GPS Data Analysis of the Impact of Tolling on Truck Speed and Routing
Case Study in Seattle, Washington

Zun Wang and Anne V. Goodchild

Roadway tolls are designed to raise revenue to fund transportation investments and manage travel demand and as such may affect transportation system performance and route choice. Yet, limited research has quantified the impact of tolling on truck speed and route choice because of the lack of truck-specific movement data. Most existing tolling impact studies rely on surveys in which drivers are given several alternative routes and their performance characteristics and asked to estimate route choices. The limitations of such an approach are that the results may not reflect actual truck route choices and the surveys are costly to collect. The research described in this paper used truck GPS data to observe empirical responses to tolling, following the implementation of a toll on the State Route 520 (SR-520) bridge in Seattle, Washington. Truck GPS data were used to evaluate route choice and travel speed along SR-520 and the alternate toll-free Route I-90. It was found that truck travel speed on SR-520 improved after tolling, although travel speed on the alternative toll-free Route I-90 decreased during the peak period. A set of logit models was developed to determine the influential factors in truck routing. The results indicated that travel time, travel time reliability, and toll rate were all influential factors during peak and off-peak periods. The values of truck travel time during various time periods were estimated, and it was found that the values varied with the definition of peak and off-peak periods.

Roadway tolls are designed to raise revenue for funding transportation investments and manage travel demand (*1*). Tolling strategies might affect both truck speed and route choice. On the one hand, tolling adds additional costs to the movement of goods, which may result in truck traffic diversion from toll roads to toll-free roads. On the other hand, tolling may reduce travel time and improve reliability along the toll road, which in turn saves logistics costs and therefore may attract trucks to toll roads. Thus, trucks may switch routes between toll roads and toll-free roads based on the trade-offs among a set of time and cost attributes.

Extensive studies of tolling impacts on passenger travel have revealed that travelers' responses include rescheduling trips, canceling trips, and consolidating trips, as well as changing routes. However, commercial trips have less flexibility for rescheduling, canceling, or consolidation of trips because of customers' require-

ments (*2*). A survey developed to examine the impacts of the Port Authority of New York and New Jersey's time-of-day pricing found that 68.9% of for-hire carriers and private carriers cannot change their schedule because of customer requirements; only 0.5% of trucks would switch to off-peak delivery (*3*). Meanwhile, the results showed even less ability to consolidate trips, with only 0.1% of carriers able to increase shipment size, 0.4% of carriers able to wait longer for mixing pickups, and 0.1% of carriers able to cut some of their runs (*3*).

Diverted truck traffic has significant impacts on regional traffic safety, travel performance (e.g., travel speed), the environment (emissions), as well as toll revenue and the regional economy. For instance, the Ohio Turnpike caused a 30% to 50% increase in truck traffic on local routes and imposed significant safety and environmental costs (*4*). Thus, it is critical to understand the effects of tolling on truck performance and route choice. Yet limited research has quantified the impacts of tolling on truck speed and trip diversion because of the lack of detailed truck data. This paper uses truck GPS data to observe truck speed and route choice following the implementation of a toll on State Route 520 (SR-520) in Seattle, Washington.

The next section of this paper will provide a brief review of the state of the practice in evaluating the effects of tolling on truck routing. The paper will then introduce the study area and describe the process by which the effects of tolling were analyzed. The study applied the discussed methods and the paper provides the results and offers conclusions from the study.

LITERATURE REVIEW

Truck travel demand elasticity modeling is a common approach to study the effects of tolling on truck trip diversion. Several freight demand elasticity models have been developed to model the impacts of tolling on truck route choice. One example is the Ohio Turnpike truck traffic diversion analysis (*4*). The toll rates of the Ohio Turnpike were increased substantially in the 1990s to fund new construction projects and were later reduced after the projects were completed. The Ohio Turnpike truck traffic diversion analysis is an ideal data set to estimate the truck demand elasticity with respect to toll rates. The truck vehicle miles traveled (VMT), toll rates, and roadway speed limit data were collected between 1973 and 2005. The ratio of Ohio Turnpike truck VMT to the U.S. total truck VMT was used to estimate truck trip diversion from the Ohio Turnpike to other free alternatives. The results indicated that a 10% increase in toll rate per VMT increased the truck traffic diversion to a toll-free route by 4.7%.

Z. Wang, 135 More Hall, and A. V. Goodchild, 121E More Hall, Department of Civil and Environmental Engineering, University of Washington, Seattle, WA 98195. Corresponding author: Z. Wang, zunwang@uw.edu.

Another study analyzed the tolling of I-81 in Virginia (5). In contrast to the Ohio Turnpike truck diversion research, which relied on historical observations, the I-81 project predicted the truck demand elasticity based on a customized nonlinear Reebie's Truck Cost Allocation Model developed by Oak Ridge National Laboratory. The model assumes that route choice is determined by travel cost only and the trucking industry behaves in an economical manner, meaning that truckers always take the route along which the travel cost is the minimum. The Truck Cost Allocation Model estimated the travel cost with a nonlinear model in which the independent variables were travel distance, travel time, toll, expected congestion, equipment type, driver type, and size of carrier. The route choice was translated into traffic diversion at each given toll rate to estimate the truck demand elasticity with respect to toll rates. Traffic diversion was expected to increase from 16% to 67% when the toll rate increased from 12 to 30 cents/mi. Furthermore, the study revealed that the commodity type did not matter to the truck VMT diversion on I-81, with the exception of coal.

