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USING GPS TRUCK DATA TO IDENTIFY AND RANK BOTTLENECKS IN WASHINGTON STATE

by

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Contents

Introduction 1
The GPS Data 1
The Bottleneck Identification Process 1
Task 1. Roadway Segmentation 3
Task 2. Add Attribute Information to the Segments 4
Task 3. Geo-Locate the Trucks 5
Task 4. Locate Bottlenecks 7
Task 5. Rank the Bottlenecks 9
Bottleneck Analysis Reports 10
References 12
Appendix A: Other Organizations' Bottleneck Identification Techniques A.1
Appendix B: GIS Techniques B.1
Appendix C: Speed Distribution Evaluation C.1

INTRODUCTION

The Washington State Department of Transportation (WSDOT), Transportation Northwest at the University of Washington, and the Washington Trucking Associations have partnered on a research effort to collect and analyze GPS truck data from commercial, in-vehicle, truck fleet management systems. This project is collecting commercially available GPS data and evaluating the feasibility of using them to support a state truck freight network performance-monitoring program. An important part of this effort consists of using these data to locate and rank truck bottlenecks on Washington's road network. This technical report discusses the bottleneck identification process.

THE GPS DATA

The project team currently receives daily GPS data from about 6,000 trucks traveling on roads throughout Washington state. A contract negotiated with a large GPS vendor has resulted in a near real-time raw data feed for all its client trucks when they travel in the state. The commercial in-vehicle GPS devices report, via cellular technology, both at preset intervals (every 10 to 15 minutes) and when the trucks stop. The resulting GPS data set includes reads for individual truck's longitude and latitude, the truck's ID (scrambled for privacy), spot (instantaneous) speeds, and a date and time stamp. Other variables in the data set include GPS signal strength, travel heading, and the status of a truck's stop (parked with engine on or engine off). More details about the data collection effort and the GPS-based performance measures program can be found in McCormack et al. (2010).

THE BOTTLENECK IDENTIFICATION PROCESS

A brief review of the techniques used by two other national organizations (the American Transportation Research Institute and the U.S. Department of Transportation) to identify truck bottlenecks is presented in Appendix A. Their approaches for calculating truck bottlenecks were not used for this effort because their approaches would not take full advantage of the high level of GPS data and roadway information available in Washington state.

The bottleneck identification process developed for Washington state is designed to find sections of Washington's roadways that perform poorly for trucks and then to develop quantitative measures that allow these bottlenecks to be ranked and compared. The process is designed to be repeatable and statistically valid while also producing results that are usable and readily comprehended by transportation professionals and decision makers. Because the results are oriented toward WSDOT's mission, the measures also have to reasonably mesh with measures that WSDOT has already developed for evaluating congestion and roadway performance for all types of vehicles.

The bottleneck process must also account for network reliability, since travel reliability (travel time consistency) is as important as travel speed to the trucking community. For example, the USDOT's office of operation noted, "Shippers and freight carriers require predictable travel times to remain competitive" (U.S. Department of Transportation 2011). This view is supported by input from local trucker's focus groups, as well as by input from WSDOT's Freight Systems Division staff.

The bottleneck identification and ranking process developed for Washington state involved the following tasks:

1. **Segment the Roadway**. Separate the state's entire roadway network into analysis segments based on the locations of ramps /major intersections and, in some cases, roadway length.
2. **Add Attribute Information to the Segments**. Assign to each analysis segment the appropriate roadway attributes (speed limits, classification, etc.) along with heading information to determine travel direction.
3. **Geo-locate the Trucks**. Assign each probe truck's GPS location reads to the appropriate segments. Account for the truck's travel direction on the segment.
4. **Locate Bottlenecks**. For segments with enough truck data, use the GPS trucks' travel speeds averaged over time to quantify the reliability and overall performance of each segment and identify as bottlenecks locations where trucks are performing unreliably or slowly.
5. **Rank the Bottlenecks**. Rank the truck bottlenecks on the basis of a range of metrics, including averaged segment travel speeds, geographic location, and the segment's Freight Goods Transportation System (FGTS) category.

Each task is explained in more detail below. Appendices provide additional information suitable for technical staff.

Task 1. Roadway Segmentation

WSDOT's entire road network, with the associated roadway attributes, is readily obtainable in a geographic information systems (GIS) compatible format. GIS software was used to divide this network into analysis segments according to the locations of junctions, ramps, or signalized intersections. Any segment longer than 3 miles was further divided into shorter segments. The data used in process are listed in Table 1.

Because most roadways involve two-way travel, the increasing and decreasing mileposts of the GIS linework (i.e., the roadway on a GIS map) were used to determine the travel direction of each roadway segment. In essence, except for a few one-way roads, each roadway segment was processed as two segments, one for each travel direction.

The following rules were applied to the GIS databases to segment Washington's state routes. Figure 1 shows the segmentation steps graphically.

1. The roadway linework was split at every junction.
2. For interstates and other major roads with ramps, the linework was further split at access ramps. Where both on- and off-ramps were situated in close proximity, the midpoint between ramps was calculated and then used as the splitting point.
3. If the route was not an interstate, it was also split at signalized intersections.
4. If, after these steps were followed, a resulting segment was longer than 3 miles, it was subdivided into several 2-mile segments plus one remainder segment between 1 and 2 miles long.

Appendix B includes technical details about the segmentation process.

TABLE 1 Roadway data and sources

1. State Highway Linework at 24K 1.1 increasing roadways 1.2 decreasing roadways 1.3 ramps 1.4 FGTS classifications
2. Intersections 2.1 signalized intersections
3. Highway Urban and Urbanized Areas
Source: WSDOT GeoData Distribution Catalog (http://www.wsdot.wa.gov/mapsdata/geodatacatalog/default.htm)

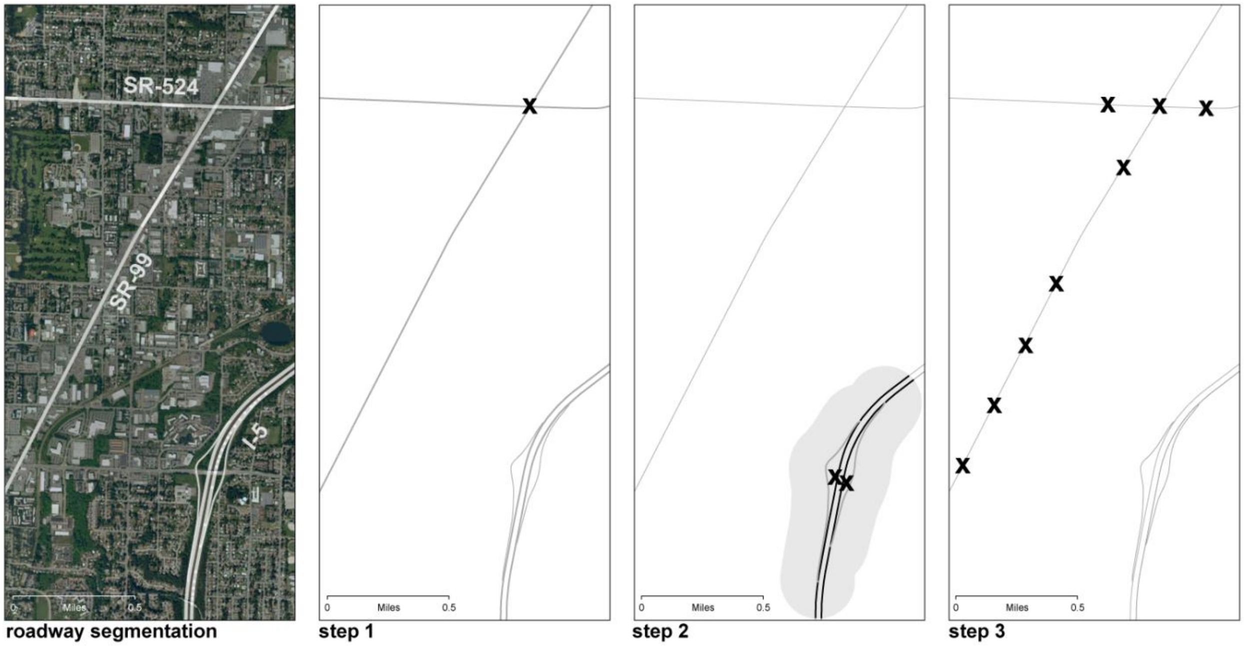

FIGURE 1 Steps used to segment the roadway network.

