYSIS OF PRAXAIR TRUCK DATA**

Unlike U.S. Xpress trucks which travel along the same north-south route between Ohio and Georgia, Praxair trucks travel to different locations in Pennsylvania, New Jersey, New York, and Connecticut. The routes use a combination of local streets and limited-access highways. It should be noted that of the five data sets received from Praxair between June and November, most of them contained very fragmented data. Based on the largest and most complete data sets received (November 2000 and January 2001) from Praxair, ORNL was able to complete some limited analysis. This set of data shows that Praxair trucks make frequent stops along the travel routes. Figures 4.10-4.14 show routes for the Praxair instrumented trucks for November 5-9, 2000.



**Figure 4.10. Praxair truck route on November 5, 2000.**

Data collected during these five days indicated that all Praxair trucks left from Stockertown, Pennsylvania, to begin their trips. In four of the five days, these trucks returned to the same location at the end of their routes. The only exception was on November 7<sup>th</sup>. On this trip (Figure 4.12), the truck left Stockertown, traveled through Danbury, Connecticut, where the Praxair Headquarters is located, traveled back to Stockertown via a different route, and continued on to New York.

Data collection operation, from the truck-mounted equipment, appeared to be incomplete for November 8<sup>th</sup> (see Figure 4.13). Because of the frequent stops, the speed measured from Praxair trucks showed a very different pattern from that of U.S. Xpress trucks. Figure 4.15 shows the speed changes for a Praxair truck on November 5. Recall that speed was only recorded when there was a difference of at least 2 MPH in the measured speed. In many cases, at the locations of the truck stops, the load also changed; Figure 4.16 shows weight changes for the November 5 route.



Figure 4.11. Praxair truck route on November 6, 2000.



Figure 4.12. Praxair truck route on November 7, 2000.

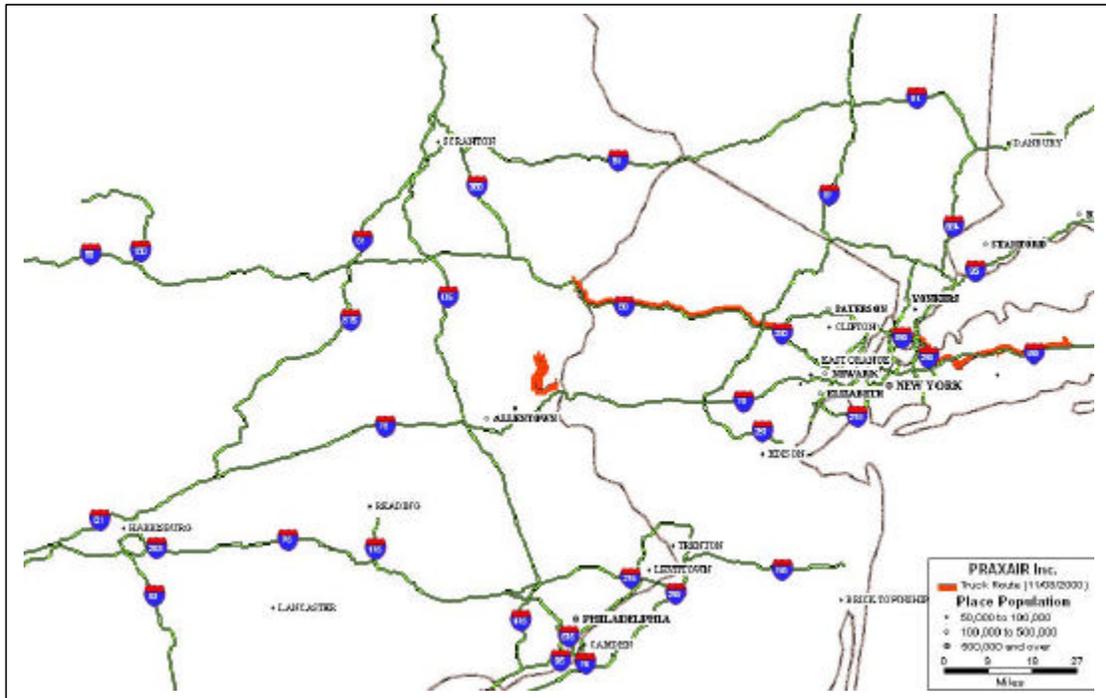


Figure 4.13. Praxair truck route on November 8, 2000.