In addition to truck VMT modeling, other researchers have attempted to model the impacts of tolling and other influential factors on truck route choice based on stated preference surveys. Arentze et al. conducted a stated preference survey to understand truck route choice behaviors (6). The survey was designed to examine how drivers trade off road accessibility characteristics against travel time and travel cost factors. Road accessibility refers to roadway geometry, for example, sharp curves and intersections. There were 78 respondents who completed the online questionnaire. A mixed logit model was formulated based on the responses. Arentze et al. noted that travel time had the strongest impact on route choice and congestion and road category were significant factors as well (6).

Sun et al. conducted interviews with truck drivers at three rest areas and truck stop locations along major highways in Texas, Indiana, and Ontario, Canada, to identify the factors that affect truck routing (7). Truck drivers were asked to choose between two hypothetical route alternatives. Two scenarios were created: the bypass scenario and the turnpike scenario. In the bypass scenario, truckers were asked to choose between an urban freeway passing through the downtown area and a bypass alternative that charges additional tolls and involves a longer travel distance, but has a shorter travel time. Under the turnpike scenario, drivers were asked to choose between the tolled freeway and free local roads. A logit model was developed to analyze the factors that determine route choice. Sun et al. found that toll cost and travel time were the most significant factors affecting truck routing (7).

Studies of the value of truck travel time also involve the examination of roadway toll impacts on truck routing. Kawamura estimated truck value of time for various types of carriers based on a stated preference survey conducted in California (8). Truck drivers were asked to choose between an existing free road and a toll road for various combinations of travel times and costs. In addition, other truck operator characteristics, including business type (for-hire or private fleet), shipment size, and pay scale (pay-by-hour, fixed salary, or commission-based), were examined. The results revealed that the value of truck travel time is closely associated with the time and toll cost trade-off, as well as the business type and pay scale. More specifically, the for-hire carriers had higher value of travel time than the private carriers. Similar results were found by Zhou et al. that travel time and toll costs are the significant factors determining route choice (9). Meanwhile, smaller carriers are more likely to avoid a toll road compared with larger companies.

The literature review has summarized the commonly applied methodologies to model the impacts of roadway tolls on truck trip diversion. In the approach based on truck travel demand modeling and the approach based on surveying and interviewing, it is costly to collect data to support the analyses. However, GPS data are able to alleviate such concerns, given the decreased costs of GPS devices and increased market penetration of GPS technology for truck fleet management.

In addition, the traditional surveys and interviews consist of hypothetical routes and estimated attributes (e.g., travel time and speed) and therefore are not able to reflect real world truck traffic performance. Since respondents are given abstract and hypothetical situations, the route preferences indicated by the respondents may not be the same as their actual choices would be. In contrast, the data retrieved from GPS devices are able to provide details of truck-specific movement (speed and travel time) and trajectory (route choice) information. Therefore the GPS data can support realistic tolling impact analyses, including quantifying changes in truck speed, identifying influential factors in truck routing, and estimating the value of truck travel time based on utility functions. This study investigated how truck GPS data can be used to implement the aforementioned tasks.

STUDY AREA AND DATA ACQUISITION

Study Area

SR-520, which is 6.8 mi long, is recognized as a critical corridor carrying traffic across Lake Washington between Interstate Highway 5 (I-5), the city of Seattle on the west, and I-405 and the Cities of Bellevue, Redmond, and Kirkland, Washington, on the east (Figure 1). The alternate routes are I-90 and SR-522. The SR-520 bridge was built in 1963 and is approaching the end of its useful life. Thus, the Washington State Department of Transportation (DOT) started tolling in December 2011 to fund the SR-520 replacement projects (10). Toll rates are predetermined and change based on time of day, truck size, and payment method (11). According to the Washington State DOT, tolling caused some traffic that used to travel along SR-520 to divert to the alternative free road, I-90.
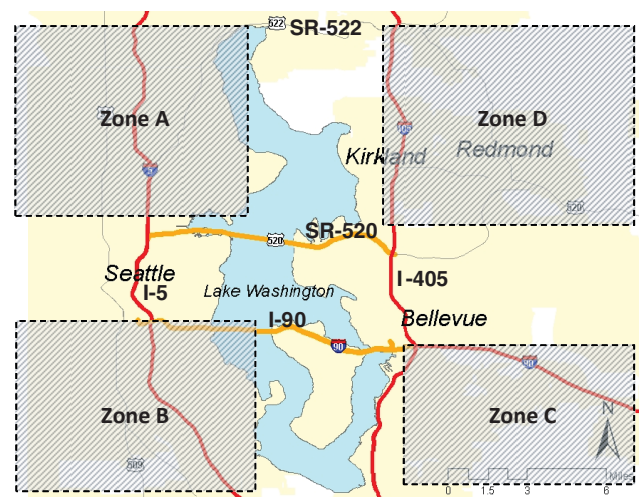

FIGURE 1 Study area and surrounding highways.

Through March 2012, the traffic on the SR-520 bridge dropped by 35% to 40%, while traffic on I-90 increased by 5% to 10% (*12*). No significant change along SR-522 was observed, since SR-522 involves a longer detour, intersections, and signal delays (*12*). Therefore, this study considered only I-90 as the alternative toll-free road for crossing the lake for commercial trips.

