THE TOLL-PRICE COMPONENT OF TRAVEL DEMAND ELASTICITY*

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ABSTRACT: The theory of marginal cost pricing maintains that setting the price of travel equal to its marginal social cost will optimize travel demand. This generally entails the addition of a toll during congested periods. The size of this congestion toll and its impact on traffic flow is dependent on the toll-price elasticity of travel demand. This is just one component of the elasticity of travel demand, which includes the elasticity of travel demand with respect to the price of gas, tolls, parking fees, maintenance costs, repair costs, the value of travel time, and other readily perceived costs of driving. This paper examines both the toll-price component of elasticity under flat-rate tolls and tolls that vary either by time of day or congestion level. Using empirical evidence it was found that the toll-price component of the elasticity of variable tolls was generally greater than that of flat-rate tolls with both rates comparable to other component elasticities of travel demand.

INTRODUCTION TO ELASTICITIES

During morning and evening peak periods, traffic congestion clogs many of our city streets and freeways. Economists argue that the reason for this congestion is simple, the true cost of travel (marginal social cost) exceeds the price that drivers must pay to travel (the average cost) during congested periods (see Figure 1) (Hau, 1992; Mohring, 1999; Small and Gomez-Ibanez, 1997; Walters, 1968). This price disparity leads to an

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inefficiently high demand (\(q_1\) on Figure 1) for travel. The optimal traffic flow (\(q^*_2\)) occurs at the point where the demand for highway use (curve D-D on Figure 1) intersects the marginal cost curve. At this flow, any increase or decrease in traffic volumes would decrease the net societal benefits derived from the use of the road. In theory, the optimal flow of traffic occurs if drivers are charged a toll of \(\tau\). This change in overall price of travel, \(p_2 - p_1\), causes a corresponding change in traffic volume, \(q_2 - q_1\). Equation 1 shows the ratio of these changes (in percent), known as the price elasticity of travel demand:

\[
E = \frac{(q_2 - q_1)}{q_1} \quad \frac{(p_2 - p_1)}{p_1}
\]  

[1]
THE ELASTICITY OF TRAVEL DEMAND

Elasticity Components

The price elasticity of travel demand is an important element both in the development of the optimal pricing of roadways and estimating the benefits from infrastructure improvements. However, drivers are a heterogeneous group and therefore react differently to changes in the price of travel. Additionally, an individual driver may react differently to the exact same change in price when that change in price occurs in different components of the total driving price. Therefore, for a set of drivers, the elasticity of demand can be disaggregated into elasticities with respect to several component costs, including (Lee, 2000; Victoria Transport Policy Institute, 2002):

- operating costs (fuel, oil, and maintenance),
- parking,
- tolls,
- travel time,
- accidents and insurance, and
- wear and ownership.

Although still somewhat limited, the empirical knowledge base on the elasticity of travel demand with respect to each of these components is growing. Two excellent sources include the Highway Economic Requirements System (HERS) Technical Report Appendix C (Lee, 2000) and the Transportation Demand Encyclopedia (Victoria Transport Policy Institute, 2002). Table 1 shows typical component elasticities with respect to travel demand.

Most of the toll-price elasticities cited in the literature were derived from changes to flat rate tolls ($E_{T,\text{flat}}$), for example a toll change from $1 to $2 regardless of time of day or congestion level. In Table 2, results of empirical studies determining the toll-price elasticity of vehicle trips on a toll road are shown. As these results indicate, an increase in the toll rate results in a decrease in traffic. However, it is unknown what percent of this decrease is derived from abandoned trips, route changes, or mode shifts.

Little empirical evidence regarding the price elasticity of travel demand with respect to tolls that vary by time of day or congestion level ($E_{T,\text{variable}}$) is available. A change in a variable toll rate offers drivers addi-
TABLE 1