Task 2. Add Attribute Information to the Segments

Within the GIS, a 50-foot buffer was added around the analysis segments developed in Task 1. The resulting area was given identifying attributes from the state roadway network. Some of these attributes already existed in the state highway GIS files from Task 1. These attributes are listed below:

1. RID - State route ID, or numerical name of the route (for example, 099 refers to highway 99)
2. ROAD_SPEED - Posted speed limit

Additional attributes were added to the segments with both custom and stock GIS processing tools. A detailed technical explanation of the steps involved below is provided in Appendix B. The attributes are listed below:

3. SECTION_ID - 6 character unique numerical identifier for each segment. For example, "099010" refers to the tenth (010) segment of SR 99 (099). This can be used in future studies to identify adjacent or related bottlenecks and assist in tracing the cause of bottlenecks. For example, 099010 and 099011 represent adjacent segments.
4. FGTS2009 - 2009 Washington State Freight and Goods Transportation System (FGTS) is a classification of state highways, county roads, and city streets according

to the average annual gross truck tonnage they carry (from www.swdot.wa.gov/Freight/FGTS/default.htm).

T-1: more than 10 million tons per year

T-2: 4 million to 10 million tons per year

T-3: 300,000 to 4 million tons per year

T-4: 100,000 to 300,000 tons per year

T-5: at least 20,000 tons in 60 days

5. ROAD_DIRECTION - The compass heading (0-360) of the roadway. Because state route segments are often sinuous, each small portion of a segment was dynamically encoded with a range of location-specific directional headings (Figure 2). This ensured that the road direction and truck's travel direction could be accurately matched.
6. FMEAS - The lowest milepost measure of a segment. This attribute did not have to be a whole number and often had three or more decimal places.
7. TMEAS - The highest milepost measure of a segment. This attribute did not have to be a whole number and often had three or more decimal places.
8. LENGTH_MILES - Segment length in miles.
9. PUGET - Identified whether a segment was in the "Central Puget Sound" analysis region (Figure 2).
10. URBAN - Identified whether a segment passed through an urban area.

Task 3. Geo-Locate the Trucks

On a daily basis, 24 hours of new truck GPS location reads are fed into the project's database. On a typical day, this data stream includes about 250,000 GPS location records. Using a GIS process, each of these location reads needs to be assigned or geocoded by latitude and longitude to a point on the map. After being geo-located to the map, the location and heading of each point are compared to the segmented linework from Task 2, and any GPS reads taken from trucks that were not traveling along a WSDOT route are filtered out. After this process, about 10 percent of all GPS reads are retained.

The GPS points are filtered in a two-step process. First, the location of each point is compared to the state route segments created in Task 2. Points that fall outside of a zone or buffer created around each segment (roughly 50 feet from the roadway's center) are eliminated.

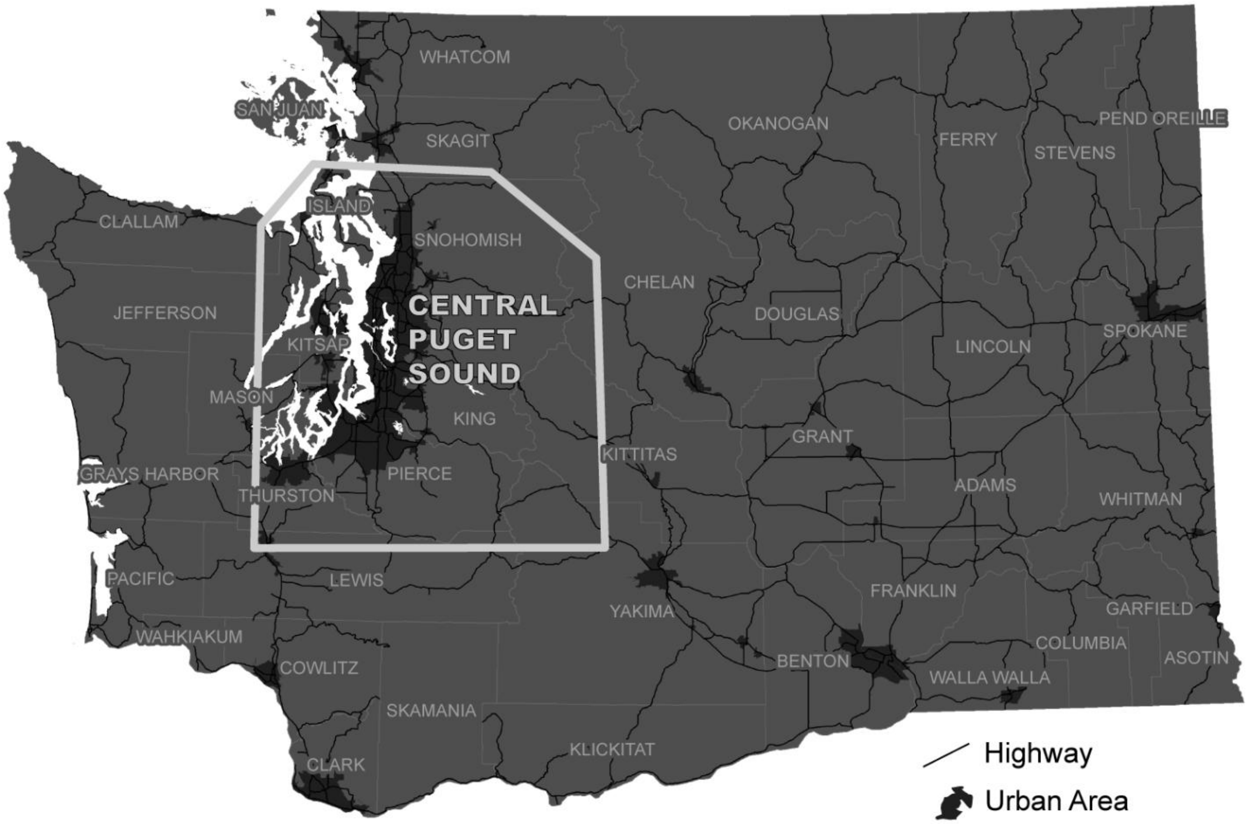

FIGURE 2 Central Puget Sound region.

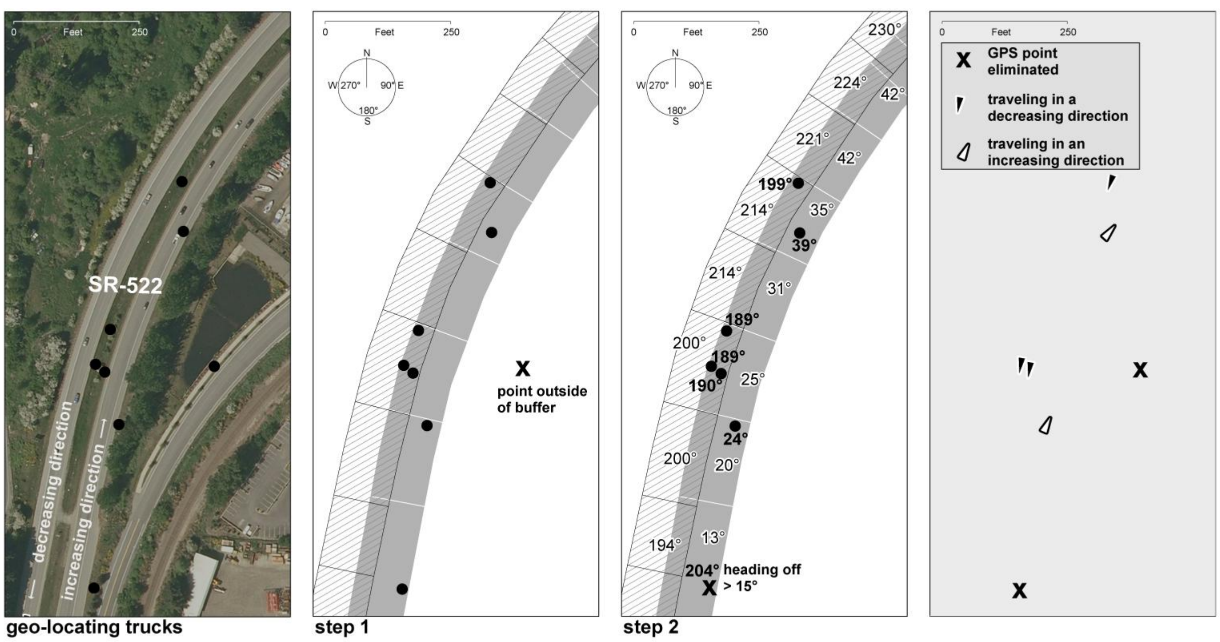

FIGURE 3 Steps used to geo-locate individual trucks.