The study area was subdivided into four zones, denoted A, B, C, and D, as shown in Figure 1. Areas outside the four zones were not considered, because the detour length would have been exceedingly long. It was less likely for truck drivers traveling between Zone A and Zone D to choose the toll-free route I-90, because it would have involved a longer detour. That is, if the SR-520 bridge was chosen, the travel distance to cross the lake is the length of east-bound SR-520 shown in Figure 1. However, if I-90 was chosen, the distance to cross the lake is the sum of the distance on southbound I-5 between SR-520 and I-90, eastbound I-90, and northbound I-405 between I-90 and SR-520. However, drivers traveling between Zone A and Zone C and between Zone B and Zone D face two comparable alternatives (similar travel distances). Whether SR-520 or I-90 is chosen depends on the trade-offs between a set of time and cost attributes. If SR-520 is chosen, drivers need to pay the toll, but may experience shorter and more reliable travel time. In contrast, if I-90 is chosen, drivers do not need to pay a toll, but may experience longer and less reliable travel time, since increased traffic was observed on I-90 after tolling.

This study examined the impacts of a set of time and cost attributes on truck route choice based on empirical observations of truck trips between Zone A and Zone C and between Zone B and Zone D during the morning and afternoon peak periods (6:00 to 9:00 a.m. and 3:00 to 6:00 p.m.) and during the off-peak period (9:00 a.m. to 3:00 p.m.).

GPS Data Acquisition

This research used GPS data collected in November 2011 (prior to the toll) and April 2012 (following the toll, which started on December 29, 2011). Data were provided on the condition of anonymity from trucks equipped with GPS devices traveling through the Puget Sound Region. The GPS data were reported every 2 to 15 min and at every stop. Information provided by the GPS data included a unique device ID, location (latitude and longitude), spot (instantaneous) speed, truck heading direction, time, and date (*13*). The truck fleet and commodity information were unknown. Before conducting any analysis, the raw GPS data were cleaned to remove problematic and duplicated data. More details of the GPS data collection and processing can be found in McCormack et al. (*13*) and Zhao et al. (*14*). In addition, an algorithm was developed to automatically identify discrete truck trips from raw GPS data based on truck dwell time (*15*).

METHODOLOGY

Impact of Tolling on Truck Travel Speed

The truck travel speeds on SR-520 and I-90 before and after tolling were compared to analyze the impacts of tolling on truck performance. The speeds on SR-520 and I-90 before and after tolling were estimated with the estimated link speed method for every 15-min interval (*14*). The segment being studied was divided into several subsegments. For each subsegment, the speed was calculated by

averaging the spot speed over the subsegment and the corresponding travel time was computed by dividing the subsegment distance by the average spot speed. The total travel time (for the entire segment) is the sum of the travel times on each subsegment. The truck travel speed of the entire link, called the estimated link speed, was computed by dividing the total distance by the total travel time. The calculation is given in Equation 1. The outcome has been compared with space mean speed and it has been demonstrated that the estimated link speed approach is a reliable method for estimating truck speed (*14*).

$$V = \frac{\sum_{i=1}^{n} l_i}{\sum_{i}^{n} \frac{l_i}{\overline{v}_i}} \tag{1}$$

where

V = estimated link speed,
i = number of subsegments,
l_i = length of the ith subsegment, and
$\overline{v}_i$ = average GPS spot speed on the ith subsegment.

Impact of Tolling on Truck Route Choice

Several studies have investigated the influential factors in truck routing. A thorough review can be found in Cullinane and Toy, who reviewed 75 articles and identified the five most common categories (*16*). These were travel cost, price, and rate; travel speed; transit time reliability; characteristics of the goods; and service. In addition, other studies have found that roadway geometric features, safety and security, accessibility, types of carriers, and drivers' payment method are significant as well (*6–9*). Not all the aforementioned variables are readily available or can be retrieved from the truck GPS data. Therefore, this study chose travel time, travel time reliability, and toll rates as the influential attributes in truck routing. These factors were also identified as the most significant variables in most studies.

A logit model was used to quantify the impact of tolling on truck route choice based on the assumption that the trucking industry behaves in an economical manner and always maximizes utility while choosing travel routes. Two alternative routes were considered: (*a*) toll bridge SR-520 and (*b*) toll-free route I-90. The utility functions are

$$U_{90} = \alpha + \beta_1 TT_{90} + \beta_2 TR_{90}$$

$$U_{520} = \beta_1 TT_{520} + \beta_2 TR_{520} + \beta_3 \text{toll} \tag{2}$$

where

U_{90} = utility function of choosing I-90;
U_{520} = utility function of choosing SR-520;
α = constant;
β = impact of corresponding parameter on utility;
TT = lake crossing time (min), as shown in Table 1;
TR = lake crossing travel time reliability, defined as the standard deviation of travel time; and
toll = toll rates.

