Evaluation of Smart Phone Weight-Mile Tax Truck Data for Supporting Freight Modeling, Performance Measures and Planning

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ABSTRACT
Oregon is one of the few states that currently charge a commercial truck weight-mile tax (WMT). This research serves to evaluate ancillary applications for a system developed by the Oregon Department of Transportation (ODOT) to simplify WMT collection. The data collection system developed by ODOT – TRUE (Truck Road Use Electronics) – includes a smart phone application with a Global Positioning System (GPS) device and microprocessor. The TRUE data has enormous advantages over GPS data used in previous research due to its level of disaggregation and its potential to differentiate between vehicle and commodity types. This research evaluates the accuracy of the TRUE data and demonstrates the results of its application to develop trip generation rates for a variety of truck types and land use categories. This research also confirms the value of the TRUE data to enhance existing ODOT transportation planning models and performance measures.

INTRODUCTION

Reliable freight transportation is particularly important to Oregon due to its geographic location. According to *The Oregon Freight Plan (1)*, Oregon is the ninth most trade-dependent state in the nation and is expected to see significant increases in freight flows in the future. This trade dependency comes with unwanted side effects such as congestion, travel unreliability, environmental and health concerns, and increased transport costs *(2) (3)*. In this regard, recent research stresses the importance of freight performance measures and associated data management processes in sustaining an effective transportation planning system *(4) (5)*. Freight data that might be used for such performance measures is usually incomplete, scarce and expensive to collect. However, a unique and highly promising data source is available through a system recently developed by ODOT to simplify its weight-mile tax (WMT) collection. Oregon is one of the few states that currently charge a commercial truck WMT; Oregon's WMT applies to trucks operating at weights of over 26,000 lbs. In February 2010, the ODOT Motor Carrier Transportation Division (MCTD) implemented a pilot project for the use of Truck Road Use Electronics (TRUE) *(6)*. The TRUE system provides an automated process for WMT collection that reduces the administrative burden on trucking firms and ODOT while also reducing reporting errors and tax avoidance. The system includes a smart phone application with a Global Positioning System (GPS) device and microprocessor. The application can be uploaded to the phones of truck drivers in order to track miles traveled; the data is then sent electronically to ODOT to produce the company's WMT "invoice" which can be paid online.

This research serves to evaluate ancillary applications for the TRUE data; applications that address ODOT needs for freight modeling, performance measures, and planning are explored. Previous research related to the use of freight GPS data provides a valuable starting point for this research. However, due to its level of disaggregation and its potential to differentiate between vehicle and commodity types, the TRUE dataset has many unique characteristics and enormous advantages over truck GPS data used in past research. Data collected through TRUE not only provides commercial truck origin-destination, space/time coordinates and trajectories, but also weight class, truck type and commodity codes. Such information can be used to understand the intricacies of freight transportation and to better inform decision makers. This paper will provide a review of relevant past research and associated applications, as well as an evaluation of the applications that will be possible for Oregon given the unique characteristics of the TRUE WMT GPS data.

LITERATURE REVIEW

Table 1 provides a summary of past academic research that explored applications for commercial truck GPS data. The work reviewed in this table is not intended to be an exhaustive list, but rather, a representation of research relevant to this project. One of the earlier, successful urban scale examples of the use of commercial truck GPS data for transportation engineering applications was performed in Australia *(7);* in this research, a trip identification algorithm was developed to determine the location of trip ends. The algorithm provided a means to differentiate between "genuine" stops and "false positive" stops (those associated with congestion, signals, etc.). Perhaps one of the more progressive uses of GPS data is associated with research on traffic in the New York City metropolitan area *(8)*. Holguin-Veras et al. used commercial truck GPS data to evaluate the use of financial incentives to shift truck traffic to off-peak hours. In 2011, Wheeler and Figliozzi *(2)* researched the potential to develop multi-criteria (mobility, cost and emissions) performance measures using truck GPS data. In particular, they showed that loop sensor data may underestimate the impact of congestion on freight travel time reliability. Subsequently, these researchers developed a new methodology and algorithms for combining freight GPS data with loop sensor data to more accurately model congestion and emissions. In later research, corridor level travel time reliability algorithms and programming logic was successfully applied to segment corridors and to estimate travel times for each segment identified *(3)*. Considerable research has also been completed in the state of Washington using commercial truck data from private GPS vendors to develop transportation metrics *(9) (10) (11) (12)*.

In general, applications of truck GPS data are limited because the data typically does not differentiate between different truck or commodity types. Further, use of truck GPS data often involves an ongoing cost as it is typically purchased from an outside provider or third party. As a result, researchers have had "limited success" in developing trip generation rates with truck GPS data. It has also been determined that improvements in the data used for previous research would be needed before it could be used for freight transportation modeling *(12)*.

The freight performance measure categories included in Table 1 are those that have been receiving increasing attention at both national and state levels. In 2011, the National Cooperative Freight Research Program (NCFRP) released *NCFRP Report 10, Performance Measures for Freight Transportation (5)*. This report proposes a "Balanced Scorecard" framework for a Freight System Report Card with 29 performance measures in six categories. The report suggests that given the ability to disaggregate freight data, the "Balanced Scorecard" framework proposed could be used to analyze the performance of individual links or bridges at the state or local level. The authors also note that a major challenge towards such efforts is the availability of useful data. At the state level, a report completed for ODOT in May 2010 *(4)* provides recommendations for Oregon freight performance measures. Most of the measures suggested for Oregon overlap with those suggested by NCFRP (see Table 2).

As cell phone technology has evolved, so too have efforts towards using these devices in a variety of roles in the transportation sector. A common goal of cell phone applications is the estimation of travel times. A report for the Florida Department of Transportation *(13)* evaluated travel time measurements that were estimated by five companies using cell phone technology. Estimates were evaluated on the basis of methodology, data filtering and aggregation, reliability of data, and other key measures. The study observed good results in free-flow or fast traffic conditions; the study was inconclusive as to the accuracy of estimations in heavy traffic. In 2000, Zhao *(14)* reviewed the three most common location detecting technologies – stand-alone (dead reckoning), satellite-based (GPS), and terrestrial-based (navigation systems, cell networks). Zhao concluded that the cell-ID-based method has the worst positional accuracy, while assisted GPS has the best. In 2008, Barbeau et al *(15)* addressed the tradeoff between data accuracy and battery life, data transmission costs, and burden on the server. The researchers introduced two algorithms, a "Critical Point" algorithm and a "Location-Aware State Machine" algorithm, intended to ensure that the GPS devices did not waste battery power obtaining point fixes that would not enhance the quality of the data. Newer uses that involve smartphones can provide emissions estimates to the user and suggestions to improve driving *(16) (17) (18)*.