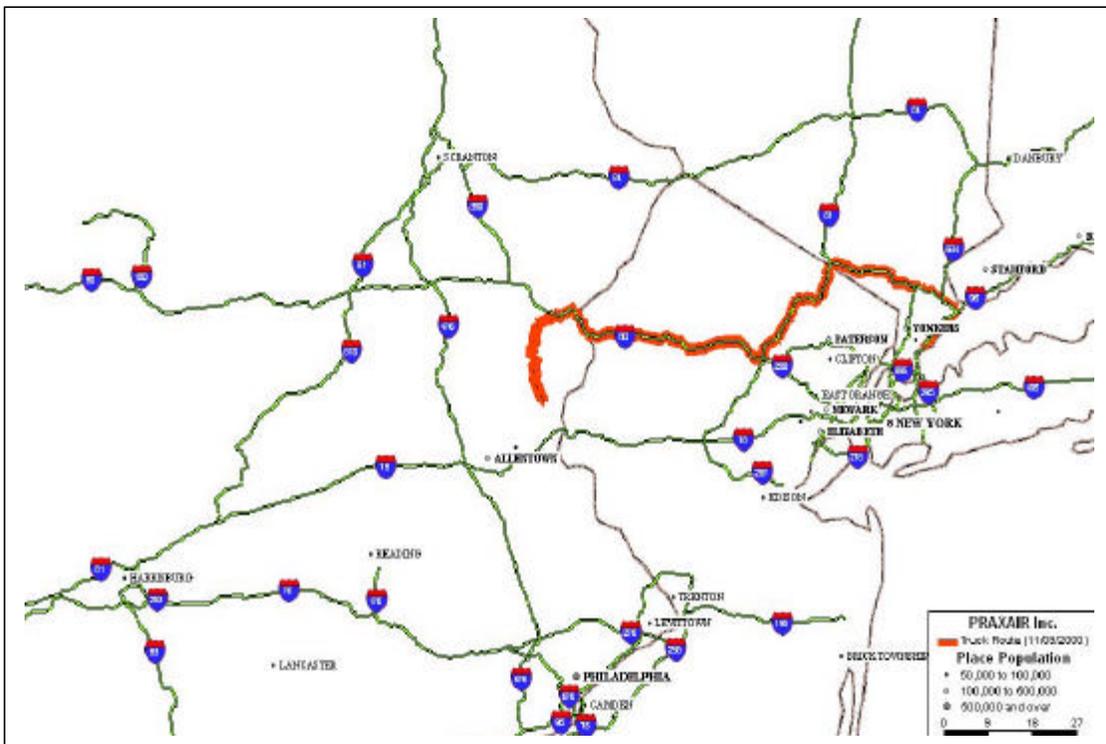


Figure 4.14. Praxair truck route on November 9, 2000.