Component Elasticities of Travel Demand

<table>
<thead>
<tr>
<th>Component</th>
<th>Elasticity Estimate</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>-0.05 to -0.55</td>
<td>Johansson and Schipper, 1997</td>
</tr>
<tr>
<td></td>
<td>-0.16 to -0.33</td>
<td>Goodwin, 1992</td>
</tr>
<tr>
<td></td>
<td>-0.1</td>
<td>Luk and Hepburn, 1993</td>
</tr>
<tr>
<td></td>
<td>-0.18 to -0.22</td>
<td>TRACE, 1999</td>
</tr>
<tr>
<td></td>
<td>-0.3</td>
<td>INFRAS, 2000</td>
</tr>
<tr>
<td></td>
<td>-0.16 to -0.26</td>
<td>Jong and Guan, 2001</td>
</tr>
<tr>
<td></td>
<td>-0.05 to -0.55</td>
<td>Ingram and Liu, 1999</td>
</tr>
<tr>
<td>Parking</td>
<td>-0.15</td>
<td>Lee, 2000</td>
</tr>
<tr>
<td></td>
<td>-0.11 to -0.16</td>
<td>TRACE, 1999</td>
</tr>
<tr>
<td>Tolls</td>
<td>See Table 2</td>
<td></td>
</tr>
<tr>
<td>Travel Time</td>
<td>-0.28 to -0.80</td>
<td>TRACE, 1999</td>
</tr>
<tr>
<td></td>
<td>-0.38 to -0.68</td>
<td>Lee, 2000</td>
</tr>
<tr>
<td></td>
<td>-0.27 to -1.33</td>
<td>Goodwin, 1996</td>
</tr>
<tr>
<td>Accidents and Insurance</td>
<td>None found</td>
<td></td>
</tr>
<tr>
<td>Wear and Ownership</td>
<td>-0.12 to -0.31</td>
<td>Lee, 2000</td>
</tr>
<tr>
<td>Overall Operating Costs</td>
<td>-0.09 to -0.52</td>
<td>Oum, Waters, and Yong, 1992</td>
</tr>
<tr>
<td></td>
<td>-0.06 to -0.28</td>
<td>Ingram and Liu, 1999</td>
</tr>
</tbody>
</table>

TABLE 2

Empirical Estimates for $E_{\text{r,dr}}$

<table>
<thead>
<tr>
<th>Toll Location</th>
<th>$E_{\text{r,dr}}$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Toll Facilities</td>
<td>-0.03 to -0.31</td>
<td>Wuestefeld and Regan, 1981</td>
</tr>
<tr>
<td>15 Toll Bridges</td>
<td>-0.15 to -0.31</td>
<td>Wuestefeld and Regan, 1981</td>
</tr>
<tr>
<td>Golden Gate Bridge</td>
<td>-0.15 (brief raise to cover cost of reconstruction)</td>
<td>Gifford and Talkington, 1996</td>
</tr>
<tr>
<td>Golden Gate Bridge</td>
<td>-0.19 (Friday traffic only)</td>
<td>Gifford and Talkington, 1996</td>
</tr>
<tr>
<td>San Francisco Bay Bridge</td>
<td>&lt; -0.05</td>
<td>Harvey, 1994</td>
</tr>
<tr>
<td>Numerous United States Facilities</td>
<td>-0.1 to -0.35</td>
<td>Wilbur Smith Associates, 1995</td>
</tr>
</tbody>
</table>
tional flexibility in travel decisions as opposed to a change in a flat toll rate. Therefore, it was hypothesized that $E_{T-\text{flat}}$ will be significantly less elastic than $E_{T-\text{variable}}$.

In the short run, $E_{T-\text{flat}}$ is caused by drivers switching to a higher occupancy mode, altering their routes, or abandoning their trips due to the change in toll rate$^1$. In the long run, drivers may also change the location of their origins (for example their residence) or destinations (for example their office location) to avoid the route with the higher toll rate. Therefore, long run elasticities are generally greater than short run (Lee, Klein, and Camus, 1999; Oum, Waters, and Yong, 1992). This paper focuses on short-term impacts, but similar arguments can be made regarding the long term. In addition to all of the options listed above, under marginal cost pricing a driver who finds the toll (and therefore the cost of travel) too high to travel during one time period has the option of rescheduling his or her time of travel to a time period with a lesser toll. Therefore:

$$
E_{T-\text{Variable}} = \frac{(\Delta Tr + \Delta Tm + \Delta Ta + \Delta Tt)/q_i}{\Delta P/P_i} = \frac{P_i \cdot \Delta Tr + P_i \cdot \Delta Tm + P_i \cdot \Delta Ta + P_i \cdot \Delta Tt}{q_i \cdot \Delta P}
$$

$$
E_{T-\text{Flat}} = \frac{(\Delta Tr + \Delta Tm + \Delta Ta)/q_i}{\Delta P/P_i} = \frac{P_i \cdot \Delta Tr + P_i \cdot \Delta Tm + P_i \cdot \Delta Ta}{q_i \cdot \Delta P}
$$