Next, the heading of each point is compared to the closest heading of a short section of the analysis segment. Points with a difference in heading of greater than 15 degrees are eliminated. Points with a difference in heading of 15 degrees or less are retained and tagged with a value indicating whether it was traveling in an increasing or decreasing direction. This process filters out trucks traveling along intersecting or non-state route roadways, and it also identifies which direction (such as north- or southbound) on a roadway segment a truck was traveling (Figure 3). Finally, each truck's GPS records was assigned the ten segment attributes listed above in Task 2.

Additional technical details about this process are in Appendix B.

Task 4. Locate Bottlenecks

This task evaluates the performance of the GPS trucks as they traveled on each analysis segment. This task can only be completed if there are enough GPS truck data reads for a valid analysis. Because the GPS data for the central Puget Sound region have been collected since October of 2008, most major truck routes have hundreds or, in many cases, thousands of reads, so there are typically adequate data for most roads commonly used as freight routes. Data for roads serving the non-central Puget Sound part of the state have only been collected since August 2010, so a number of lower-level roads do not yet have enough probe truck reads for analysis to be valid. This situation will improve as the data continue to accumulate over time. Fortunately, important truck corridors, by definition, have higher truck volumes and are therefore more likely to have been used by more of our probe trucks and can be included in the bottleneck analysis.

After the roadway segments with enough reads (a minimum of a 100 trucks per segment) have been identified, the bottleneck identification process determines the travel reliability of that segment.

Because each GPS report by a device in a truck includes a spot or instantaneous speed, the distribution of speeds for the different trucks that travel on that segment can be calculated and plotted (Figure 4). On the basis of this speed distribution, the reliability of each roadway segment can be placed into one of three categories: reliably slow, reliably fast, and unreliable. For the urban areas in the central Puget Sound region, the truck speed data are analyzed by determining speed distributions during different time periods:

- AM (6:00 AM – 9:00 AM)
- Midday (9:00 AM to 3:00 PM)
- PM (3:00 PM to 7:00 PM)
- Night (12:00 AM – 6:00 AM and 7:00 PM – 12:00 AM).

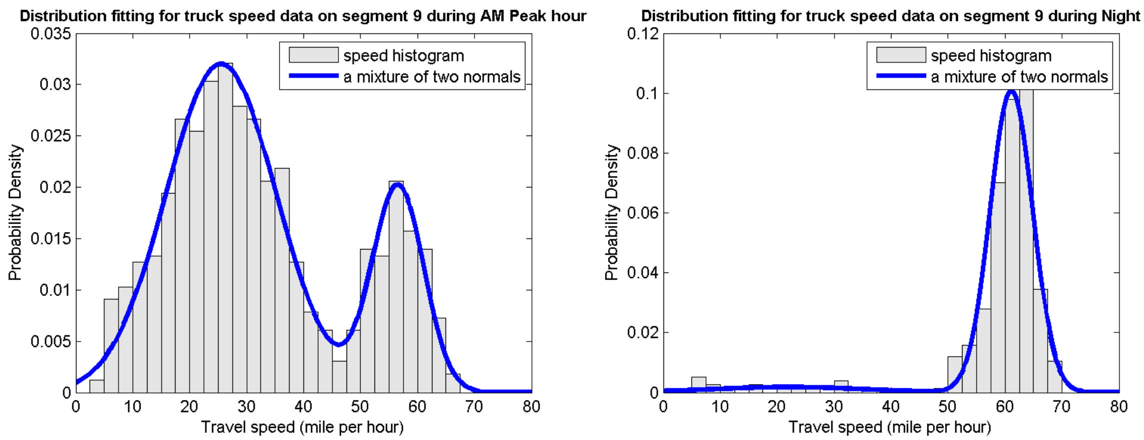

FIGURE 4 Speed distribution: (a) speed distribution with a bimodal feature (b) speed distribution with a unimodal feature.

Each time period is fit with a statistical distribution based on the trucks' spot speed data. Because the other areas of the state have fewer data points and less time-related congestion, their analysis period is a full day.

The reliability evaluation criteria include two levels:

A. Evaluate whether the travel condition during a given time period (the central Puget Sound region) or a given day (the non-Puget Sound areas of the state) is reliable given the speed distribution and a statistical fitting process. Generally speaking, if the speed distribution has two speed "humps" and is bimodal (such as in Figure 2a), then the travel condition is considered unreliable. Otherwise, the travel condition is unimodal and is considered reliable with one average speed (as in Figure 2b) and goes to level B for further evaluation of whether the travel speed is reliably slow or reliably fast. For the Puget Sound roadways, this measure can identify how the reliability condition changes over different times of the day.
B. Evaluate whether the travel condition during a given time period is reliably slow or fast. If the average speed is higher than 70 percent to 85 percent of posted speed limit, then the travel condition is considered reliably fast; otherwise, the travel condition is considered reliably slow. This measure has been adopted by WSDOT as the speed threshold for evaluating the duration of a congested period (WSDOT 2010, page 11). For example, on a freeway with a 60 mph speed, the threshold value is 45 mph because this is between 70 percent and 85 percent of the posted speed.

For detailed technical information about the speed distribution evaluation process, see Appendix C.

Task 5. Rank the Bottlenecks

Once the bottlenecks have been identified on the basis of their level of (un)reliability, three different measures are used to further rank and sort the truck bottlenecks' severity. They are as follows:

Average Speed

For the central Puget Sound region, this method first calculates the mean speed for each freeway segment during the four different time periods. The four mean values are combined to get an average speed measurement. This measure weighs different time periods equally and reflects the overall performance of the freeway segment. For the non-Puget Sound roadways the ranking of average speed for the entire day is used.

Frequency of Truck Speed Falling below 60 Percent of the Posted Speed Limit

This measure reflects the severity of congestion on the freeway segments. For the central Puget Sound region, this method calculates the percentage of truck speed falling below 60 percent of the posted speed limit during the different time periods and then averages those four percentage values to evaluate the frequency of truck speed falling below 60 percent. For most urban freeways, 35 mph is used because this is 60 percent of the posted speed of 60 mph. WSDOT uses the 60 percent value as the speed threshold for evaluating whether the freeways are experiencing severe congestion (WSDOT 2010, p.11). This threshold is adjusted for roadways with different posted speed limits.

For non-Puget Sound regions this process is completed for a full day.

Geographic Areas and Freight and Goods Transportation Systems (FGTS) Categories

This evaluation step reflects policy decisions made by WSDOT. The bottleneck process as currently developed separates the state into the central Puget Sound area and the rest of the state. This step acknowledges that the Puget Sound area's freight issues and truck volumes are notably different than those in other areas of the state.

An additional sorting of the bottlenecks based on the Freight Goods Transportation System (or FGTS) is possible. Use of the FGTS allows freight routes with inherently more importance (a higher FGTS category) to be given greater weight. This measure captures a segment's strategic importance to freight mobility.