Among proprietary uses of commercial truck GPS data, a private company, INRIX, anonymously collects GPS data from "probe vehicles", in part through agreements with fleet operators who have GPS devices in their trucks, but also from personal vehicles (individuals who have downloaded the INRIX application to their smart phone) and taxis *(19)*. The data is compiled into average speed profiles for freeways, highways and arterials. INRIX uses the results to provide travel information for a variety of users including individual travelers, commercial fleets and the public sector. Customers from commercial fleets are provided services such as dispatch services, traffic map overlays, fastest routes, next-day planning and congestion pricing *(20)*. In addition, INRIX provides the majority of the data used to produce the Texas Transportation Institute's Urban Mobility Report (UMR) *(19)*. INRIX also offers a mobile application developer kit (MDK) for smartphone application developers wishing to use INRIX data. A technology with applications similar to ODOT's TRUE system is "Xata Turnpike" *(21)*. Xata Turnpike is a fleet management and optimization technology that provides real time information for commercial trucking companies. Xata charges users a subscription price per vehicle per month. Xata's Electronic On Board Recorder (EOBR) tracks hours of service, data for International Fuel Tax Association (IFTA) and State Mileage forms, actual route driven (with online mapping), auto arrival and departure, engine diagnostics, speed, RPM hard braking, idle time, and fuel efficiency. In 2009, a company named EROAD used a similar device to implement an autonomous Global Navigation Satellite System/Cellular Network (GNSS/CN) tolling system for commercial trucks in New Zealand *(22)*. EROAD uses a secure On Board Unit (OBU) to collect road charges based on vehicle distance, location, mass, time and emissions. EROAD has a web application that monitors logistical information for clients including tracking driver compliance, fuel efficiency, messaging and maintenance.

DATA DESCRIPTION & PRELIMINARY ANALYSIS

Data available for this research consists of 172,385 records from the TRUE pilot study for the entire year of 2011. Seventeen trucks subject to Oregon's WMT were equipped with a TRUE device for the pilot study. These trucks represent three different carriers. The TRUE devices were configured to collect the latitude and longitude locations of each vehicle every five minutes. The travel of the pilot study vehicles was tracked through seven U.S. states and three regions in Canada; however, the geographic limitations of future data collection would be dependent on the degree of partnership with the private sector. Through trips using Oregon's highway network are required to pay WMT, and hence may be included in future datasets if companies adopt the system. The intention of the pilot project was to test the TRUE system, potential applications, and associated data processes rather than to provide data that is representative of the entire population of trucks in Oregon. Likewise, regardless of the sample rate of this pilot study, the methodologies proposed could be applied to the statewide implementation of the TRUE system.

According to the "GPS_ACCURACY" field of the data, the accuracy of the GPS readings range from three to 840 feet. Figure 1 provides a histogram of the cumulative distribution of the values from the "GPS Accuracy" field for readings of up to 80 feet (the small number of records with accuracy worse than 80 feet are not included in the figure). An accuracy of within ten feet was recorded for over fifty percent of the GPS records; within twenty feet for over 75%; within 53 feet for over 95%; and within 79 feet for over 98%.

In addition to the GPS records, the data set available for this research includes corresponding weigh-in-motion (WIM) station records for the pilot project vehicles. Figure 2 provides a schematic showing data fields available through the TRUE dataset and the WIM dataset. Using the "DEVICE_ID","BASE_PLATE", "WAYPOINT_TIME" and "WEI_PSTDATETIME" fields, a TRUE record can be found for each WIM record that is: a) from the same truck as the WIM record; and b) closest in time to the WIM record. This process can be completed using RStudio. Preliminary review of the TRUE records and corresponding WIM data indicates that the TRUE records from the pilot project represent vehicles of nine different weight classes (ranging from 46,000 lbs. to 105,500 lbs.), with four to eight axles, and three different commodity codes ("empty", "machinery" and "other"). The linkage of these two datasets provides the ability to cross check the WIM system data with TRUE data and vice versa. Further applications available through the linkage of these two datasets are described in the proceeding sections of this paper.

Each of the applications explored in this paper require some degree of data processing; however, the TRUE data in its "raw" format provides values for the fields listed in the top and middle sections of Figure 2, including latitude and longitude coordinates with corresponding timestamps, weight class and axle count of vehicles, and GPS record accuracy. The initial data processing steps consisted of formatting including conversion of timestamp values to database readable time format. Data processing required for specific applications are discussed in the proceeding sections of this paper.

POINT/LOCATION BASED APPLICATIONS

Previous work related to the use of freight GPS data provides a valuable starting point for this research. The "Balanced Scorecard" methodology proposed by *NCFRP Report 10* and the suggestions from the *Freight Performance Measures: Approach Analysis* prepared for ODOT propose a useful framework from which to develop ancillary applications for the Oregon WMT GPS data. Table 3 provides a list of potential applications, along with the data fields required to provide accurate results for each. All of the data fields listed in Table 3 are provided by the TRUE system.

The ability to disaggregate the TRUE GPS data by vehicle type provides an opportunity for development of trip generation rates that has not been available with previous truck GPS datasets. Such rates could allow planners and modelers to relate the number of truck trips from different categories of trucks to the land use (i.e., commercial, industrial, residential) that generated the trip. For example, the number of trips relative to the following vehicle categories can be determined using the integrated TRUE and WIM data: weight class, number of axles, vehicle type, vehicle class, commodity code, gross weight, and calculated value of vehicle.

In addition to truck trips associated with particular land uses, similar analysis could be completed considering areas of different population densities, employment levels, parcel sizes, counties, or other Traffic Analysis Zones (TAZ). As an example, an analysis was performed in ArcGIS to determine the proportion of GPS records from the TRUE pilot project that were within different land use categories in the Portland metropolitan area. A 2010 land use GIS file from Portland Metro's Regional Land Information System (RLIS*) (23)* was used for this analysis. The results (provided in Figure 3) not only demonstrate the relative proportion of records within different land use categories (i.e., "Mixed Use Residential" (MUR) areas were generally traveled in more than "Rural" areas), but also the relative proportion of records from different weight classes for each land use category (i.e., trucks over 98,000 lbs. traveled in "Rural" areas more than MUR areas). The GIS plot in Figure 4 provides a second example of the ability to disaggregate this dataset by truck type categories. This plot provides a visual analysis of the spatial distribution of the pilot project GPS records for the 1030 weight class trucks (103,000 lbs.). The number of GPS records for various segments of interstate, U.S. and state highways in Oregon is shown for this weight class. Similar disaggregation by other vehicle type categories (i.e., commodity type, gross weight and axle weight) is also possible.

As demonstrated by Figures 3 and 4, the TRUE GPS data provides the level of detail needed to determine the location of truck travel at the TAZ level, and thus to develop truck trip generation rates with a level of accuracy that has not been possible using previous truck GPS data. However, the accuracy of such trip generation rates could be further enhanced by identifying the TRUE GPS records that represent "trip ends" (origin and destination locations); for example, a methodology is presented in reference *(7)* to identify trip origins and destinations using GPS data. Subsequently, if the TRUE system were implemented state-wide, the resulting data could be used to develop highly accurate trip generation rates that could be used as an alternative to, or to complement, less accurate employment or production based trip generation rates. Further, results from TRUE analyses could be compared to other regional analysis tools such as the Commodity Flow Survey (CFS) of the Bureau of Transportation Statistics (BTS) or the Freight Analysis Framework (FAF) of the Federal Highway Administration (FHWA). Such resources provide aggregated commodity flow data that could be calibrated or disaggregated using TRUE data.