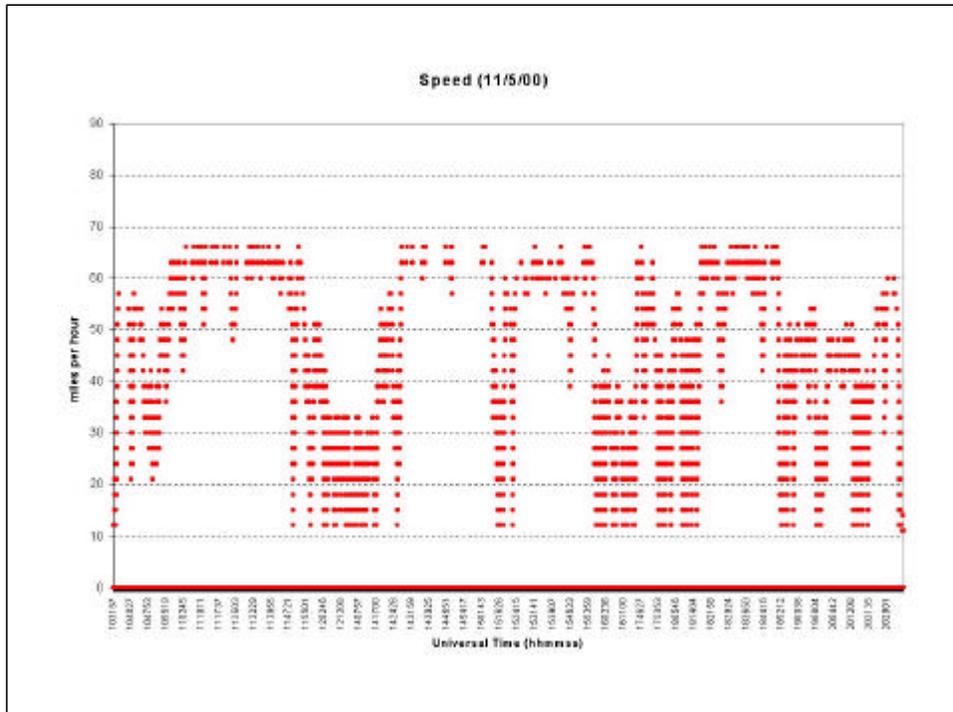


Figure 4.15. Speed measured on November 5, 2000, for a