Therefore

$$
E_{T-\text{Variable}} = E_{T-\text{Flat}} + \frac{P_i \cdot \Delta Tt}{q_i \cdot \Delta P}
$$

Where:  
$\Delta Tr = \text{Change in traffic volume due to drivers switching route}$  
$\Delta Tm = \text{Change in traffic volume due to drivers switching mode}$

$^1$ This discussion assumes an increase in the toll rate. The opposite driver reactions would be expected if there was a decrease in the toll rate.
\[ \Delta T_a = \text{Change in traffic volume due to drivers abandoning their trip} \]
\[ \Delta T_t = \text{Change in traffic volume due to drivers switching time of travel} \]
\[ q_i = \text{Flow of traffic before the toll change} \]
\[ \Delta P = \text{Change in toll} \]
\[ P_i = \text{Original toll} \]

Knowing that traffic follows an inverse demand curve and assuming the elasticity is not perfectly inelastic (\( \Delta T_t \neq 0 \)) we derive equation [5]:

\[ \frac{P_i \cdot \Delta T_t}{q_i \cdot \Delta P} > 0 \text{ and } E_{T-\text{Variable}} > E_{T-\text{Flat}} \]  

[5]

**EMPIRICAL EVIDENCE WITH RESPECT TO** \( E_{T-\text{VARIABLE}} \) **AND** \( E_{T-\text{FLAT}} \)

Elasticity estimates from the few toll roads and bridges around the world that use variable toll rates were examined. One such facility, State Route 91 near Los Angeles, California, has offered drivers the option of using toll lanes with variable toll rates or parallel free lanes since December 1995. In addition to altering times of travel to obtain lesser tolls, drivers could readily change their routes or modes (prior to 1998) to avoid the tolls altogether. Therefore, researchers used survey results to isolate the elasticity of demand with respect to toll price. Using logit modeling, researchers (Sullivan, 2000, p. 160, Table 5-XI) found \( E_{T-\text{Variable}} \) to be between -0.9 to -1.0 for altering time of travel, approximately -0.01 for changing mode from single occupant vehicle (SOV), and approximately -0.75 for a change from the tolled road to the parallel free route. Since this was a route and mode choice model, it implicitly assumed no abandoned trips.

South of State Route 91, on I-15 near San Diego, a high occupancy/toll (HOT) lane with dynamic pricing has been operational since March 1998. As on SR 91, drivers have readily available options including traveling on the toll road or the parallel free route, or carpooling to avoid the toll. Therefore, toll-price elasticity calculations are complicated by these options. In this case, researchers (San Diego Association of Governments, 1999, p. 11, Table 4) estimated the change in traffic volumes related to a change in the maximum allowable toll to be between -0.34 and -0.42. In other research (Dahlgren, 1999) the relationship between:
the volume of vehicles paying to use the HOT lane and the toll cost per minute saved was examined, providing a value similar to the price elasticity of demand. This was estimated to be between -0.02 and -0.16 in the eastbound direction (unfortunately, the model provided results that were both suspect and not statistically significant for westbound traffic.)

The Singapore Area Licensing Scheme (ALS) began charging drivers traveling into Singapore city center during the morning period in 1975. These new tolls dramatically reduced traffic flow into the city (Menon, Lam, and Fan, 1993; Gomez-Ibanez and Small, 1994). However, with the change in toll rate equaling infinity, no attempt was made to determine elasticity. Fees for private cars were reduced by 40 percent in the morning period beginning in 1989. This toll decrease resulted in a 10 percent increase in traffic (Menon, Lam, and Fan, 1993) and an $E_{variable}$ of -0.254. This elasticity estimate is complicated by modal shifts and the different licensing schemes available, including the availability of both daily and monthly passes resulting in different tolls. Also in 1989 a fee was added for inbound vehicles in the afternoon, significantly reducing afternoon inbound traffic by up to 53 percent (Small and Gomez-Ibanez, 1997; Seik, 1997).

During a three-month period in 1990 the Hardy Toll Road in Houston, Texas, experimented with an off-peak toll discount for patrons. Patrons using the road from 10 a.m. to 2 p.m. were charged only 50 percent of the usual toll rate. Traffic increased by 20 percent to 40 percent during the period yielding an $E_{variable}$ of -0.4 to -0.8 (Spock, 1998). Due to the decrease in price, it is unlikely that these elasticity values would include any abandoned trips. Rather, the change in traffic volumes would be comprised of trips from other times of day, other routes, other modes, and possibly some induced travel.