The *Freight Performance Measures: Approach Analysis* report for ODOT *(4)* suggests that the ratio of "total cost of freight loss and damage from accidents" to "total freight Vehicle Miles Traveled (VMT)" is the ideal safety freight performance measure for both statewide analysis and specific highway segments. "Total cost of freight loss" includes: 1) cost of lost and damaged equipment, 2) value of lost and damaged cargo, and 3) delay imposed to other freight carriers on the same highway corridor. The vehicle type, class, weight and commodity data available through TRUE data (in combination with WIM data) would assist in estimating such costs. The 2010 report also suggests "Motor Carrier Crash Rate and Triple Trailer Crash Rate as worthwhile performance measurements for Oregon. If a system such as TRUE were implemented on a statewide level, it could be combined with Oregon's existing data sources for safety performance measures to assist in determining more accurate estimations for these performance measures.

Accessibility and connectivity performance measures are particularly relevant to Oregon due to the multi-modal nature of the state with respect to freight (i.e., ports, airports and highways). McMullen and Monsere *(4)* suggest 'percent of freight originating or terminating within a certain number of miles of Longer Combination Vehicle (LCV) corridors' as a potential measure of accessibility. The expansion of the LCV network was frozen by the Intermodal Surface Transportation Efficiency Act (ISTEA) in 1991. McMullen and Monsere note that 'shipment origin or destination data does not contain [the] level of specificity' needed to make such a measurement; however, as demonstrated in Figures 3 and 4, the TRUE data has potential to provide such detail. Truck turnaround time at terminals (ports), as measured in research by You and Ritchie *(24),* is another potential performance measure available to Oregon through the TRUE data.

Maintenance and preservation efforts by state DOTs typically focus on highway bridge and pavement management *(4).* Bridge wear is primarily a function of gross vehicle weight (GVW); pavement wear is primarily a function of axle weights. As such, the capability of TRUE data (in combination with WIM data) to provide estimates of both GVW and axle spacing of traveling vehicles on virtually any segment of state highway could be very useful to determine user impacts. According to *Infrastructure Costs Attributable to Commercial Vehicles (25)* DOTs typically allocate 40% or more of their annual budgets to pavement maintenance and rehabilitation projects. Further, the relationship between axle loads and consequent pavement damage is known to be exponential *(26).* For these reasons, it is pertinent to consider applications of detailed truck GPS data within the field of pavement management. Applications for the TRUE GPS data could include: 1) pavement forensics; 2) more accurate estimates for highway design ESALs; and 3) decreases to the frequency of pavement condition surveys for highway segments receiving minimal truck traffic. The integrated TRUE and WIM data could also provide the route information for trucks of various gross vehicle weights in order to determine weight limit violations on bridges.

ODOT recently developed the Oregon Freight Plan (OFP) to consider infrastructure investment and policy options related to freight *(1)*. In order to account for current economic uncertainty, the OFP analyzed various alternative futures. ODOT's Second Generation Statewide Integrated Model (SWIM2) was used to complete this analysis. SWIM2 is a spatial economic modeling system that represents transportation, economics and land use, as well as the interactions between them *(27)*. In 2010, short, mid and long-term improvements were proposed to the Commercial Truck (CT) module of SWIM2 *(28)*. It was noted that SWIM2 provides a comprehensive approach to household travel activity, but that the CT module was in need of enhancements to more adequately forecast freight movements and the impacts of energy price changes, and to provide sound policy analysis regarding GHG emissions, taxes and tolling. According to the researchers, applications for the CT module are limited to "a subset of freight policy problems that can be appropriately modeled with simple behavior rules and limited data". The TRUE data provides an excellent opportunity to produce more accurate results in SWIM2, and for the OFP analysis in particular. Given the disaggregated nature of the TRUE data, it would be an asset in performing SWIM2 analysis at a regional level in Oregon and for implementing the suggested improvements to the CT module.

In summary, given the accuracy of the data (shown in Figure 1), and the associated analysis capabilities (i.e., represented in Figures 3 and 4), it is clear that several applications ranging from trip generation, commodity and land use planning, to infrastructure management would greatly benefit from the state-wide utilization of the TRUE dataset.

SPEED BASED APPLICATIONS

Of the freight performance measures listed in Tables 1 and 2, those associated with mobility have probably received the most attention on a national level, specifically in relation to travel time reliability and congestion at bottlenecks *(4)*. As demonstrated in Table 1, all of the freight GPS data research from the literature review of this project explored applications in this area. Below are some commonly used mobility performance measures for which the TRUE data could provide estimations.

- <u>Travel Time:</u> the time taken by a driver to travel between an origin and a destination *(3)*.
- <u>Travel Time Reliability:</u> NCHRP 618 *(29)* recommends use of 90th and 95th percentile travel times (reflecting travel delays that can occur during heavy congestion) as an indicator of travel time reliability.
- <u>Travel Time Index (TTI):</u> the ratio of the average speed for a given highway segment at a particular time of day to the functional free flow speed of the same segment of highway *(30)*.
- <u>Planning Time Index (PTI):</u> the ratio of the "worst-case scenario" average travel speed for a given highway segment at a particular time of day to the functional free flow speed of the same segment of highway *(30)*.

In order to estimate space-mean speeds using the TRUE dataset, highway mileages between GPS records were used rather than "straight-line" or "great circle" distances. The distances between GPS records in the TRUE dataset are typically on the order of five miles. As such, significant error would result along curved highway segments if "straight line" or "great circle" distances were used. The use of highway mileages reduces such error, and thus, is a more accurate measure of traveled distance. The highway mileages of the GPS records were determined through interpolation by comparing latitude/longitude measurements of the GPS records to those of known mileposts. The source of the highway milepost locations was an ArcGIS file from Portland Metro's RLIS *(23)*. The interpolation process was completed using RStudio. Subsequently, an automated process was developed in RStudio to determine the speeds between GPS records. In order to assess the accuracy of space-mean speeds calculated from the GPS data, the calculated space-mean speeds were compared to speeds from the Portland, Oregon Regional Archive Listing (PORTAL) – the official Archived Data User Service (ADUS) for the Portland metropolitan area. Speed measurements available through PORTAL are based on inductive-loop detector data from nearly 600 sensors located throughout the Portland metropolitan area on I-5, I-205, I-405, I-84, OR-207 and US-26 *(31)*.

A set of all TRUE GPS records within 2.5 miles of a PORTAL station was created and a random sample of thirty TRUE records was selected from this set. For each of the thirty TRUE records in the random sample, the next downstream TRUE record was determined in order to calculate space-mean speeds. Subsequently, the PORTAL station closest to each of the sampled TRUE records was determined in order to create sixty "TRUE-PORTAL pairs" (or thirty "TRUE-PORTAL groups"). PORTAL speed estimates corresponding to the location and timestamp of the each of the corresponding TRUE records were then determined. At the time of analysis, speeds were available at PORTAL stations in five minute increments. As such, PORTAL speed records just before and just after the corresponding TRUE timestamp were selected for each "TRUE-PORTAL pair". The PORTAL speeds at the exact times of each corresponding TRUE record were then determined by interpolation. The average speed between PORTAL stations in each "TRUE-PORTAL group" was then determined for comparison to the calculated space-mean speed between the corresponding TRUE records. PORTAL speed records are available for each individual lane at the location of each PORTAL station. For purposes of this analysis, it was assumed that trucks from the TRUE dataset were always traveling in the right "truck lane" (the lane furthest from the median); likewise, PORTAL records from the "truck lane" were used for comparison to the TRUE space-mean speeds. The five minute time intervals used for this research were considered more appropriate than a smaller time interval because flow rates become unstable as the period of analysis becomes smaller (e.g., the Highway Capacity Manual recommends 15 minute intervals to study peak period flow rates).