As illustrated in Equation 2, to construct the logit model, six variables are required for each lake crossing trip: actual route choice,

TABLE 1 Truck Travel Time on Each Alternative

Truck Trip	Route	Lake Crossing Time
Zone A to Zone C	SR-520	$TT_{SR\text{-}520\_EB} + TT_{I\text{-}405\_SB}{}^{a}$
	I-90	$TT_{I\text{-}5\_SB} + TT_{I\text{-}90\_EB}$
Zone C to Zone A	SR-520	$TT_{I\text{-}405\_NB} + TT_{SR\text{-}520\_WB}$
	I-90	$TT_{I\text{-}90\_WB} + T_{I\text{-}5\_NB}$
Zone B to Zone D	SR-520	$TT_{I\text{-}5\_NB} + TT_{SR\text{-}520\_EB}$
	I-90	$TT_{I\text{-}90\_EB} + TT_{I\text{-}405\_NB}$
Zone D to Zone B	SR-520	$TT_{SR\text{-}520\_WB} + TT_{I\text{-}5\_SB}$
	I-90	$TT_{I\text{-}405\_SB} + TT_{I\text{-}90\_WB}$

$^{a}TT_{SR\text{-}520\_EB}$ represents travel time on eastbound SR-520, and $TT_{I\text{-}405\_SB}$ represents travel time on southbound I-405 on the segment between SR-520 and I-90.

actual travel time, potential travel time on the alternative route, actual travel time reliability, potential travel time reliability on the alternative route, and toll cost on SR-520. The remainder of this section will discuss how these variables were observed and estimated.

Truck Route Choice

The selection of lake crossing trips and identification of route choice consisted of three steps. First, the processed GPS data were geocoded to the network and GPS reads on SR-520 and I-90 were selected separately. Second, the truck trips containing GPS reads on SR-520 and I-90 were identified based on the unique GPS device ID. Third, the truck trips that were between Zones A and C and those between Zones B and D were selected as the input to support the modeling process. The corresponding route choice of each truck trip was identified depending on whether it contained GPS reads on SR-520 or on I-90. The complete process was accomplished inside the ArcGIS environment.

Truck Travel Time

The travel time considered in the model was the lake crossing travel time, as presented in Table 1. The actual lake crossing time was calculated by dividing travel distance by the truck GPS spot speed. To formulate the logit model, the potential travel time on the alternative route was needed as well. The travel time on the alternative route was estimated by dividing the travel distance of the alternative route by the estimated link speed (calculated with Equation 1) on that alternative route during the corresponding 15-min interval. Travel time was measured in minutes in the logit model.

Travel Time Reliability

Travel time reliability represents the level of consistency in travel times during a time period (*17*). Many approaches have been developed to quantify travel time reliability, including the travel time standard deviation, the 95th percentile of travel time, buffer time, probability of on-time arrival, and so forth (*17*). In this study, the standard deviation of travel time was chosen as the reliability metric, which was consistent with the measure used in the SHRP 2 highway pricing study Project C04 (Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand)

(*18*). The travel time reliabilities for the actual selected route and the alternative route were calculated for each 15-min interval.

Toll Rate

Toll rates on SR-520 vary depending on the time of day, truck type, and payment method. The rate ranges from $0 between 11:00 p.m. and 5:00 a.m. for all types of trucks to $10.50 between 7:00 and 9:00 a.m. for six-axle trucks paying by the electronic tolling system. It was assumed that all trucks on SR-520 used the electronic tolling system. Higher toll rates were expected for other payment methods, such as paying by mail (*11*). Since the truck size was unknown, the toll rate on SR-520 during each time period was calculated as a weighted average of the Washington State DOT truck counts by number of axles.

RESULTS

Impacts of Tolling on Truck Speed

Figure 2 presents the weekday average truck speed on eastbound SR-520 and eastbound I-90 before and after tolling, between 6:00 a.m. and noon. The speed was aggregated for every 15-min interval. According to Figure 2*a,* before tolling, truck speed on SR-520 was always lower than on I-90. The lowest speed was about 30 mph between 8:00 and 9:00 a.m. However, as illustrated in Figure 2*b,* travel speed on SR-520 improved significantly following the implementation of the toll. The truck speed was around 50 mph during the morning peak period, which exceeded the speed on I-90. In addition to the improvement in travel speed, the travel time on SR-520 was more stable with reduced fluctuation. The difference in travel speed was greater than 20 mph in November 2011 and was less than 10 mph in April 2012. Changes in travel speed on I-90 were much less pronounced than on SR-520. The truck travel speed on I-90 decreased slightly between 7:30 and 9:00 am. The changes in truck speed on both bridges mainly resulted from the traffic diversion from SR-520 to I-90. According to the data collected by the traffic count devices deployed along the SR-520 bridge in April 2012, the eastbound number of passenger car trips was reduced by 32% compared with the volume recorded in November 2011 and commercial truck trips dropped by 26%.