BOTTLENECK ANALYSIS REPORTS

The results of this bottleneck process are placed in tables sorted by severity. These tables can be based a range of measures, as identified in Task 5. However, for easier use by transportation professionals and decision makers, the results can also be summarized into a one page per bottleneck report. An example for a Puget Sound area bottleneck report is shown in Figure 5. A non-Puget Sound bottleneck report is shown in Figure 6. The bottleneck report includes a map and description of the bottleneck location, daily truck volume if available, and other relevant information.

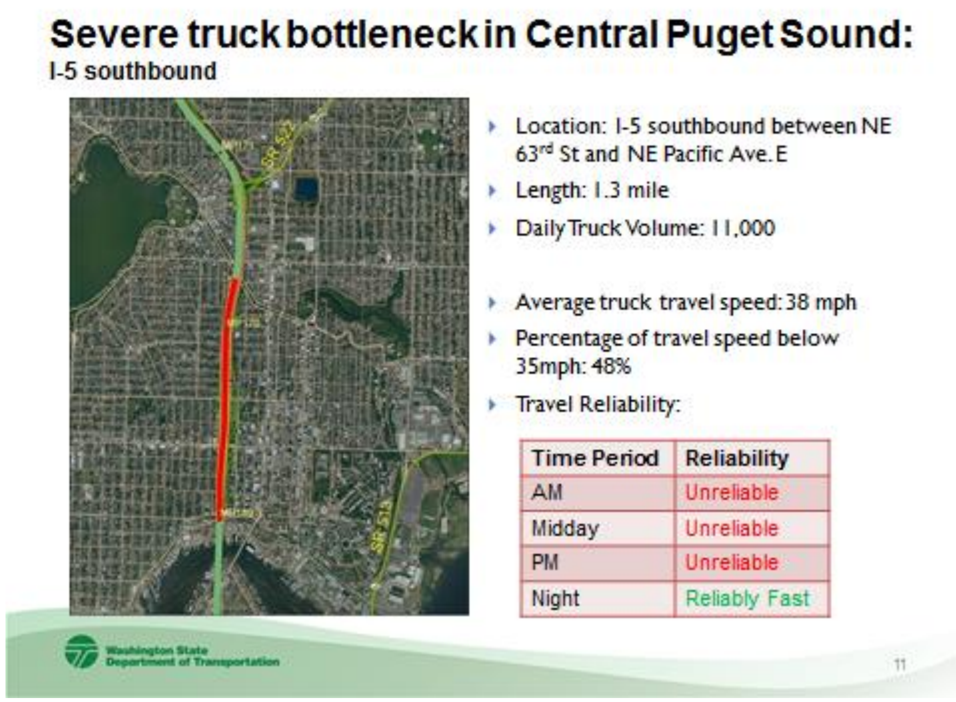

FIGURE 5 Example of a bottleneck report in the central Puget Sound region.

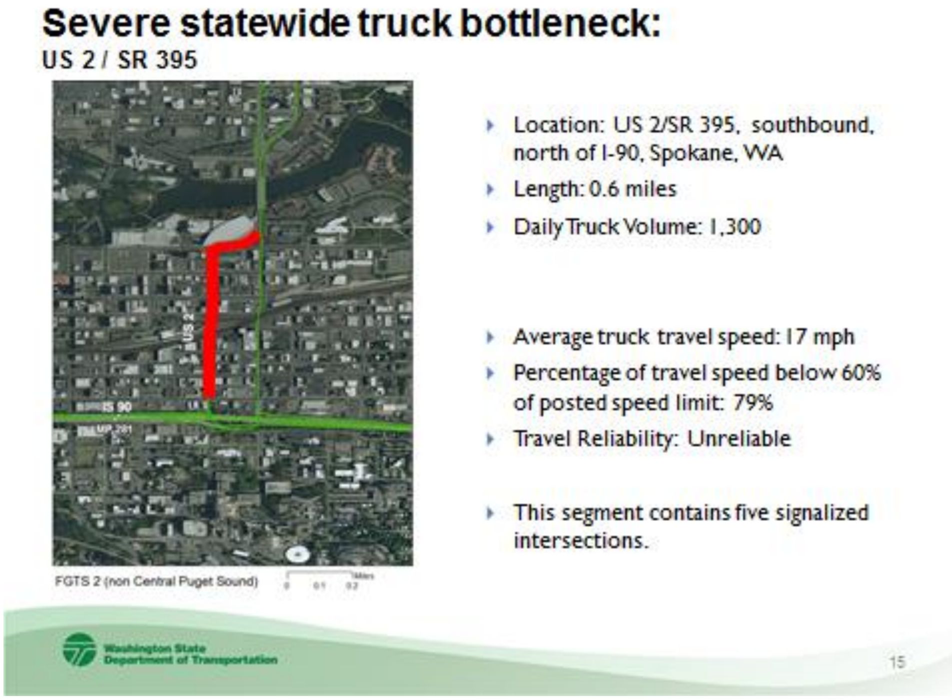

FIGURE 6 Example of a statewide bottleneck report.

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McCormack, E., X. Ma, C. Klocow, A. Currarei, and D. Wright (2010) *Developing a GPS based-Truck Freight Performance Measures Platform*, WA-RD 748.1, April http://www.wsdot.wa.gov/research/reports/fullreports/748.1.pdf.

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U.S. Department of Transportation (2011) Travel Time Reliability Measures, Website: http://ops.fhwa.dot.gov/perf_measurement/reliability_measures/index.htm.

APPENDIX A: OTHER ORGANIZATIONS' BOTTLENECK IDENTIFICATION TECHNIQUES

AMERICAN TRANSPORTATION RESEARCH INSTITUTE (ATRI)

The approach of the ATRI, completed in conjunction with the Federal Highway Administration (FHWA) Office of Freight Management and Operations, uses GPS data and free flow speeds on roadway segments as a base. Their truck GPS data are used to calculate the average miles per hour below free flow speed on the segment of interest. This number is multiplied on an hour-by-hour basis by the number of trucks on that section of roadway. For each hour over the course of a day, "vehicle population by hour" is multiplied by "Free Flow – Average MPH" to result in an "hourly freight congestion value." The sum of the 24 hourly freight congestion values is used to produce the "total freight congestion value." This congestion value is used to rank the severity the bottlenecks.

One possible limitation to this approach is that it is only valid for the bottlenecks pre-selected for the list. Some bottlenecks may not be identified.

Source: Short J., R. Pickett, J. Christianson, (2009) *Freight Performance Analysis of 30 Bottleneck*, American Transportation Research Institute, http://knowledge.fhwa.dot.gov/cops/pm.nsf/All+Documents/C28180EDEA33E0F68525756F00782804/$File/ATRI%20Freight%20Bottleneck%20Analysis_L.PDF

FHWA AND CAMBRIDGE SYSTEMATICS

This approach is the result of a federal program to identify freight bottlenecks (Cambridge Systematics 2005). The methodology for locating highway truck bottlenecks is as follows:

1. Locate highway segments with a high volume of traffic in proportion to the available roadway capacity (the volume-to-capacity ratio).
2. Determine truck volumes at these locations.
3. Calculate truck hours of delay by using queuing models. The bottleneck can then be ranked by hours of delay.

This approach has some limitations related to quality of the input data. Much of the data are derived and do not directly account for real-world truck behavior.

Source: Cambridge Systematics, (2005) *An Initial Assessment of Freight Bottlenecks on Highways*, A white paper prepared for Office of Transportation Policy Studies, http://www.fhwa.dot.gov/policy/otps/bottlenecks/.

APPENDIX B: GIS TECHNIQUES

OVERVIEW

This appendix discusses the Geographic Information Systems (GIS) techniques used to process the truck GPS data for the bottleneck identification process.

After first segmenting the Washington state roadway network into 3-mile or shorter segments, truck GPS records were obtained from a commercial GPS vendor, converted to geographic points, filtered by location and heading, and finally, each of the retained truck GPS records was matched to a specific roadway segment. All of this was done using geographic GIS software.

Matching truck GPS points to a segment of the Washington state roadway network was accomplished by first comparing the location of each point to the location of nearby state roadways. Truck GPS points that were within 50 feet of a state route were retained. Other points were eliminated. Next, the travel heading of each truck GPS point was compared with any state roadway within 50 feet. Trucks with a difference in heading, compared to a nearby state roadway, of 15 degrees or less, were matched to that segment of the Washington state roadway network and retained.