It should be noted that records representing destinations or origins were identified and removed from the speed comparison process. Destinations or origins usually consist of a cloud of observations which can be consolidated into one observation (representing a trip origin or trip end) to avoid erroneous speed calculations (false low speeds). In addition, Tukey's method to identify outliers *(32)* was used to determine if the percent difference in speed for any of the thirty "TRUE-PORTAL pairs" was an outlier. Outliers were then removed from the analysis and a randomly selected TRUE record was selected as a replacement. Such outliers were often indicative of a geocoding error in which ArcView GIS assigned one of the two TRUE GPS records to an incorrect highway segment. Removal of outliers also served to eliminate records from the analysis that represented trucks at rest or slowing down in an auxiliary lane, thus limiting the review to "through movements" more representative of the general traffic conditions.

As can be seen in Figure 5, over fifty percent of the space-mean speeds calculated from the TRUE dataset were within eight percent of the speeds calculated from PORTAL; all of the TRUE speeds were within 25% of the PORTAL speeds. The absolute values of the speed differences averaged nine percent; however, the TRUE speeds were, on average, approximately seven percent (3.65 mph) less than the PORTAL speeds; the speed differences had a standard deviation of eight percent (4.41 mph). Eighty percent of the TRUE speeds were less than the PORTAL speeds. This is likely because PORTAL speeds are an aggregation of speed measurements from a variety of vehicle types (i.e., mostly passenger vehicles that typically travel at a faster speed than trucks). The TRUE speeds ranged from 21% (12.4 mph) less than the PORTAL speeds to ten percent (5.6 mph) greater than the PORTAL speeds.

The results of a paired sample t-test indicate that at the 0.01 significance level there is sufficient evidence from the tested sample to conclude that the difference between the PORTAL speeds and those calculated from the TRUE data is significant. This conclusion appears to be consistent with the findings of previous research on the same freeway segments in the Portland region *(2)*; previous research results indicated that during the peak PM period, speeds estimated from loop detectors were generally greater than speeds estimated by truck GPS data provided by the American Transportation Research Institute (ATRI). However, it should be noted that due to the following limitations of this analysis, further analysis would be required to more precisely calculate the statistical relationship between speeds estimated by TRUE and those estimated by PORTAL: 1) PORTAL speed estimates are time mean speeds; TRUE speed estimates are space mean speeds. Differences in the methods used to calculate each type of speed estimate will impact the results, especially when loop detectors are far apart (in the case of the PORTAL system, loop detectors are on average separated approximately one mile, and hence the error is not likely to be high); 2) Limitations of sample size – the analysis included a variety of locations and time periods; the change in relationship for different locations and time periods was not considered; and 3) Errors in interpolation – this could be of particular concern for hours during the transition to peak periods; however, 22 of the 30 "TRUE-PORTAL pairs" represented time periods well outside peak hours (8pm-5am and 11am-3pm). This is likely because commercial trucks typically avoid traveling during more congested, 'unreliable' times.

Emission rates are highly correlated with travel speeds and traffic conditions *(33)*. Hence, accurate environmental performance measures related to emissions are greatly dependent on the availability of detailed mobility performance measures. Performance measures used by state DOTs to measure the success of environmental stewardship include emissions of volatile organic compounds (VOC), nitrous oxides (NOx), carbon monoxide (CO), ozone (O3), particulate matter (PM), and greenhouse gas (GHG). Truck GPS data integrated with WIM data could be input into air quality modeling programs such as EPA's MOVES to improve the accuracy of model results. The methodology employed by Wheeler and Figliozzi *(2)* could be used and further developed to estimate freight emissions using ODOT's TRUE GPS and WIM data. According to *NCFRP Report 10 (5)*, national targets for most types of large/heavy-duty truck emissions are on track, but the industry's GHG emissions continue to rise. ODOT recognizes the need to address this concern and has developed the Greenhouse Gas Statewide Transportation Emissions Planning (GreenSTEP) Model to assess the effects of policies and other factors (i.e., gas prices) on GHG emissions from the transportation sectors *(34)*. Specifically, the model estimates and forecasts: vehicle ownership, vehicle travel, fuel consumption, and GHG emissions. As of October 2011, GreenSTEP focused on emissions from household and light duty commercial vehicles (i.e., autos, SUVs, pickup trucks, vans); modeling of GHG emissions from freight is still under development. According to ODOT reports *(34)*, estimates from GreenSTEP could further be used to assess the relative equity of different policy proposals for different road users. Given that commercial vehicle emissions are greatly dependent on vehicle weight and speed, TRUE data (in combination with WIM data) would be highly valuable in further developing the freight portion of GreenSTEP and in anticipating impacts of proposed policies as they relate to the freight sector.

CONCLUSIONS & FUTURE RESEARCH

This research clearly demonstrates the potential to use ODOT's WMT data for a variety of important applications. Highly accurate commodity or vehicle type truck trip generation rates are possible given that the accuracy of most TRUE GPS data is within 50 feet; this is an accuracy level that is more than appropriate to determine the location of truck travel at the TAZ level (TAZ areas are usually several miles wide/long). The accuracy of such trip generation rates could be further enhanced by identifying the TRUE GPS records that represent "trip ends" (origin and destination locations of truck tours). If the TRUE system were implemented state-wide, the resulting data could be used to develop highly accurate trip generation rates as an alternative to more inaccurate employment or production based trip generation rates and to calibrate the outputs of statewide freight models. Further, TRUE data provides a valuable resource towards mobility performance measures specific to freight vehicle type and commodity type. The findings of this research indicate that in general, space-mean speeds calculated from the TRUE GPS data are less than those estimated from loop detector measurements, and that the difference is statistically significant. This finding appears consistent with previous research *(2)* which found that for peak PM periods, speeds estimated by truck GPS data were generally less than those measured by loop detectors.

In addition to applications towards trip generation rates and mobility measures, this data exhibits strong potential to be used for performance measure categories such as safety, accessibility and connectivity, system condition, and environmental stewardship. The Applications Framework developed through this research proposes applications in each of these areas, along with the data fields required to provide accurate results in each. All of the data fields required for the proposed applications are available through the integration of TRUE and WIM data. Although previous research had limited success with the use of commercial truck GPS data for planning and modeling purposes, the TRUE data has an advantage in its level of disaggregation and its ability to differentiate between vehicle and commodity types. Previous assumptions made within SWIM2 and the Oregon Freight Plan regarding freight behavior could be reassessed since they were made in a significantly poorer freight data environment. ODOT's GreenSTEP model has previously focused on the impact of policies and investments on emissions from household and light duty commercial vehicles. The TRUE data provides opportunity to develop the freight portion of this model by providing details of vehicle type and travel behavior, as well as the possibility of more accurate weight loads, fuel consumption and speed estimates. Likewise, the potential to use the TRUE data to obtain emissions estimates from MOVES should be explored. Previous research *(2)* provides example of the successful use of truck GPS data in MOVES; however, the TRUE data (in combination with WIM data) provides opportunity to enhance the accuracy of such estimates by incorporating vehicle weight and speed estimates more representative of actual conditions.