Praxair truck.

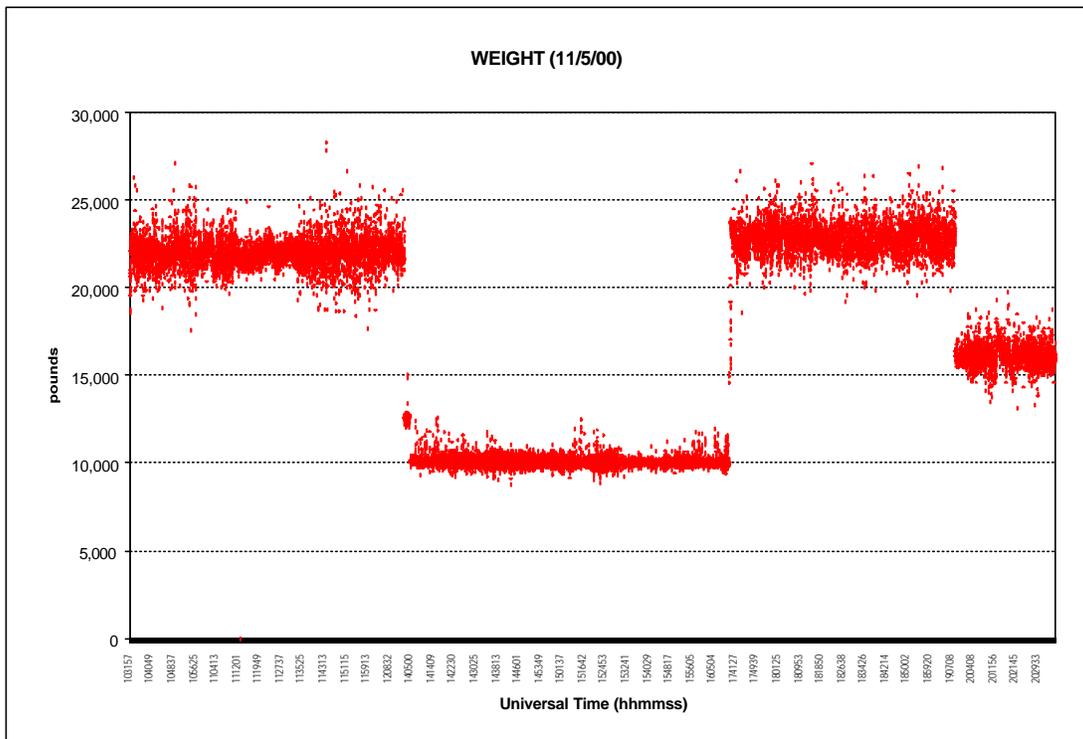
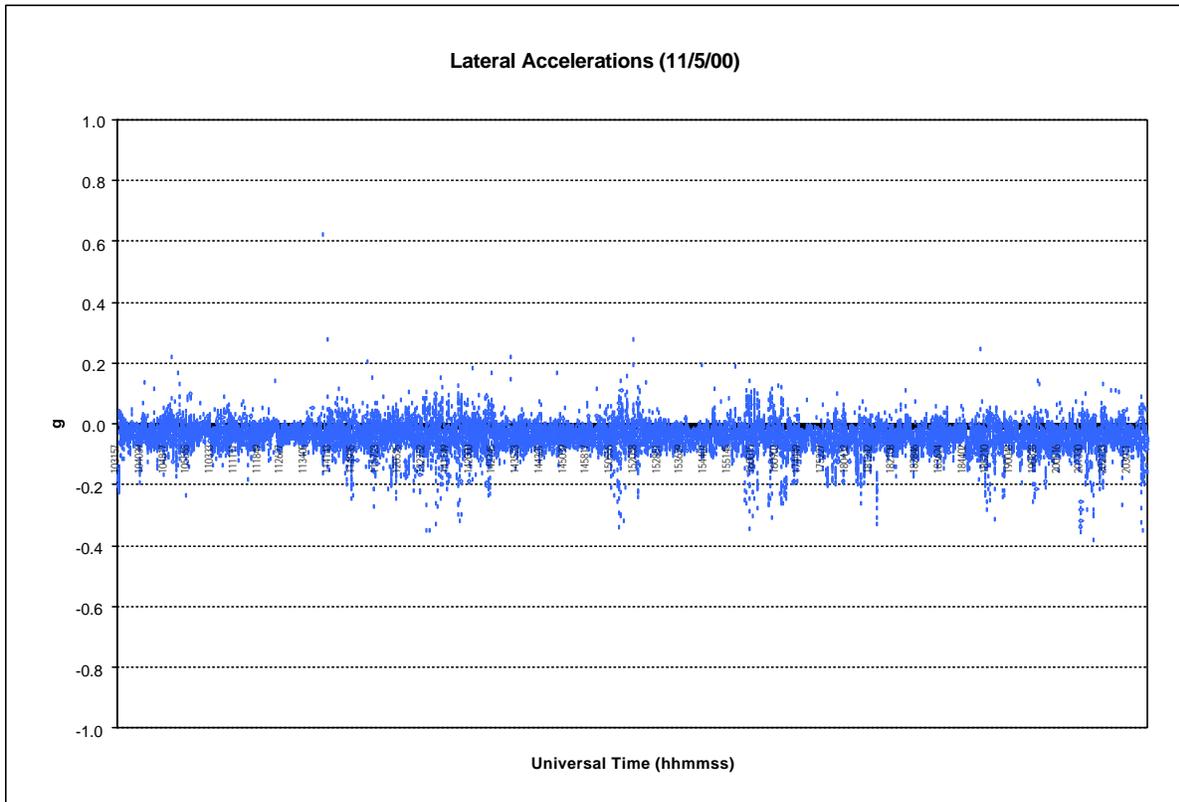