This process filtered out trucks traveling along intersecting, non-state route roadways, and it also identified which segment a truck was traveling along if it was positioned within 50 feet of both increasing and decreasing SR segments. After filtering, each retained GPS record was assigned the values of all of the identifying attributes coded in its respective roadway segment. These attributes include Freight Goods Transportation System (FGTS) ranking, posted speed limits, section location, and others.

In this appendix, the GIS techniques that were used during data processing are explained in sequence. There were three general processing tasks: 1) roadway segmentation; 2) segment attribute coding; and, 3) geo-locating GPS truck points and matching them to segments. For each of these three tasks, a general explanation is accompanied by a table or process diagram, and is then followed by a technical outline of the protocol.

DATA USED

Prior to GIS processing, geographic transportation and land use data were obtained from the Washington State Department of Transportation GeoData Distribution Catalog (http://www.wsdot.wa.gov/mapsdata/geodatacatalog/default.htm). Truck GPS point data were obtained from a daily data feed from a commercial GPS vendor. The data used in GIS processing are.

1. WSDOT GeoData Distribution Catalog
    a. State Highway Linework at 24K
        i. Increasing roadways
        ii. Decreasing roadways
        iii. Ramps
        iv. FGTS classifications
    b. Intersections
        i. Signalized intersections
    c. Highway Urban and Urbanized Areas
        i. Urban area polygons
2. Commercial Vendor GPS Data
    a. Truck GPS Records
        i. ~ 250,000 daily records

GIS PROCESSING TASKS INVOLVED

TASK 1: Roadway Segmentation

This task created a set of segments from the Washington state roadway network, all of which were less than three miles long. Unique segments were created for both the increasing roadway network and the decreasing roadway network.

To segment the entire Washington state roadway network using GIS software, the centerlines of Washington state routes were first split at all junctions, then at or between access ramps, and finally at signalized intersections (Figure B-1). After these steps, segments that were greater than three miles long were further subdivided, resulting in all segments to be less than three miles long. All of the steps involved in Task 1 were applied independently to both the increasing and decreasing SR roadway networks.

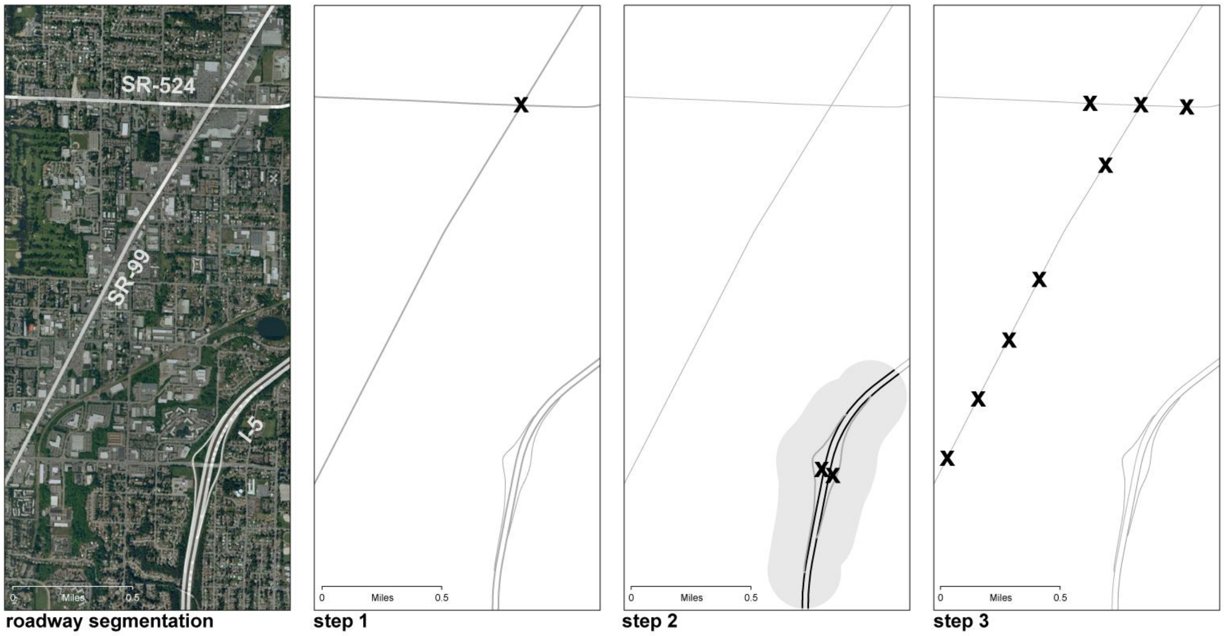

FIGURE B-1 Roadway segmentation method.

Task 1 Protocol

1) Roadway Segmentation (in ArcInfo 10.0)

This task was run independently for the increasing and decreasing state roadways in Washington State. Because both sets of linework were processed independently, any use of "SR linework" in the following protocol refers to two distinct feature classes and processing tasks: one each for the increasing and decreasing SR roadway networks.

a) Split at junctions
   i) Dissolve SR linework and define the feature class as follows: "RT_TYPEA" <> 'LC' AND "RRT" <> 'LX'. Then use "dissolve feature tool" to create a single connected polyline.
   ii) Find intersections - use Hawths Analysis Tools "intersect lines - make points" by selecting the dissolved SR linework as both the intersecting layer and the overlaying layer. This process creates points at all roadway junctions.
   iii) Add original SR linework & the intersection points from 1.1.2 to a new map document. Use "split line at points" tool.
b) Split at on and off ramps
   i) Add SR roadway linework and SR ramps linework to a new map document and define the feature class as follows: "RT_TYPEA" <> 'LC' AND "RRT" <> 'LX'.
   ii) Create an 800' buffer polygon from the SR ramp linework using the "create buffer" tool, and applying 800' as the buffer value.

iii) Using the “union” tool, union the SR linework with the 800’ SR ramp buffer polygon created in 1.2.2.
iv) Select and export only the SR linework that is situated within the 800’ ramp buffer union, and add this exported linework to the map document.
v) With the polyline feature created in the previous step, use the “convert feature to point” tool, and assign “centroid” as the output point location. This will place the points at the midpoint of the line.
vi) Add SR linework from 1.1.3 & the ramp centroid points from 1.2.5 to a new map document. Use “split line at points” tool.

c) Split at Signalized intersections
i) Add SR intersections point dataset (where “INTTRAFCNTRLTYPECD” = ‘SG’) & the SR roadway linework (where “RT_TYPEA” <> ‘LC’ AND “RRT” <> ’LX’) to a new map document.
ii) Snap signalized intersections to SR linework with the Hawths Analysis “snap points to lines” tool, applying a buffered search of 20’.
iii) Add the SR linework from 1.2.6 & the signalized intersection points from 1.3.2 to a new map document. Use the “split line at points” tool.

TASK 2: Code Roadway Segments with Attributes

This task added attributes to each segment, and calculated the values of the added attributes. The attributes added to each segment are listed below (Table B-1).