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REFERENCES

1. CAMBRIDGE SYSTEMATICS, INC. & ODOT FREIGHT MOBILITY UNIT. *Oregon Freight Plan, An Element of the Oregon Transportation Plan.* Transportation Development Division Planning Section. Salem, OR : ODOT, 2011.
2. WHEELER, N. & FIGLIOZZI, M. *Multicriteria Freeway Performance Measures for Trucking in Congested Corridors.* Civil and Environmental Engineering, Portland State University. Portland, OR : Transportation Research Record: Journal of the Transportation Research Board, 2011. pp. 82-93. Volume 2224.
3. FIGLIOZZI, M., WHEELER, N., ALBRIGHT, E., WALKER, L., SARKAR, S. & RICE, D. *Algorithms to Study the Impacts of Travel Time Reliability along Multi-Segment Trucking Freight Corridors.* Civil and Environmental Engineering, Portland State University. Portland, OR : Transportation Research Record: Journal of the Transportation Research Board, 2011. pp. 26-34. Volume 2224.
4. MCMULLEN, S.B. & MONSERE, C. *Freight Performance Measures: Approach Analysis.* Oregon State University & Portland State University. s.l. : ODOT/OTREC, 2010. SPR 664; OTREC-RR-10-04.
5. NCFRP (NATIONAL COOPERATIVE FREIGHT RESEARCH PROGRAM). *Performance Measures for Freight Transportation.* s.l. : Transportation Research Board (TRB), 2011. NCFRP Report 10.
6. OREGON DEPARTMENT OF TRANSPORTATION (ODOT). Truck Road Use Electronics Pilot Project. *Office of Innovative Partnerships and Alternative Funding.* [Online] Oregon Department of Transportation (ODOT). [Cited: July 31, 2012.] http://cms.oregon.egov.com/ODOT/HWY/OIPP/Pages/TRUE.aspx.
7. GREAVES, S. & FIGLIOZZI, M. *Collecting Commercial Vehicle Tour Data with Passive Global Positioning System Technology: Issues and Potential Applications.* Institute of Transport and Logistics Studies, University of Sydney. New South Wales, Australia : Transportation Research Record: Journal of the Transportation Research Board, 2008. pp. 158-166. Volume 2049.
8. HOLGUIN-VERAS, J., OZBAY, K., KORNHAUSER, A., BROM, M.A., IYER, S., YUSHIMITO, W.F., UKKUSURI, S., ALLEN, B. & SILAS, M.A. *Overall Impacts of Off-Hour Delivery Programs in New York City Metropolitan Area.* Civil and Environmental Engineering, Resselaer Polytechnic Institute. Troy, NY : Transportation Research Record: Journal of the Transportation Research Board, 2011. pp. 68-76. Volume 2238.
9. MCCORMACK, E. *Developing Transportation Metrics from Commercial GPS Truck Data.* Department of Civil and Environmental Engineering, University of Washington. Seattle, WA : Transportation Northwest (TransNow), 2011. TNW2011-12.
10. BASSOK, A., MCCORMACK, E., OUTWATER, M. & TA, C. *Use of Truck GPS Data for Freight Forecasting.* Puget Sound Regional Council. Seattle, WA : Transportation Research Record: Journal of the Transportation Research Board, 2011.
11. MA, X., MCCORMACK, E. & WANG, Y. *Processing Commercial Global Positioning*

System Data to Develop a Web-Based Truck Performance Measures Program. Civil and Environmental Engineering, University of Washington. Seattle, WA : Transportation Research Record: Journal of the Transportation Research Board, 2011. pp. 92-100. Volume 2246.

12. ZHAO, W., GOODCHILD, A.V. & MCCORMACK, E.D. *Evaluating the Accuracy of Spot Speed Data from Global Positioning Systems for Estimating Truck Travel Speed.* Civil and Environmental Engineering, University of Washington. Seattle : Transportation Research Record: Journal of the Transportation Research Board, 2011. pp. 101-110. Volume 2246.
13. WUNNAVA, S., YEN, K., TADEUSZ, B., ZAVALETA, R., ROMERO, R. & ARCHILLA, C. *Travel Time Estimation Using Cell Phones for Highways and Roadways.* Florida Department of Transportation. 2007.
14. ZHAO, Y. *Mobile Phone Location Determination and Its Impact on Intelligent Transportation Systems.* s.l. : Intelligent Transportation Systems, IEEE Transactions, 2000. pp. 55-64.
15. BARBEAU, S., LABRADOR, M.A., PEREZ, A., WINTERS, P., GEORGGI, N., AGUILAR, D. & PEREZ, R. *Dynamic Management of Real-Time Location Data on GPS-Enabled Mobile Phones.* UBICOMM 2008. s.l. : The Second International Conference On Mobile Ubiquitous Computing, Systems, Services and Technologies, 2008, 2008. pp. 343-348.
16. ZHENG, Y., LIU, L., WANG, L. & XIE, X. *Learning Transportation Mode from Raw GPS Data for Geographic Applications on the Web.* Bijing, China: ACM : Proceedings of the 17th International Conference on World Wide Web, 2008. pp. 247-256.
17. MANZONI, V., MANILO, D., KLOECKL, K. & RATTI, C. *Transportation Mode Identification and Real-time CO2 Emission Estimation Using Smartphones.* SENSEable City Lab, Massachusetts Institute of Technology.
18. FROEHLICH, J., DILLAHUNT, T., KLASNJA, P., MANKOFF, J., CONSOLVO, S., HARRISON, B. & LANDAY, J.A. *UbiGreen: Investigating a Mobile Tool for Tracking and Supporting Green Transportation Habits.* Boston, MA, USA: ACM : Proceedings of the 27th International Conference on Human Factors in Computing Systems, 2009. pp. 1043-1052.
19. SCHRANK, D., LOMAX, T. & EISELE, B. *TTI's 2011 Urban Mobility Report Powered by INRIX Traffic Data.* Texas Transportation Institute. 2011.
20. INRIX, INC. *Inrix.* [Online] 2012. [Cited: February 11, 2012.] http://inrix.com/.
21. XATA CORPORATION. Xata Turnpike. *XATA.* [Online] 2012. [Cited: February 5, 2012.] http://www.xata.com/fleet-management-solutions/xata-turnpike-enterprise-fleet-management/.
22. EROAD LIMITED. *EROAD.* [Online] 2011. [Cited: February 10, 2012.] http://eroad.com/.
23. PORTLAND METRO. RLIS Live, Geographic Information System Data. [Online] Metro, 2012. [Cited: June 4, 2012.] http://www.oregonmetro.gov/index.cfm/go/by.web/id=593.
24. YOU, S. & RITCHIE, S. *Tour Behavior of Clean Drayage Trucks in Southern California.* Civil and Environmental Engineering, University of California. Irvine, CA : Transportation Research Board (TRB) Annual Meeting, 2012. Paper 12-1544. Session 497.
25. BOILE, M., OZBAY, K. & NARAYANAN, P. *Infrastructure Costs Attributable to Commercial Vehicles.* 2001. Final Report. FHWA-NJ-2001-030.
26. PAVEMENT INTERACTIVE. Equivalent Single Axle Load. *Pavement Interactive.* [Online]