Figure 4.16. Weight measured on November 5, 2000, for a Praxair truck.

Analysis of the Praxair lateral acceleration data produced results similar to those collected from the U.S. Xpress trucks. Figure 4.17 shows lateral acceleration for a Praxair truck on November 5. Unlike the U.S. Xpress data, the Praxair lateral acceleration measurements did not indicate any instrument shifting. In other words, no systematic bias was observed from the Praxair data. The relatively frequent stops and truck-weight changes are mainly due to the characteristics of Praxair's operation.



**Figure 4.17. Lateral acceleration measured on November 5, 2000, for a Praxair truck.**

A review of Praxair data from the January data set revealed similar patterns in the driving behavior to that of the November data. Most routes began from Stockertown, Pennsylvania, made the runs in similar regions, and then returned to Stockertown.

## 4.6 EVALUATION OF GPS DATA ACCURACY

Originally developed by the Department of Defense (DOD) as a military system, GPS has become a global utility. It benefits users around the world in many different applications, including air, road, marine, and rail navigation, telecommunications, emergency response, oil exploration, mining, and others. In an effort to protect the security interests of the United States and its allies, a feature called Selective Availability (SA) was implemented on March 25, 1990, on all GPS Block II satellites. SA was a technique to reduce the accuracy of un-augmented, single-receiver GPS measurements. This purpose was accomplished by altering the GPS satellite clock signals, and by modifying orbital elements of the broadcast navigation message. These alterations were done in a coded fashion and could be removed by authorized users. This alteration caused horizontal positional errors on the order of 100 meters (95%) and varied in a manner that prevented rapid averaging of positional data.<sup>6</sup>

SA was discontinued during Operation Desert Storm in September 1990 and was returned to standard level on July 1, 1991. On May 1, 2000, President Clinton announced that the United States would stop the intentional degradation of GPS signals available to the public. Therefore, beginning at midnight on May 1, 2000, the discontinuation of SA meant that civilian users of GPS were able to pinpoint locations with much more accuracy, although the total improvement might be expected to vary depending upon the particular receiver and the level of solar disturbance of the ionosphere. Effort was made by the ORNL project team to evaluate the accuracy of GPS data collected by the GPS receiver mounted on tractors participating in this project, during periods before and after May 1, 2000.

Two locations along the U.S. Xpress truck route were selected for the initial assessment. The first location was on a straight segment of I-75 around Farragut, Tennessee, and the second location was on a straight segment of I-275 at the eastern suburb of Cincinnati, Ohio. The first location had east-west traffic with three lanes in each direction and no dividing grass mall area. The second location had north-south traffic with two lanes in each direction and a 70- to 80-foot-wide median grass mall.

Data received from U.S. Xpress in June 2000 was selected for this preliminary investigation because it was a fairly large file which contained more “runs” along this route. As mentioned previously, U.S. Xpress GPS data do not contain information on date of data collection. A few system initialization records from the on-board system in these U.S. Xpress trucks contained date data, however, and these dates were used to approximate the GPS data collection dates. Although the data set used was received in June 2000, data on dates reflected that the data were collected prior to May 1, 2000.

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<sup>6</sup> Federal Geographic Data Committee. [http://www.ngs.noaa.gov/FGCS/info/sans\\_SA/](http://www.ngs.noaa.gov/FGCS/info/sans_SA/) .

Using a GIS tool and overlaying these GPS data with satellite images of these roadways, it appeared that GPS data collected along the first location had significantly large variations. GPS data collected at the second location, however, showed much smaller variations. To further examine the precision of the GPS system used during this study, ORNL developed an analytical methodology to quantitatively measure the degree of variations (i.e., accuracy) in these GPS data. This method is described as the following.

First, at each selected location, a line perpendicular to the highway alignment was determined. Line segments connecting two successive GPS data pairs in each truck “run,” intersecting this perpendicular line, were then marked. Ten GPS data points were extracted from each of the “runs” passing the selected locations. Five were immediately prior to, and the other five were immediately after, the intersection point. Because of the time series nature of data collected from the GPS receiver, direction of travel could be easily identified and “runs” could be distinguished. There are over forty data sets, each representing a “run” passing the study site, in each travel direction at these two locations.

Next, another line parallel to the highway alignment was determined as a reference line. Distances in feet for the above-described 10 points in each data set to this reference line were calculated. The standard deviations of these distances for each data set were also calculated. These standard deviations were used to quantify variations of the truck trajectories or the “width” of the truck trajectories “band.”

Based on preliminary observation, the GPS receiver used in this study did generate good “relative” longitude and latitude data series. In other words, geographic information generated by the GPS receiver produced smooth trajectories. However, significant discrepancies were visible when the truck trajectories were overlaid on the aerial photograph.

At the first location, the calculated standard deviations were 193.13 and 83.38 feet for east-bound (Figure 4.18) and west-bound (Figure 4.19), respectively, truck trajectories. On the other hand, the standard deviations were 6.85 and 9.74 feet for north- and south- bound traffic, respectively, at the second location (Figure 4.20). Assuming that truck trajectories follow the normal distribution, 95% of the truck trajectories fell within a band of two standard deviations on each side of the mean (i.e., average). This results in a width of  $193.13 \times 4 = 772.52$  feet for the east-bound traffic at the first location. This band is quite wide. On the contrary, 95% of the truck trajectories for the north-bound traffic at the second location were within a band less than 28 feet wide.