Table B-1 Roadway Segment Attributes

Attribute	Description	Source
RID	State route ID, or numerical name of the route (for example, 099 refers to highway 99	WSDOT GeoData Distribution Catalog, State Highways, at 24K
ROAD_SPEED	Posted speed limit	WSDOT GeoData Distribution Catalog, State Highways at 24K
SECTION_ID	6 character unique numerical identifier for each segment. For example, “099010” refers to the tenth (010) segment of SR 99 (099). This can be used to in future research to identify adjacent or related bottlenecks. For example, 099010 and 099011 represent adjacent segments.	Internal GIS Processing
FGTS2009	2009 Washington State Freight and Goods Transportation System (FGTS) is a classification of state highways, county roads, and city streets according to the average annual gross truck tonnage they carry (from www.swdot.wa.gov/Freight/FGTS/default.htm).	WSDOT GeoData Distribution Catalog, FGTS - Freight and Goods Transportation System

Attribute	Description	Source
	T-1: More than 10 million tons per year T-2: 4 million to 10 million tons per year T-3: 300,000 to 4 million tons per year T-4: 100,000 to 300,000 tons per year T-5: At least 20,000 tons in 60 days	
ROAD_DIRECTION	The compass heading (0-360), of the roadway. Because SR segments are often sinuous, each segment was dynamically encoded with a range of location-specific directional headings (Figure B-2). Each segment can have thousands of values for ROAD_DIRECTION.	Internal GIS Processing
F_MEAS	The lowest milepost measure of a segment. This attribute does not have to be a whole number, and often has 3 or more decimal places.	Internal GIS Processing
T_MEAS	The lowest milepost measure of a segment. This attribute does not have to be a whole number, and often has 3 or more decimal places.	Internal GIS Processing
LENGTH_MILES	Segment length in miles.	Internal GIS Processing
PUGET	Identifies if a segment is in the "Central Puget Sound" analysis region.	Internal GIS Processing
URBAN	Identifies if a segment passes through an urban area.	WSDOT GeoData Distribution Catalog, Highway Urban and Urbanized Areas

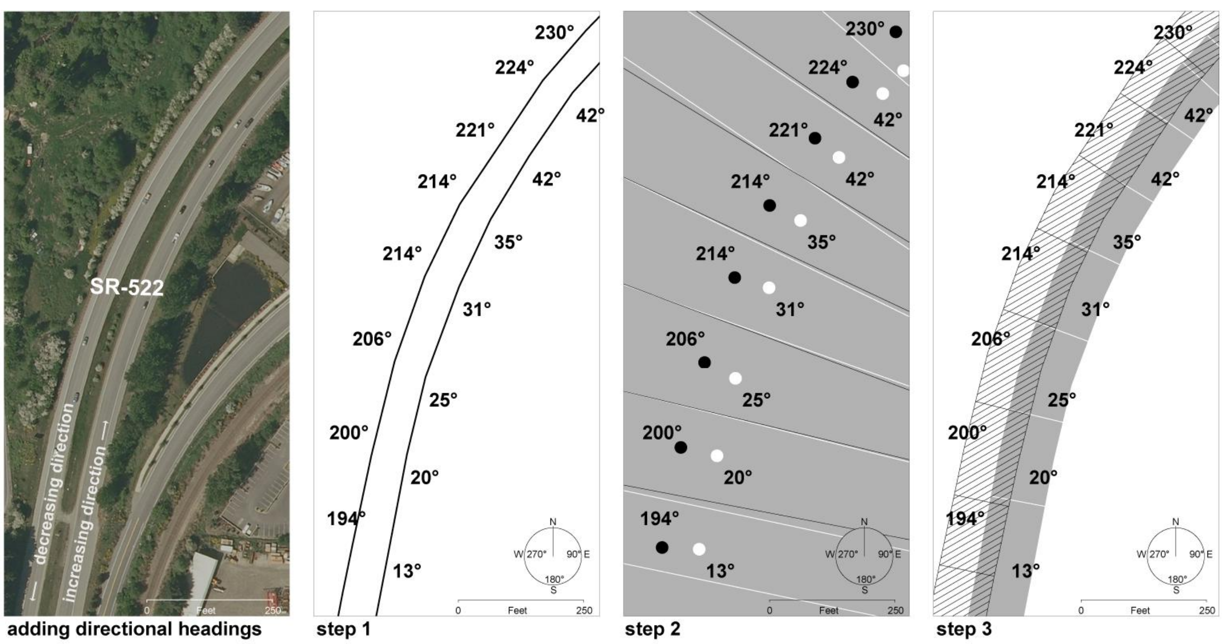

FIGURE B-2 Adding Directional Headings

Task 2 Protocol (In ArcInfo 9.3.1)

2) Add attribute information to the segments from 1.3.3
   a) Existing Attributes
      i) RID (text)
         (1) Route Identification (RID) is retained from the original SR linework
      ii) ROAD_SPEED (short integer)
         (1) The posted speed limit is retained from the original SR linework
   b) External Attributes
      i) SECTION_ID (text)
         (1) 6 character unique identifier for each segment. For example, "099010" refers to the tenth (010) segment of SR 99 (099).
            (a) To calculate, or "enumerate," the SECTION_ID values, a 2-column table from the segment feature class created in 1.3.3 that included RID and the lowest milepost (FMEAS) of each section was exported and processed. In Microsoft Excel, the columns were sorted first by RID, and then by FMEAS. A new field was created "SECTION_ID" = RID and the ordered count of instances of unique RIDs.
      ii) FGTS2009 (short integer)
         (1) FGTS2009 - 2009 Washington State Freight and Goods Transportation System (FGTS) classification of state highways, county roads, and city streets according to the average annual gross truck tonnage they carry. FGTS linework was obtained from WSDOT and spatially joined to the segmented roadway linework from 1.3.3.
      iii) ROAD_DIRECTION (short integer) (Figure B-2)
         (1) The compass heading (0-360), of the roadway. Because SR segments are often sinuous, each segment was dynamically encoded with a range of location-specific directional headings. This means that one roadway segment may have thousands of ROAD_DIRECTION values.
            (a) Using ArcInfo's advanced editing "COGO" tools, the SR linework from 1.3.3 was assigned directional values to all polyline vertices. This was done by first adding a new text field "DIRECTION" to the linework attribute table.
            (b) Next, an editing session was opened in in a new map document, and the entire SR linework feature class was added to the map and selected.
            (c) Then, the COGO command "update COGO attributes" was applied to the selected feature class. This process splits the SR linework into short segments (some shorter than 10' long) and encodes each short segment with its compass heading (0 - 360 degrees).
            (d) Next, the midpoint of each short line segment was calculated and encoded with the "DIRECTION" field of its parent short line segment. The "convert feature to point" tool was used here, with "centroid" assigned as the output

point location. These points retained the heading information in the "DIRECTION" field.

(e) Thiessen polygons were created using the "create thiessen polygons" tool from the point feature class created in the previous step. These polygons retained the heading information in the "DIRECTION" field.

(f) A new field "ROAD_DIRECTION" was created as a short integer and calculated where 'ROAD_DIRECTION" = "DIRECTION."

(g) A 50' buffer polygon was created from the original SR linework, using the "create buffer" tool, in order to be used in the next step.

(h) The thiessen polygons created earlier were clipped to the 50' buffered SR polygon.

iv) FMEAS (double)

(1) The lowest milepost measure of a segment. This attribute does not have to be a whole number, and often has 3 or more decimal places.

(a) This attribute was created using the LRS information encoded into the original SR linework. The SR segments created in 1.3.3 were added to a new map document, along with the original SR linework.

(b) Next, the "Create route event" tool was used to calculate the starting and ending milepost value for each roadway segment, listed by "SEGMENT_ID." This process generated a table.

(c) The table created in the previous step was joined the SR linework segment feature class by the common field "SEGMENT_ID"

v) TMEAS (double)

(1) "TMEAS," the highest milepost measure of a segment, was calculated along with "TMEAS" in the process described above.

vi) LENGTH_MILES (double)

(1) The length, in miles, of each SR roadway segment. This was calculated by applying the "Calculate length" tool to the SR roadway segment linework, and assigning "Files" as the measure.

vii) PUGET (short integer, binary)

(1) A value of 1 indicates that the segment sits within the Central Puget Sound region. The Central Puget Sound region is a casual geographic area that represents the extent of the commercial GPS vendors truck GPS data delivered prior to expanding the extent of analysis to the entirety of Washington State, and beyond. This attribute was calculated by:

(a) First, a new field was created, "PUGET" as a short integer to the SR segment feature class.

(b) Next, the Central Puget Sound polygon layer was added to the map document.

(c) The "Select feature by location" tool was run with the SR segment feature class assigned as the input layer and the Central Puget Sound polygon layer as the selecting layer.

(d) Selected features were then calculated as, "PUGET" = 1

viii) URBAN (short integer, binary)

(1) A value of 1 indicates that the segment sits within an urban area, as defined by WSDOT's urban area polygon GIS layer. This attribute was calculated by:

(a) First, a new field was created, "URBAN" as a short integer to the SR segment feature class.