2012. [Cited: July 31, 2012.] http://www.pavementinteractive.org/article/equivalent-single-axle-load/.
27. HUNT, J.D., WEIDNER, T., KNUDSON, R., BETTINARDI, A. & WARDELL, E. *Applying the SWIM2 Integrated Model in Freight Planning in Oregon.* Civil Engineering, University of Calgary. NW Calgary, AB, Canada : Transportation Research Board (TRB) Annual Meeting, 2011. Paper 11-3553. Session 625.
28. FIGLIOZZI, M.A. & SHABANI, K. *Critical Review and Analysis of Existing CT Module.* Portland State University. Portland, OR : s.n., 2010. Technical Memorandum and Final Report. IGA # 24620 WOC 4.
29. NCHRP (NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM). *Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability.* Washington, D.C. : Transportation Research Board (TRB), 2008. Report 618.
30. PARK, L., PIERCE, D. & SHORT, J. *A System for Utilizing Truck GPS Data to Monitor Urban Highway Congestion.* American Transportation Research Institute (ATRI). Marietta, GA : Transportation Research Board (TRB) Annual Meeting, 2012. Paper 12-1754. Session 497.
31. LI, H. & BERTINI, R.L. *Comparison of Algorithms for Systematic Tracking of Patterns of Traffic Congestion on Freeways in Portland, Oregon.* Civil and Environenmental Engineering, Portland State University. Portland, OR : Transportation Research Record: Journal of the Transportation Research Board, 2010. pp. 101-110. Volume 2178.
32. SULLIVAN, M. *Statistics: Informed Decisions Using Data.* Fourth. s.l. : Pearson, 1967. p. 169.
33. FIGLIOZZI, M.A. *The Impacts of Congestion on Time-definitive Urban Freight Distribution Networks CO2 Emission Levels.* Maseeh College of Engineering and Computer Science, Portland State University. Portland, OR : Transportation Research Part C, 2011. pp. 766-778. v.19 (5).
34. OREGON DEPARTMENT OF TRANSPORTATION (ODOT) & DEPARTMENT OF LAND CONSERVATION AND DEVELOPMENT. Greenhouse Gas Strategic Transportation Energy Planning Model. *OREGON.gov; Oregon Sustainable Transportation Initiative (OSTI).* [Online] October 2011. [Cited: February 25, 2012.] http://www.oregon.gov/ODOT/TD/OSTI/docs/Media/Model.pdf?ga=t.

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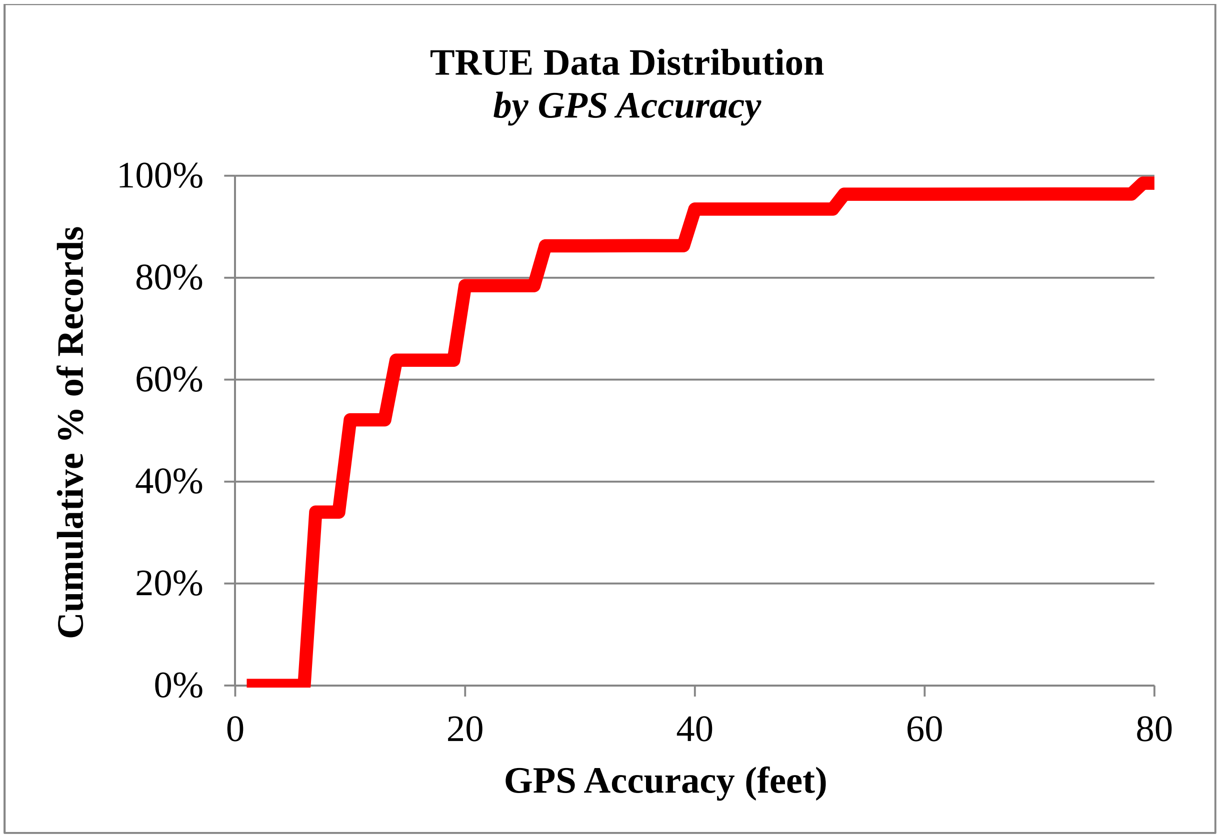

FIGURE 1 Distribution of GPS Accuracies

	FIELD	**DESCRIPTION**
TRUE GPS RECORDS	ROW_ID	System generated row id
	DEVICE_ID	Unique identifier for each smartphone
	LATITUDE	Latitude of device
	LONGITUDE	Longitude of device
	WAYPOINT_TIME	Timestamp of GPS record
	WEIGHT_CLASS	Weight class of vehicle
	AXLES	Axle count of vehicle
	RECEIVED_TIME	Timestamp waypoint was received by server
	LOCATION_NAME	General location name
	PERMIT_NO	Permit number vehicle is operating under
	GPS_ACCURACY	Accuracy of the GPS fix in meters
	ODOMETER	Most recent odometer entry by driver

	FIELD	**DESCRIPTION**
DEVICE / TRUCK	DEVICE_ID	Unique identifier for each smartphone
	ACCT_NO	Oregon taxpayer id
	CARRIER_UNIT_ID	Unit number of vehicle assigned by carrier
	PHONE_NO	Phone number of mobile device
	BASE_PLATE	Base plate of vehicle
	BASE_ST	Base state of vehicle
	ASSIGNED_DATE	Timestamp mobile device was assigned to carrier

	FIELD	**DESCRIPTION**
WEIGH-IN-MOTION RECORDS	WEI_ID	System generated row id
	WEI_AUTHNO	Oregon taxpayer id
	WEI_BASEPLATE	Base plate of vehicle
	WEI_BASESTATE	Base state of vehicle
	WEI_PSTDATETIME	Timestamp of event in PST
	WEI_SCALENO	Scale number
	WEI_LOCATION	Location
	WEI_CARRIERNAME	Carrier name
	WEI_VTID	Vehicle class id (VEHTYPE)
	WEI_VCID	Vehicle type id (VEHCLASS)
	WEI_AXLES	Vehicle axle count
	WEI_COMMODITY	Commodity code of what vehicle is hauling
	WEI_GROSS	Gross weight
	WEI_WGT[1:12]	Weight at axle [1:12]
	WEI_DIRECTION	Direction of lane
	WEI_VEHICLE	Calculated value, based on class and type ids