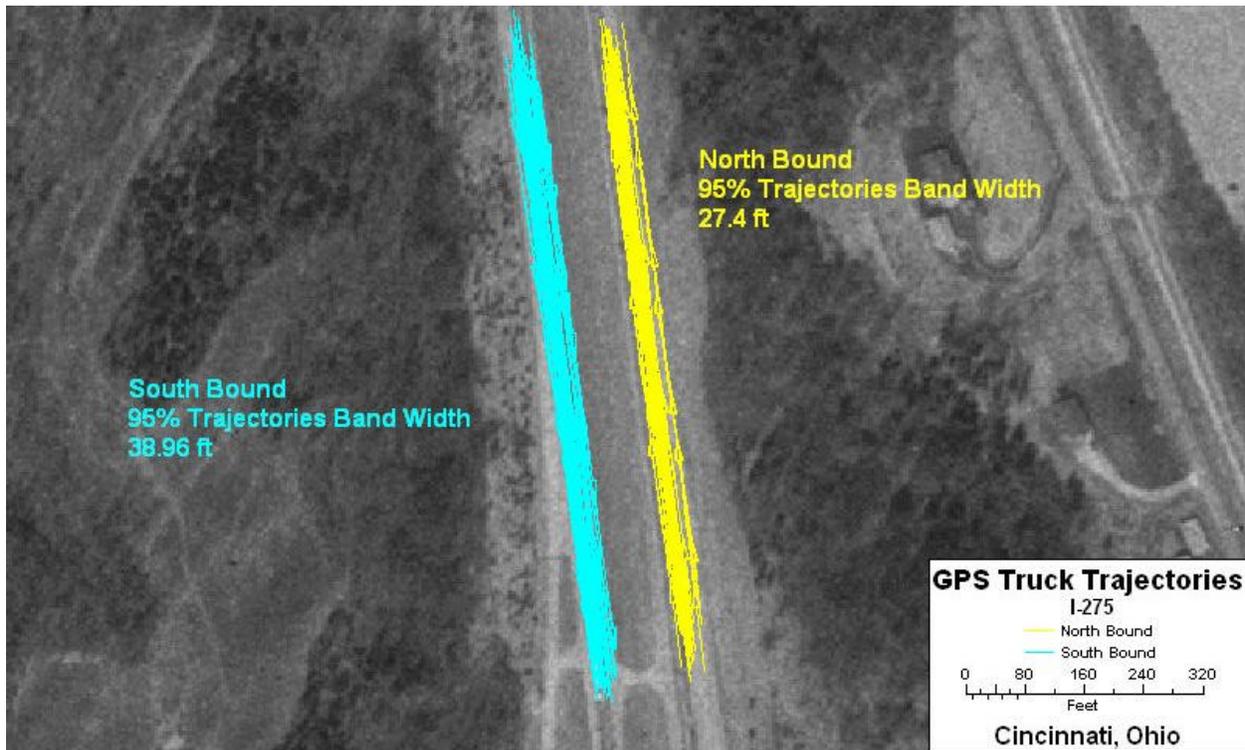
To see the GPS accuracy improvement after the discontinuation of SA, data collected from U.S. Xpress trucks after May 2000 were reviewed. Due to equipment failure in U.S. Xpress trucks, unfortunately, GPS data for this time period were very limited. ORNL could only identify data for three truck “runs” from a data set received in August 2000. Nevertheless, when overlaid on a satellite image of roadways, these GPS data appeared to be right on the highway lanes (Figure 4.21). Interestingly, one can clearly see the drifting of GPS signals when they were blocked by the I-40 overpass.