More recently, HOT lanes were implemented on both the Katy Freeway and U.S. 290 in Houston, Texas. In reviewing the literature, researchers found no elasticity estimates. This was not surprising since the change in toll rate was equal to infinity and there are several complexities surrounding mode and route shifts.

France implemented variable tolls in April 1992 on the A-1 motorway between Paris and Lille. The toll on the longest stretch of freeway had been 52 French francs. However, starting in April 1992, the toll increased by 25 percent during peak traffic conditions on Sunday afternoons. Similarly, there was a 25 percent off-peak discount early Sunday afternoon and late Sunday evening. This variable toll was designed to spread the
peak congestion caused by motorists returning to Paris after a weekend in the country. This variable pricing program reduced peak traffic by 4 percent and increased shoulder traffic by 7 percent. Therefore, price-elasticities ranged from -0.16 to -0.28. Since the decrease in volume of peak-period traffic was similar to the increase in volume of off-peak traffic, it appears that this toll-price elasticity was due primarily to shifts in time of travel among drivers on A-1.

Highway 407 in Toronto, Canada, opened in June 1997 with three toll payment levels for passenger cars depending on the time of day: the daytime peak-period toll rate was 10 cents per kilometer, the daytime off-peak-period toll rate was 8 cents per kilometer, and the nighttime-period toll rate was 4 cents per kilometer (all toll rates in Canadian currency). Tolls on this highway increased in September 1999, May 2000, January 2001, and most recently in January 2002 (Bridson-Boyczuk, 2002). Unfortunately, no elasticity analysis using actual traffic volumes was found. However, Mekky (1999) did predict (prior to these changes in toll rate) the elasticity of travel demand on the road to be -0.3. Also, estimates performed by a consultant’s detailed model of traffic on the road indicated a 29 percent decrease in traffic during the a.m. peak period and a 52 percent decrease in the off-peak period due to the introduction of tolls on the highway (Halcrow Fox, 1999).

DETAILED EXAMPLE OF \( E_{T\text{-variable}} \) CALCULATION

Lee County, Florida, has a population of over 435,000 (census 2000) and is split diagonally by the Caloosahatchee River. Two toll-free bridges (Business 41 and U.S. 41) cross the river on the north side of the county, and two toll bridges (the Midpoint and Cape Coral) are located farther south. The distance between the bridges is sufficient such that most drivers choose to travel across the bridge that is most convenient to them and do not switch. The tolls on both toll bridges did not vary by time of day until August 1998.

Beginning August 3, 1998, two-axle vehicle drivers paying their tolls using electronic toll collection (ETC) could get a 50 percent discount if they drove during specific “discount periods” which included 6:30 a.m. to 7:00 a.m., 9:00 a.m. to 11:00 a.m., 2:00 p.m. to 4:00 p.m., and 6:30 p.m. to 7:00 p.m. on weekdays. Approximately 25 percent of the total traffic on both bridges was eligible for this discount while the remaining 75
percent used a payment option (for example, cash) that was not eligible for the discounts. Due to the frequent user toll discount programs developed by the county, 94 percent of drivers eligible for the variable pricing toll discount normally paid a toll of 50 cents and only paid 25 cents during the discount periods. The remainder (6 percent) normally paid a toll of $1 and only paid 50 cents during the discount periods.

The short-term assessment for the impact of the variable toll on traffic volumes was to compare the pre-variable pricing period of January to July 1998 to the January to July 1999 period with variable pricing operational. In the analysis of travel demand elasticities, the short term is defined as a period during which exogenous variables remain relatively constant and is usually one year (Lee, Klein, and Camus, 1999). Due to the unique characteristics of this project the elasticity rates are comprised entirely of travelers who altered their times of travel (Burris, 2002). Equation [6] was used to calculate the elasticity as follows:

$$ E_{T-variable} = \frac{(q_{1999} - q_{1998})}{q_{1998}} = \frac{(t_{vp} - t_{pre-vp})}{t_{vp}} - 50\% $$

Where: $q_{1999}$ = Average flow of vehicles eligible for the variable pricing toll discount (eligible vehicles) during the discount periods from January to July 1999.
$q_{1998}$ = $q_{1998} \times$ growth factor
$q_{1998}$ = Average flow of vehicles eligible for the variable pricing toll discount (eligible vehicles) during the discount periods from January to July 1998.