(b) Next, the "Highway Urban and Urbanized Areas" polygon layer was added to the map document.

(c) The "select feature by location" tool was run with the SR segment feature class assigned as the input layer and the Highway Urban and Urbanized Areas polygon layer as the selecting layer.

(d) Selected features were then calculated as, "URBAN" = 1

ix) INCREASING (short integer, binary)

(1) A value of 1 indicates that the segment represents a roadway traveling in an increasing direction. A value of 0 indicates a decreasing direction. Because the above processes were executed independently for both increasing roadways and decreasing roadways, it was calculated by:

(a) Both SR segmented roadway feature classes were given a new field "INCREASING"

(b) The following calculation was then applied to the increasing SR segmented roadways, "INCREASING"= 1.

(c) The following calculation was then applied to the decreasing SR segmented roadways, "INCREASING"= 0.

c) Combine heading and 50' buffer information to the SR segment linework.

i) For both the increasing and decreasing buffered thiessen polygon feature class created in step 2.2.3, the other 9 attributes encoded into the SR segment linework (listed above) were spatially joined to the feature class from step 2.2.3.

TASK 3: Geo-Locate Truck GPS Points and Code With Attributes From Matching Roadway Segment

In this task, daily GPS truck records were obtained (~250,000 a day), filtered by location and heading, and then matched to a specific roadway segment (Figure B-3). After matching to a roadway segment, each GPS record, or point, was then assigned all of the values of the attributes of its matching SR segment.

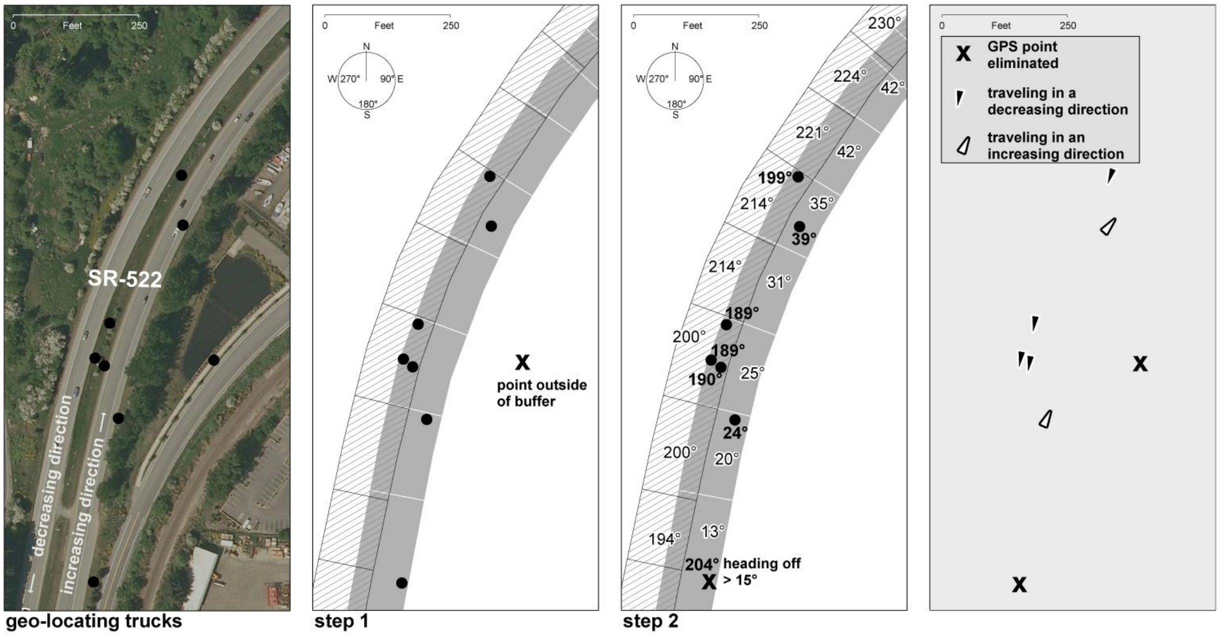

FIGURE B-3 Geo-locating truck reads.

Task 3 Protocol (ArcInfo 9.3.1)

3) Geo-locate trucks
   a) Assign points to map by latitude and longitude
      i) Each day of GPS points was downloaded from a central server as a .csv file
      ii) Descriptive headings were then added to the daily .csv file
         (1) DEVICE_ID
         (2) DATA_TYPE
         (3) LATITUDE
         (4) LONGITUDE
         (5) GPS_STATUS
         (6) SPEED
         (7) DIRECTION
         (8) MILEAGE
         (9) LOCATION_TIMESTAMP
      iii) Many of the GPS points had unusable "DIRECTION" or heading information. The bad headings were encoded with a value of "/N" or "382". Records with these headings were removed by first selecting the records with a usable heading: [DIRECTION] <> "/N" AND [DIRECTION] <> '382' AND [DIRECTION] IS NOT NULL
      iv) Records selected with the above query were retained in the .csv file and added to a map document.
      v) Next, the "display xy data" tool was applied to the .csv file where: spatial reference = "D_North_American_1983_Harn."

vi) In ArcEditor, the temporary layer created from the above process was then exported as a feature class, using the “feature class to feature class” tool. This feature was then added to the map, and the temporary layer was removed.

b) Compare points to 50’ buffer around SR’s

i) GPS points were filtered if they did not sit within 50’ of a Washington SR

(1) The “select feature by location” tool was used to select features from the point feature class created in 3.1.6 that intersected with the original SR linework, with a buffer distance value of 50’.

(2) The selected features from the previous step were then exported to a new feature class and added to the map.

c) Compare point heading roadway segments

i) To compare the heading of GPS points to the heading of the SR linework, the remaining points were spatially joined to the increasing and decreasing SR buffered polygon linework feature class created in step 2.3.1. The “spatial join” tool was used, the target features were the point feature class from 3.2.1.2, and the following additional rules were assigned: “join operation” = join one to one; “keep all target features” = true.

ii) Some pre-processing was required prior to calculating the difference in heading:

(1) A new field, “INT_DIRECTION” was added to the point feature class as a short integer.

(2) “INT_DIRECTION” was then calculated where “INT_DIRECTION” = DIRECTION

(3) A new field, “i_d” was added to the point feature class as a short integer.

(4) A new field, “PCT_Speed” was added to the point feature class as a short integer.

iii) Values were calculated for “i_d,” where a value of 1 indicates that the truck was traveling along an increasing roadway and a value of 0 indicates a truck was traveling along a decreasing roadway.

(1) “i_d” was calculated = 1 if the difference in heading was equal to or less than 15 degrees between a truck GPS point and an increasing roadway.

(2) “i_d” was calculated = 0 if the difference in heading was equal to or less than 15 degrees between a truck GPS point and a decreasing roadway.

iv) If, after step 3.3.3, “ i_d” IS NULL, points were selected and removed because their heading did not match a SR. This indicated that the truck was probably traveling along a nearby or intersecting roadway.

(1) The ‘select feature by attributes’ tool was used to select all records where ‘I_d IS NOT NULL.

(2) Next, selected records were exported using the ‘feature class to feature class” tool.

d) Export and append records to master tables

i) Records were then selected from the feature class created in 3.3.4.2 and appended to tables that expand with each day of appended data. Records were selected and appended to the master tables using the following selection rules: i_d = 1, 0; PUGET = 1, 0; FGTS = 1, 2, 3, 4, 5

ii) Selected records were then appended to one of the 20 master tables--10 tables each (5 FGTS x 2 directions) for the roadway segments in the Central Puget Sound, and those outside of the Central Puget Sound.

APPENDIX C: SPEED DISTRIBUTION EVALUATION

This speed distribution analysis evaluates travel reliability on roadway analysis segments. For the central Puget Sound region this is completed for different time periods (AM, Midday, PM, and Night). For the rest of the state, the same process is completed for a full 24-hour day. On the basis of the speed distribution of the GPS trucks' spot speeds, this process classifies the segment's reliability into three categories: reliably slow, reliably fast, and unreliable.