**Figure 4.18. East-bound, I-75, pre-May 1, 2001, truck trajectories, measured near Knoxville, Tennessee. Note: band width = 773 feet.**



**Figure 4.19. West-bound, I-75, pre-May 1, 2001, truck trajectories, measured near Knoxville, Tennessee. Note: band width = 334 feet.**



**Figure 4.20. North-bound and south-bound, I-275, pre-May 1, 2001, truck trajectories measured near Cincinnati, Ohio. Note: band widths = 27 feet (north-bound) and 39 feet (south-bound).**



**Figure 4.21. North-bound and south-bound, post May 1, 2001, truck trajectories, measured near Knoxville, Tennessee. Note the drift when signals were blocked by the overpass.**

Since there is no large set of data available from the U.S. Xpress trucks after May 2000, data from Praxair files were used to illustrate the change in GPS data accuracy. Due to the nature of Praxair's business, their trucks did not travel on a single fixed route as did the U.S. Xpress trucks. Praxair routes, generally, started from a distribution facility located near Stockertown, Pennsylvania, and returned to the same location at the end of their "runs." Therefore, to maximize the number of truck trips passing through a segment of roadway, two locations on SR-33, one on the north and the other on the south of Stockertown, were selected for this evaluation.

Using a similar method as that described earlier, it was found that standard deviations for these two locations were extremely narrow. The standard deviations were approximately 4 feet for both north-bound and south-bound trucks at the location north of Stockertown (Figure 4.22). This yields a 16-foot band in which 95% of the trajectories of trucks that pass this location (either north- or south-bound) fall. Similarly, the standard deviations for the second location, which is south of Stockertown, were 5 feet for the north-bound trucks and 6 feet for the south-bound trucks (Figure 4.23). In other words, about 95% of the truck trajectories will fall within a band that is less than 25 feet wide for both travel directions at this second location.



**Figure 4.22. North-bound and south-bound, post May 1, 2001, truck trajectories, measured north of Stockertown, Pennsylvania. Note: band widths = 16 feet (north-bound) and 15 feet (south-bound).**



**Figure 4.23. North-bound and south-bound, post May 1, 2001, truck trajectories, measured south of Stockertown, Pennsylvania. Note: band widths = 19 feet (north-bound) and 24 feet (south-bound).**

To put this in perspective, a typical highway lane has a width of 12 feet. Two lanes plus the shoulder would be about 26-28 feet. Furthermore, assuming an average travel speed of 55 MPH on these roadways, the truck would be moving about 81 feet per second. Using these criteria as “benchmark” measurements, one can easily see that GPS data received from Praxair trucks participating in this study were quite accurate.

#### **4.7 ESTIMATES BASED ON THE GPS DATA**

GPS data (time and geographic location) are available from the 80+ runs logged by the U.S. Xpress vehicles. Using these data, one can mathematically estimate vehicle speed, vehicle traveling directional change (i.e., turning angle), as well as lateral and longitudinal accelerations at a given location. It is then possible to compare the estimated values with the actual recorded measurements. For simplicity, a “flat” roadway was assumed for the analysis in this section. Computer program codes written in Microsoft’s *Visual FoxPro* to perform these calculations are included in Appendix C of this document.

### 4.7.1 Mathematical method to calculate turning angle

The mathematics used to calculate the turning angles along the travel path is as follows: suppose a polyline is defined by three points  $P_1$ ,  $P_2$ , and  $P_3$  in a two-dimension Euclidian plane. The objective is to find the angle,  $\alpha$ , between lines  $P_2P_1$  and  $P_2P_3$ . Assume the coordinates of these three points are  $(x_1, y_1)$ ,  $(x_2, y_2)$ , and  $(x_3, y_3)$  for  $P_1$ ,  $P_2$ , and  $P_3$ , respectively.

Then, the angle  $\alpha$  can be calculated as:

$$\alpha = \alpha_2 - \alpha_1, \text{ if } \alpha_2 \geq \alpha_1,$$

or

$$\alpha = \alpha_2 - \alpha_1 + 360^\circ, \text{ otherwise,}$$

where  $\alpha_1$  is the angle between line  $P_2P_1$  and the line passed through  $P_2$  and parallel to the X-axis, and  $\alpha_2$  is the angle between line  $P_2P_3$  and the line passed through  $P_3$  and parallel to the X-axis.