Truck speeds over westbound SR-520 and I-90 were compared before and after tolling and are presented in Figure 3. Similar impacts were observed on westbound truck speed. As displayed in Figure 3*a,* before tolling, average truck speed on SR-520 was lower than the speed on I-90 (except between 6:00 and 6:15 a.m.), with the lowest speed at 30 mph around 8:00 a.m. The speed increased dramatically after tolling and was greater than the speeds on I-90 between 7:15 and 9:00 a.m., as shown in Figure 3*b.* Meanwhile, the variation in speed on SR-520 was reduced after tolling. The truck speed on westbound I-90 after tolling did not change considerably between 6:00 and 7:30 a.m. However, the speed declined significantly between 7:30 and 9:15 a.m., possibly because the toll rate increased by 25% between 7:00 and 9:00 a.m. compared with the rate during 6:00 to 7:00 a.m., and resulted in considerable traffic diversion from SR-520 to I-90. The monthly traffic volume collected by the traffic count devices shows that passenger car trips on the westbound SR-520 bridge decreased by 31% in April 2012 compared with the data collected in November 2011 and the truck traffic declined by 26%.
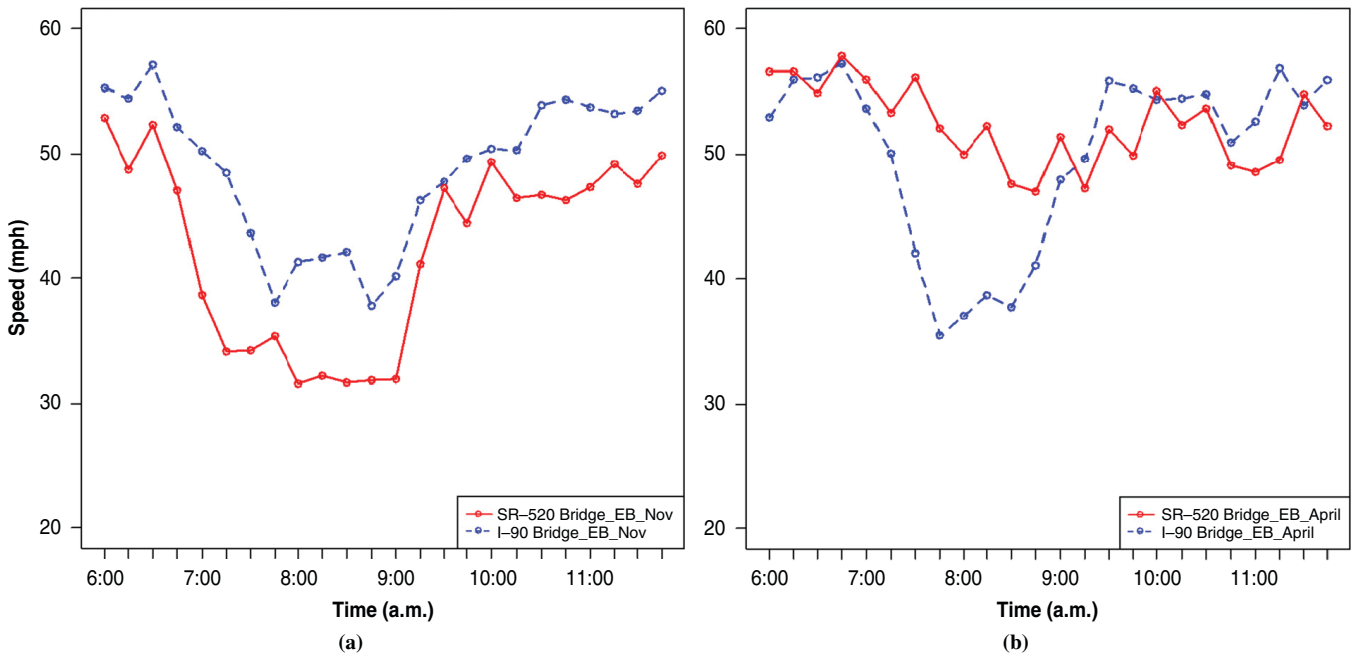
FIGURE 2   Truck speed on (*a*) eastbound SR-520 and eastbound I-90 in November 2011 and (*b*) eastbound SR-520 and eastbound I-90 in April 2012.

Impacts of Tolling on Truck Route Choice

There were 185 truck trips observed during the peak period, among which 25 trips selected SR-520 and 160 trips selected I-90. For the off-peak period in April 2012, there were 203 trucks trips observed, among which 37 trips chose SR-520 and 166 trips chose I-90. The logit model was implemented with R software. The results are shown in Table 2. Two traffic phases were modeled: the peak period (6:00 to 9:00 a.m. and 3:00 to 6:00 p.m.)

and the off-peak period (9:00 a.m. to 3:00 p.m.). Travel time and toll rate are significant variables for both phases. The signs of the travel time and toll rate coefficients are negative, which means that the increase in travel time and toll rate of a specific route will reduce the utility of that route as well as the probability that it will be chosen.