FIGURE 2 Data Fields

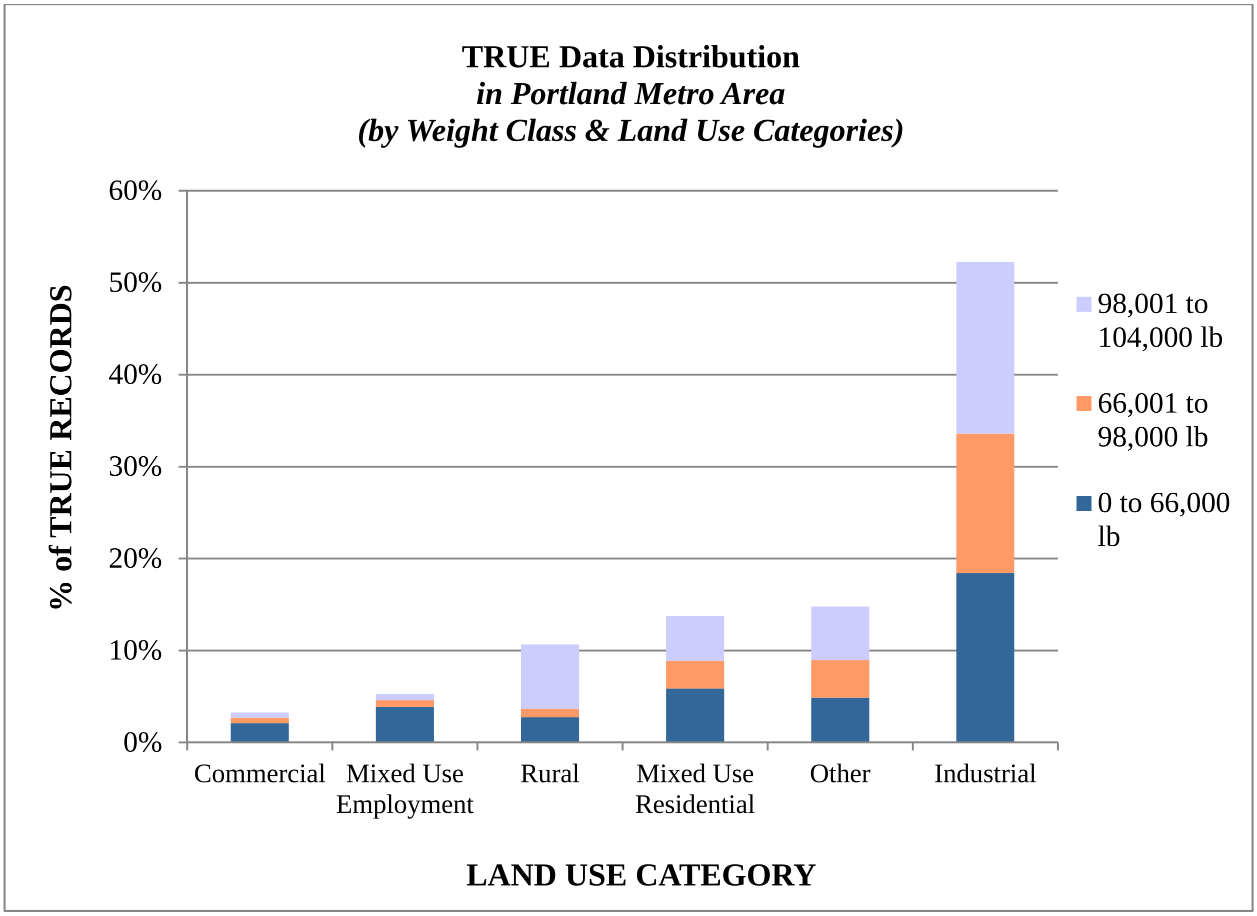

FIGURE 3 Density of GPS Records by Weight Class and Land Use

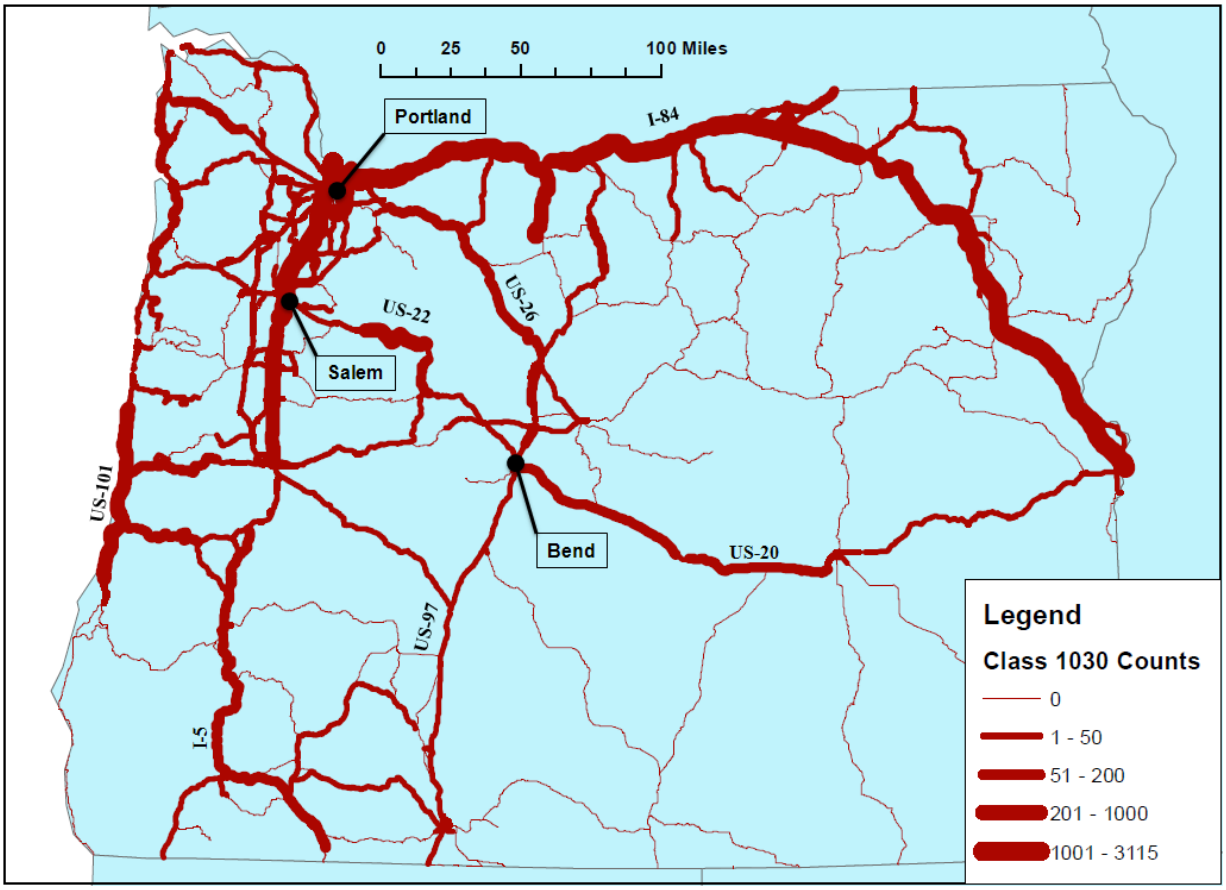

FIGURE 4 GPS Record Counts for 1030 Weight Class

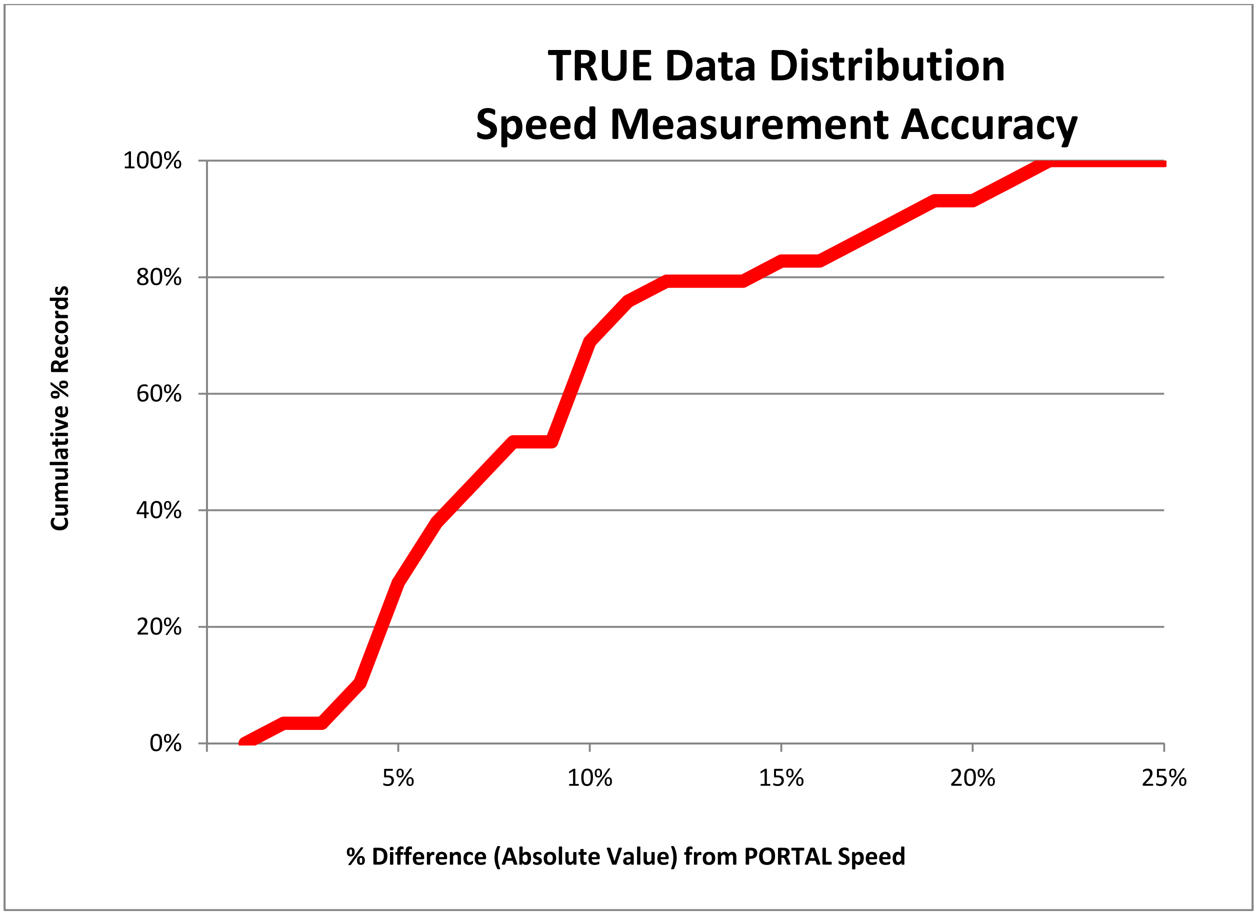

FIGURE 5 TRUE Speed Measurement Accuracy

TABLE 1 Research Categories – shaded cells represent the research categories addressed by each research project

Date	Authors	Performance Measures					Oregon	Data Processing & Integration	Planning & Modeling
		Mobility	System Condition	Environment	Safety	Connectivity			
2008	Greaves & Figliozzi	■						■	
2010	Sharman & Roorda	■		■				■	■
2010	Holguin-Veras et al	■		■		■		■	■
2011	Wheeler & Figliozzi	■		■			■		
2011	Figliozzi et al	■		■			■	■	
2011	McCormack et al	■		■		■		■	■
2012	You & Ritchie	■		■		■		■	
2012	FHWA/ATRI	■							
2012	Park, Pierce & Short	■		■					

TABLE 2 Freight Performance Measure Categories

FREIGHT PERFORMANCE MEASURE CATEGORIES	
NCHFRP Report 10	**ODOT Report**
Demand	Mobility, Congestion and Reliability
Efficiency	
System Condition	Maintenance & Preservation
Environmental Impact	Environmental
Safety	Safety
	Accessibility & Connectivity
Adequacy of Investment	

TABLE 3 Applications Framework – shaded cells represent the data fields that are required for each performance measure / application