These two angles,  $\alpha_1$  and  $\alpha_2$ , can be mathematically expressed as:

$$\alpha_1 = \text{ArcCosine}[(x_2 - x_1) / ((x_2 - x_1)^2 + (y_2 - y_1)^2)^{0.5}], \text{ if } P_1 \text{ is in the first or second quadrant,}$$

$$\alpha_1 = 180^\circ - \text{ArcSine}[(y_2 - y_1) / ((x_2 - x_1)^2 + (y_2 - y_1)^2)^{0.5}], \text{ if } P_1 \text{ is in the third quadrant,}$$

$$\alpha_1 = 360^\circ + \text{ArcSine}[(y_2 - y_1) / ((x_2 - x_1)^2 + (y_2 - y_1)^2)^{0.5}], \text{ if } P_1 \text{ is in the fourth quadrant;}$$

and

$$\alpha_2 = \text{ArcCosine}[(x_2 - x_3) / ((x_2 - x_3)^2 + (y_2 - y_3)^2)^{0.5}], \text{ if } P_3 \text{ is in the first or second quadrant,}$$

$$\alpha_2 = 180^\circ - \text{ArcSine}[(y_2 - y_3) / ((x_2 - x_3)^2 + (y_2 - y_3)^2)^{0.5}], \text{ if } P_3 \text{ is in the third quadrant,}$$

$$\alpha_2 = 360^\circ + \text{ArcSine}[(y_2 - y_3) / ((x_2 - x_3)^2 + (y_2 - y_3)^2)^{0.5}], \text{ if } P_3 \text{ is in the fourth quadrant.}$$

### 4.7.2 Estimate of speed

The on-board equipment also collects truck operating speed information. Truck speed is recorded only if it changes by 2 MPH from the previously recorded speed. This preserves the general pattern of the truck travel speed but provides less detailed information on speed variations. The message recorded from the on-board GPS unit contains the geographic location of the truck, and of course, the precise time. Based on these data, ORNL was able to calculate truck operating speed for each GPS data point. The GPS receiver also performs such a calculation, but it is not included in the currently-programmed message.

Suppose  $P_{n-1}$  and  $P_n$  are two consecutive GPS data points with associated time stamps  $T_{n-1}$  and  $T_n$ , respectively. The speed of a truck at location  $P_n$  can be calculation as

Speed at location  $P_n = (\text{distance between } P_{n-1} \text{ and } P_n)/(\text{travel time between } P_{n-1} \text{ and } P_n)$  .

Great circle distance between the two points was calculated based on their coordinates of latitude and longitude. Travel time was the difference between  $T_{n-1}$  and  $T_n$ , or  $T_n - T_{n-1}$  in seconds. The result was then converted to the unit of miles per hour.

### 4.7.3 Calculation of lateral and longitudinal accelerations

Using the methods described in Sections 4.7.1 and 4.7.2, travel speed and the related turning angle at each GPS data point location was calculated. Using these estimates, ORNL then mathematically computed the longitudinal and lateral accelerations in term of  $g$  (i.e., acceleration of one earth gravity).

Let  $P_{n-1}$ ,  $P_n$  and  $P_{n+1}$  be three consecutive GPS data points and angle  $2$  be the angle between lines  $P_n P_{n-1}$  and  $P_n P_{n+1}$ . Suppose  $S_n$  and  $S_{n+1}$  are the speeds at  $P_n$  and  $P_{n+1}$ , respectively. Then the longitudinal and lateral accelerations can be calculated as

$$\begin{aligned} \text{Longitudinal Acceleration} &= S_{n+1} H \sin(2_n) - S_n, \text{ per unit time (i.e., 1 sec), and} \\ \text{Lateral Acceleration} &= S_{n+1} H \cos(2_n), \text{ per unit time,} \end{aligned}$$

where  $2_n = 2 - 90E$  if  $2_n < 90E$ , or  $2_n = 270E + 2$ , otherwise .

Comparisons of the estimated and recorded lateral acceleration measurements were evaluated for four specific cases selected from the U.S. Xpress travel route. All four cases include locations with relatively sharp roadway curves. Results from this effort are presented in Appendix E.

Note that the instrument on the truck does not record elevation information at this time. The accelerations calculated from the above-mentioned formulas represent the accelerations of the truck when traveling on a flat surface. By comparing these estimated accelerations to those actual measurements of accelerations from the on-board accelerometer, it is possible to estimate pavement features such as super-elevation and the grades of vertical incline and decline. Collection and analysis of this sort of data is a straightforward extension of the collection and analysis presented here.