The constant in the I-90 logit function is positive and indicates that, everything being equal, the utility of choosing I-90 is greater than choosing SR-520, which reveals that I-90 is more preferable to
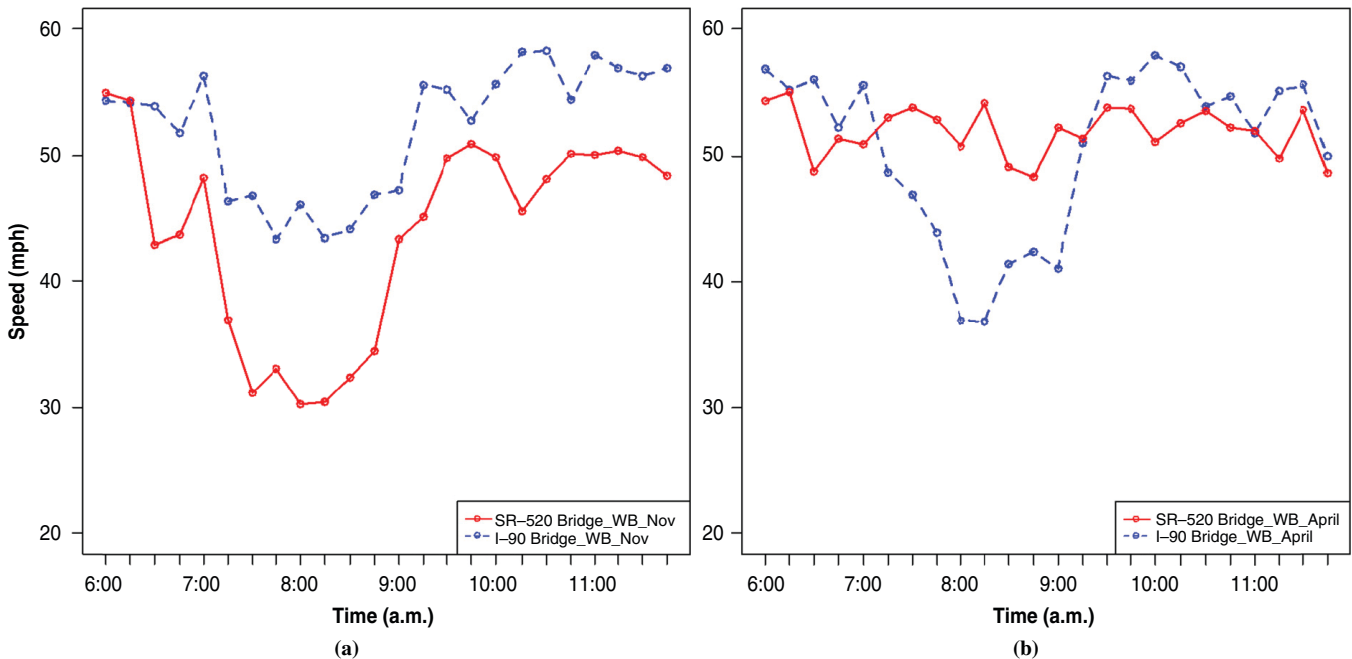

FIGURE 3   Truck speed on (*a*) westbound SR-520 and westbound I-90 in November 2011 and (*b*) westbound SR-520 and westbound I-90 in April 2012.

TABLE 2   Logit Model Results

Time Period	Variables	Coefficient	z-Value	p-Value
Peak period (6:00–9:00 a.m. and 3:00–6:00 p.m.)	Constant	4.717	4.278	<.005
	Travel time	−0.207	−2.190	.028
	Travel time reliability	0.001	0.022	.983
	Toll rate	−0.680	−10.041	<.005
Off-peak period (9:00 a.m.–3:00 p.m.)	Constant	5.586	3.563	<.005
	Travel time	−0.301	−2.134	.033
	Travel time reliability	−0.044	−0.826	.408
	Toll rate	−0.703	−9.997	<.005

TABLE 3   Logit Model Results Without Travel Time

Time Period	Variables	Coefficient	z-Value	p-Value
Peak period (6:00–9 :00 a.m. and 3:00–6:00 p.m.)	Constant	2.529	5.902	<.005
	Travel time reliability	−0.046	−2.183	.029
	Toll rate	−0.707	−10.642	<.005
Off-peak period (9:00 a.m.–3:00 p.m.)	Constant	2.385	5.803	<.005
	Travel time reliability	−0.112	−2.528	.012
	Toll rate	−0.760	−11.415	<.005

truck drivers. I-90 is an interstate highway with four lanes in each direction and sufficient shoulder width, while SR-520 has two lanes in each direction and insufficient shoulder width. These geometric features may make I-90 more attractive for trucks than SR-520. In addition, there are weight and size restrictions on SR-520 and some heavy or large trucks may be required to choose I-90.

The constants of the two logit functions also reveal that if there is zero toll, the SR-520 and I-405 combination will be more attractive only if it is on average 23 min faster during the peak period and 19 min faster during the off-peak period. Travel time reliability is not significant at the 95% confidence level and therefore was eliminated from both models. The utility functions for the two time periods are written as follows:

Peak period:

$$U_{90} = 4.717 - 0.207\,\mathrm{TT_{I\text{-}90}}$$

$$U_{520} = -0.207\,\mathrm{TT_{SR\text{-}520}} - 0.68\,\mathrm{toll}$$

Off-peak period:

$$U_{90} = 5.586 - 0.301\,\mathrm{TT_{I\text{-}90}}$$

$$U_{520} = -0.301\,\mathrm{TT_{SR\text{-}520}} - 0.703\,\mathrm{toll}$$

For both time periods, travel time reliability was not observed to be a significant variable in route choice, because of the correlation between travel time and travel time reliability. Travel time reliability is low when travel times are high. Travel times are at their lowest when drivers can travel at free flow speed. If this is the case, travel times are reliable because there is no congestion. Figure 4 presents a scatter plot of travel time versus travel time reliability during the peak and off-peak periods. Linear relationships between the two variables during both periods are observed and the correlations are 0.702 and 0.525, respectively. To eliminate the influence of correlation, travel time was removed from both utility functions and only travel time reliability and the toll rate were considered. The updated model results are shown in Table 3. Travel time reliability and toll rate are statistically significant and their signs are negative. The results indicate that travel time reliability
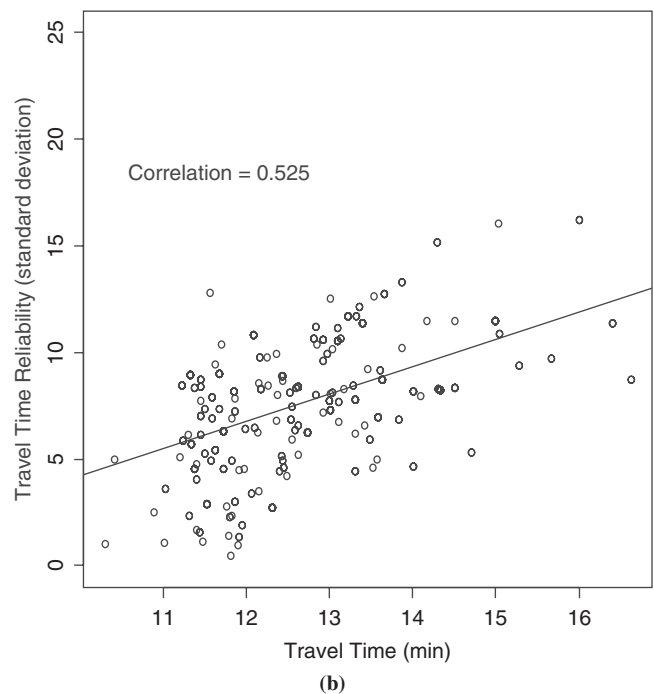

FIGURE 4   Scatter plots of travel time versus travel time reliability during (*a*) peak period (6:00 to 9:00 a.m. and 3:00 to 6 p.m.) and (*b*) off-peak period (9:00 a.m. to 3:00 p.m.).

is an influential factor determining truck route choice as well and the trucking industry is willing to pay a toll for a reliable route.

Value of Truck Travel Time

The coefficients of travel time and the toll rate reflect the sensitivity of commercial trips to changes in travel time and cost. The travel time–toll rate ratio captures the trade-off between travel time and the toll rate, as shown in Equation 3. According to Equation 3 and the model results presented in Table 2, the value of truck travel time during the peak and off-peak periods can be calculated; the values are $18.26/hr and $25.69/hr, respectively:

$$\beta_1 = \frac{\partial U}{\partial TT}$$

$$\beta_3 = \frac{\partial U}{\partial toll} \tag{3}$$

$$\text{value of truck travel time} = \frac{\beta_1}{\beta_3}$$

If this study had a bias, it would underestimate the value of truck travel time. First, it was assumed that all trucks on SR-520 used the most economical payment method. It is possible that other payment methods were used, which would have generated higher toll costs and consequently yielded higher value of truck travel time. Second, there were vehicle weight and size restrictions on the SR-520 bridge and therefore the study may have undersampled heavy trucks compared with other facilities. Third, trucks may have had less flexibility in rescheduling and changing routes.

The value of truck travel time during off-peak period was greater than the value during peak periods. This outcome can be explained in the commercial trips context. The peak period value of travel time for passenger vehicles was expected to be greater than the off-peak period value, since most trips that occur during peak periods, such as work trips, have fixed destinations and there is less flexibility to change the departure time or route. However, many commercial trips with strict delivery window and customer requirements do not necessarily occur during the peak period defined for passenger trips. To verify this assumption, the same data were used but the truck-specific peak period was redefined as 9:00 a.m. to 5:00 p.m. and the off-peak periods were redefined as 6:00 to 9:00 a.m. and 5:00 to 6:00 p.m. The updated model results are shown in Table 4. Accord-

ing to the model results, the values of truck travel time during the truck-specific peak period and the truck-specific off-peak periods are $25.15/hr and $19.44/hr, respectively.

CONCLUSIONS

This research used SR-520 as a case study to investigate how truck GPS data can be used to quantify the impacts of tolls on truck speed and routing. It was found that roadway tolls affect truck speed on the toll route and the alternative toll-free route. Tolling may alleviate the congestion on a toll road during peak and off-peak periods and increase the congestion on the alternate free route during peak periods.

A logit model was developed to understand the effects of toll rate, travel time, and travel time reliability on truck routing. Two traffic phases were examined: the peak period (6:00 to 9:00 a.m. and 3:00 to 6:00 p.m.) and the off-peak period (9:00 a.m. to 3:00 p.m.). It was found that travel time and toll rate were significant factors during both phases. Travel time reliability was not significant in the combined model results because of the correlation between travel time and travel time reliability. However, travel time reliability was significant when travel time was eliminated from the model, which demonstrated that travel time reliability was an influential factor determining truck route choice as well.

The value of truck travel time varies with the definition of peak and off-peak periods. The values during the general traffic peak period (6:00 to 9:00 a.m. and 3:00 to 6:00 p.m.) and off-peak period (9:00 a.m. to 3:00 p.m.) are $18.26/hr and $25.69/hr, respectively. For the truck-specific peak period (9 a.m. to 5 p.m.) and truck-specific off-peak period (6:00 to 9:00 a.m. and 5:00 to 6:00 p.m.), the values of truck travel time were $25.15/hr and $19.44/hr, respectively. The values were comparable with the estimates discussed in the sources in the literature, in which the value of truck travel time ranged from $20/hr to $50/hr (in 2012 dollars) (*8*). The results can be used to inform tolling rates and forecast the impact of tolling on truck route choice. The fleet information was unknown, as the data were provided on condition of anonymity. Any bias presented by differences between the fleet represented in the GPS data set and the truck population at large was not known.