For urban areas, this index is computed as the number of time periods that the freeway segment under study is unreliable or reliably slow, divided by the total number of time periods. This metric is used as the travel reliability measure because it measures the percentage of time that the travel condition on the roadway is unreliable or congested and reflects the severity of travel condition.

To apply this metric, the truck speed data are analyzed by determining the speed distributions during different time periods (AM, Midday, PM and Night) and then by fitting the speed data with statistical distributions. A mixture of two normal distributions is applied on the basis of the maximum likelihood method to fit the collected truck spot speed data. The probability density function of a mixture of two normal distributions is as follows:

$$f(x) = \alpha \cdot n(x, \mu_1, \sigma_1) + (1 - \alpha) \cdot n(x, \mu_2, \sigma_2)$$

Where for i = 1, 2,

$$n(x, \mu_i, \sigma_i) = \frac{1}{\sqrt{2\pi\sigma_i^2}} \cdot \exp\left[-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right]$$

with $0 < \alpha < 1$. Function $f(x)$ has five parameters: α is the mixing proportion of the first normal distribution; μ_1, σ_1 are the mean and standard deviation of the first normal distribution; and μ_2, σ_2 are the mean and standard deviation of the second normal distribution. An example of the fitting results is shown in Table C-1.

The graphical illustration of the speed fitting results during AM and Night for the same roadway section is shown in Figure C-2. For the AM period for example, the meaning of the fitting results can be interpreted as follows:

Table C-1 Estimated parameters for speed distribution fitting during different time periods

Time Period	Weighting proportion (α)	Mean 1 (μ_1)	mean 2 (μ_2)	STDV 1 (σ_1)	STDV 2 (σ_2)
AM	77.3%	25.5	56.5	9.6	4.5
Midday	14.1%	29.2	58.5	11.5	4.1
PM Peak	12.1%	36.5	58	14.5	4.5
Night	6.1%	21.9	61.1	13.5	3.7

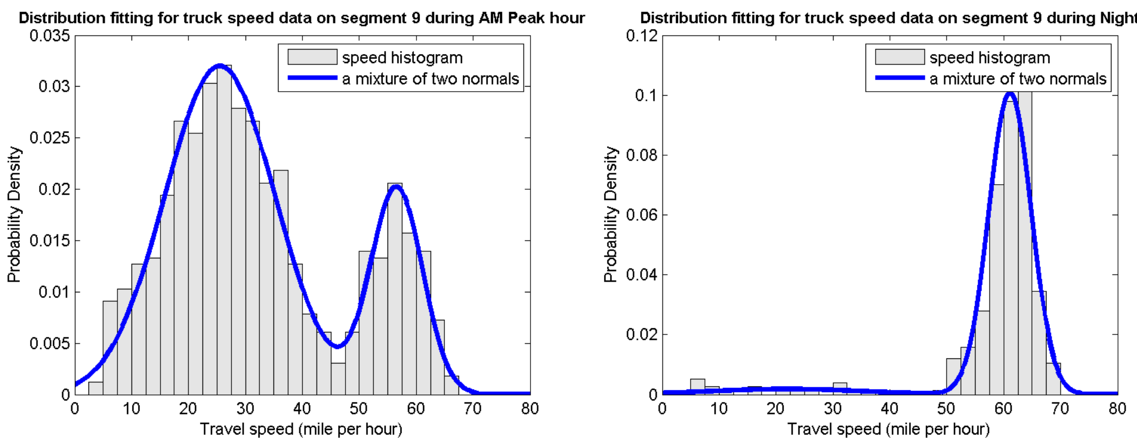

Figure C-1 Speed distribution: (a) speed distribution with a bimodal feature; (b) speed distribution with a unimodal feature

During the AM peak hour there are two speed operating regimes for trucks. The probability of truck travel speed falling within the low-speed regime is 77.3 percent, for which the mean speed is 25.5 mph; the probability of truck travel speed falling within the high-speed regime is 25.8 percent, for which the mean speed is 56.5 mph.

The estimated parameters from the fitting results quantify the characteristics of the truck speed distribution. On the basis of the estimated parameters, a set of rules are used to evaluate whether the travel condition on the freeway segment is unreliable, reliably slow, or reliably fast:

a) The travel condition is unreliable if and only if $|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$, $\alpha \geq 0.2$, *and* $\mu_1 \leq 0.75 * V_p$ (V_p is the posted speed). Otherwise, it is reliable.

b) If the travel condition is reliable, evaluate whether it is reliably slow or reliably fast on the basis of the average speed. It is reliably slow if $v \leq 0.75 * V_p$. Otherwise, it is reliably fast. v is the average speed computed as one of the congestion measures.

The first rule incorporates both statistical judgment and engineering judgment. The first condition, $|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$, is the statistical rule for evaluating whether a mixture of two normal distributions is bimodal or not. The second condition, $\alpha \geq 0.2$, is included to complement the first condition because from an engineering point of view, the travel condition is still considered reliable if α value is very small, which indicates that the probability of truck speed falling within the low-speed regime is very small. A value of 0.2 was chosen as the threshold value for α because a clustering analysis of I-5 corridor data found that 0.2 is a conservative estimate of the break point between different speed clusters. The third condition, $\mu_1 \leq 0.75 * V_p$, is included because from an engineering point of view, the travel condition could still be considered reliable and free of congestion if μ_1 is higher than the congestion threshold, 75 percent of posted speed. That indicates that even the mean speed of the low-speed regime is above the congestion threshold, and the freeway segment is free of congestion. A value of 75 percent of posted speed is used because it is between 70 percent and 85 percent of posted speed and has been adopted by WSDOT as the speed threshold for evaluating the duration of congested period.

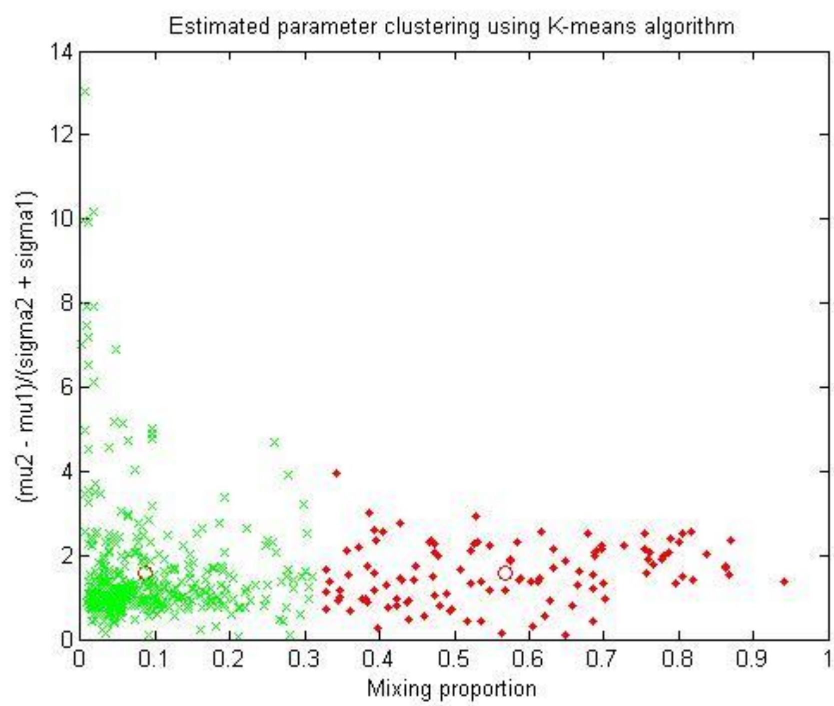

Figure C-2. Two-cluster analysis results using the K means clustering method for I-5 freeway segments

The second rule is an engineering judgment. Again, 75 percent of posted speed is used as the threshold of reliability evaluation is because it has been adopted by WSDOT as the speed threshold for evaluating the duration of congested period. If the average speed of the freeway segment is above 75 percent of posted speed, it can be considered free of congestion, and the travel condition can be evaluated as reliably fast. Otherwise, the freeway segment experiences traffic congestion, and the travel condition is evaluated as reliably slow.