		Data Fields									
Category	**Performance Measure / Application**	Lat / Long	Time Stamp	Weight Class	Axle Count	Accuracy of GPS	Vehicle Class	Vehicle Type	Commodity Code	Gross Weight	Axle Weights
Mobility	Travel Time	■	■			■					
	Travel Time Reliability	■	■			■					
	Travel Time Index (TTI)	■	■			■					
	Planning Time Index	■	■			■					
	Volume to Capacity (V/C)	■	■			■					
	% Congested Miles	■	■			■					
	Interstate MC VMT	■	■			■					
	Freight tonnage by commodity	■	■			■			■		
System Condition	Estimate Pavement Condition	■	■	■	■	■	■	■		■	■
	Scope Pavement Condition Surveys	■	■	■	■	■	■	■		■	■
	Pavement Forensics	■	■	■	■	■	■	■		■	■
	Bridge Weight Limit Violations	■	■	■	■	■	■	■		■	■
Environment	GHG Emissions Estimations	■	■	■	■	■	■	■		■	■
	Other Emissions Estimations	■	■	■	■	■	■	■		■	■
	GreenSTEP Integration	■	■	■	■	■	■	■	■	■	■
Safety	*Miscellaneous*	■	■			■					
Accessibility & Connectivity	LCV Network Access	■	■			■					
	Truck turnaround time at terminals	■	■			■					
Planning & Modeling	Trip Generation Rates	■	■	■	■	■	■	■	■	■	■
	SWIM2 Integration	■	■	■	■	■	■	■	■	■	■
	Visual Analysis (i.e., GIS)	■	■	■	■	■	■	■	■	■	■
	Partner with Regional Projects	■	■	■	■	■	■	■	■	■	■
	Route Choice	■	■	■	■	■	■	■	■	■	■
	Vehicle Choice	■	■	■	■	■	■	■	■	■	■
	Freight Activity Modeling	■	■	■	■	■	■	■	■	■	■
	Mode Choice	■	■	■	■	■	■	■	■	■	■