REFERENCES

1. *International Scan: Reducing Congestion & Funding Transportation Using Road Pricing.* AASHTO, 2010. http://international.fhwa.dot.gov/pubs/roadpricing/roadpricing.pdf.
2. Roth, D. Effects of Pricing on Trucks in the United States. In *Conference Proceedings 34: International Perspectives on Road Pricing,* Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 45–46.
3. Holguín-Veras, J., Q. Wang, N. Xu, K. Ozbay, M. Cetin, and J. Polimeni. The Impacts of Time of Day Pricing on the Behavior of Freight Carriers in a Congested Urban Area: Implication to Road Pricing, *Transportation Research Part A: Policy and Practice,* Vol. 40, No. 9, 2006, pp. 744–766.
4. Swan, P. F., and M. H. Belzer. Empirical Evidence of Toll Road Traffic Division and Implications for Highway Infrastructure Privatization, 2007. http://www.motorists.org/tolls/tolldiversion.pdf.
5. Reebie Associates. *The Impact of Tolls on Freight Movement for I-81 in Virginia: Examining the Potential Freight Diversion Impact of Tolling on I-81 in Virginia.* Virginia Department of Rail and Public Transportation, 2004. http://www.drpt.virginia.gov/studies/files/I81-Toll-Analysis-FinalVersion.pdf.
6. Arentze, T., T. Feng, H. Timmermans, and J. Robroeks. Context-Dependent Influence of Road Attributes and Pricing Policies on

TABLE 4   Logit Model Results for Truck-Specific Peak and Off-Peak Periods

Time Period	Variables	Coefficient	z-Value	p-Value
Truck peak period (9:00 a.m.–5:00 p.m.)	Constant	5.169	3.972	<.005
	Travel time	−0.285	−2.433	.015
	Travel time reliability	−0.002	−0.052	.959
	Toll rate	−0.680	−11.338	<.005
Truck off-peak period (6:00–9:00 a.m. and 5:00–6:00 p.m.)	Constant	4.794	3.783	<.005
	Travel time	−0.219	−1.988	.047
	Travel time reliability	0.003	0.102	.919
	Toll rate	−0.676	−8.064	<.005

Route Choice Behavior of Truck Drivers: Results of a Conjoint Choice Experiment. *Journal of Transportation,* Vol. 39, No. 6, 2012, pp. 1173–1188.

7. Sun, Y., T. Toledo, K. Rosa, M. Ben-Akiva, K. Flanagan, R. Sanchez, and E. Spissu. Decision Making Process and Factors Affecting Truck Routing. Presented at 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.

8. Kawamura, K. Perceived Value of Time for Truck Operators. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1725,* TRB, National Research Council, Washington, D.C., 2000, pp. 31–36.

9. Zhou, L., M. W. Burris, R. T. Baker, and T. C. Geiselbrecht. Impact of Incentives on Toll Road Use by Trucks. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2115,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 84–93.

10. Parsons Brinckerhoff. *SR-520 and I-90 Toll Feasibility Analysis: Traffic and Revenue Forecasts Technical Memorandum.* Washington State Department of Transportation, Olympia. May 2007. http://www.wsdot. wa.gov/NR/rdonlyres/B0CF3B97-7013-45FB-83F2-D1E8BB6437E0/0/ Tolling_Tech_Memo.pdf. Accessed Oct. 2012.

11. *SR-520 Bridge Toll Rates.* Washington State Department of Transportation, Olympia. http://www.wsdot.wa.gov/Tolling/TollRates.htm. Accessed Oct. 2012.

12. Craig, J. S., D. Dye, P. Hammond, and S. Reinmuth. *SR 520 Bridge Tolling Update.* Transportation Policy Board, Puget Sound Regional Council, Seattle, Wash., 2012. http://psrc.org/assets/8046/Tolling-2012-4-12_520UpdatePSRC.pdf. Accessed Oct. 2012.

13. McCormack, E., X. Ma, C. Klocow, A. Currarei, and D. Wright. *Developing a GPS-Based Truck Freight Performance Measure Platform.* Washington State Department of Transportation, Seattle, 2012. http:// www.wsdot.wa.gov/research/reports/fullreports/748.1.pdf.

14. Zhao, W., A. V. Goodchild, and E. D. McCormack. Evaluating the Accuracy of Spot Speed Data from Global Positioning Systems for Estimating Truck Travel Speed. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2246,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 101–110.

15. Ma, X., E. D. McCormack, and Y. Wang. Processing Commercial Global Positioning System Data to Develop a Web-Based Truck Performance Measures Program. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2246,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 92–100.

16. Cullinane, K., and N. Toy. Identifying Influential Attributes in Freight Route/Mode Choice Decisions: A Content Analysis. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 36, No. 1, 2000, pp. 41–53.

17. Lomax, T., D. Schrank, S. Turner, and R. Margiotta. *Selecting Travel Reliability Measures.* 2003. http://d2dtl5nnlpfr0r.cloudfront.net/tti. tamu.edu/documents/TTI-2003-3.pdf. Accessed April 8, 2013.

18. Parsons Brinckerhoff. *SHRP 2 Capacity Research Report C04: Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand.* Transportation Research Board of the National Academies, Washington, D.C., 2012. http://onlinepubs.trb.org/onlinepubs/ shrp2/SHRP2prepubC04.pdf. Accessed May 2013.