Growth Factor = \frac{1999 \text{ Weekday ADT (January → July) of Eligible Vehicles}}{1998 \text{ Weekday ADT (January → July) of Eligible Vehicles}}

\[ t_{vp} = \text{toll with the variable pricing discount.} \]
\[ t_{pre-vp} = \text{toll prior to the implementation of variable pricing.} \]

Using Equation [6] and data collected on the toll bridges (data include a record of every vehicle that crossed the bridges, the time of crossing, payment method, and payment amount) the toll-price elasticities
(E<sub>variable</sub>) in Table 3 were found. The E<sub>variable</sub> of drivers traveling across the bridges was greatest during the period of 6:30 a.m. to 7:00 a.m. (see Table 3). Results for drivers crossing the Midpoint Bridge are shown graphically in Figure 2.

### Table 3

<table>
<thead>
<tr>
<th>Time</th>
<th>Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Midpoint</td>
</tr>
<tr>
<td>6:30 a.m. to 7:00 a.m.</td>
<td>-0.362</td>
</tr>
<tr>
<td>9:00 a.m. to 11:00 a.m.</td>
<td>-0.096</td>
</tr>
<tr>
<td>2:00 p.m. to 4:00 p.m.</td>
<td>-0.112</td>
</tr>
<tr>
<td>6:30 p.m. to 7:00 p.m.</td>
<td>-0.056</td>
</tr>
</tbody>
</table>

Figure 2: Result of Variable Pricing Toll Discount on Midpoint Bridge from 6:30 a.m. to 7:00 a.m.
The $E_{\text{variable}}$ of drivers traveling across the bridges was clearly inelastic and in some time periods was very close to having no impact on travel. However, the change in toll rate amounted to only a small portion of the driver's total cost of travel\(^2\). Ninety-four percent of drivers participating in the variable pricing program saved only 25 cents on their tolls. The remaining 6 percent saved 50 cents. Due to the lack of congestion, it is unlikely that drivers altering their times of travel to the discount periods saved any travel time or altered their costs of driving in any way except for the toll discount (see Figure 2).

**DISCUSSION**

Empirical estimates of both $E_{\text{variable}}$ and $E_{\text{flat}}$ range from (almost) perfectly inelastic (-0.02) to unit elastic (-1.0). As expected, $E_{\text{variable}}$ was generally more inelastic than was $E_{\text{flat}}$. It is hypothesized that the extenuating factors in each case examined contribute significantly to the fact that $E_{\text{variable}}$ varies considerably. Table 4 is this author’s rough estimate of how exogenous factors may have impacted each of the calculated values for $E_{\text{variable}}$.

The easier it is for drivers to alter their routes, their modes, or abandon their trips, the more sensitive (higher elasticity) trips will be to a change in cost. Therefore, it is not surprising that $E_{\text{flat}}$, like $E_{\text{gas}}$ and $E_{\text{wrt ownership}}$, is very inelastic (see Tables 2 and 3). There are few convenient alternative routes to many of the flat-rate toll facilities. That is a primary reason why the facility exists and can be funded through tolls. In addition, increases in toll rates generally do not keep pace with inflation. For example, Spock (1998) found that toll increases in the U.S. from 1980 to 1997 averaged 40 percent with the majority ranging from 20 percent to 30 percent. The inflation rate increased by over 120 percent during that same time period. Therefore, patrons of toll facilities may find the

\(^2\) Using only the cost of fuel, maintenance, and travel time a conservative estimate of an average driver’s cost of travel was estimated. Based on typical fuel prices, values of travel time, maintenance costs, and trip length it was estimated that the total cost of travel (without the toll) was approximately $4.20. The average toll savings of variable pricing participants was just over $0.25 or 6 percent of the total trip cost.
### TABLE 4

**Factors Influencing $E_{T\text{variable}}$ at Functioning Toll Facilities**

<table>
<thead>
<tr>
<th>Location</th>
<th>Driver's Ability to Readily Change This Aspect of Their Travel in Order to Lessen or Avoid the Toll:</th>
<th>$E_{T\text{variable}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lee County (Cape Coral) and Midpoint Bridges</td>
<td>Did not occur</td>
<td>Abandon Trip: Did not occur (found no evidence of induced travel either)</td>
</tr>
<tr>
<td>California (S.R. 91)</td>
<td>Easy</td>
<td>Typical</td>
</tr>
<tr>
<td>California (I-15)</td>
<td>Easy</td>
<td>Typical</td>
</tr>
<tr>
<td>Singapore (City Center)</td>
<td>Impossible</td>
<td>Difficult</td>
</tr>
<tr>
<td>Toronto (407)</td>
<td>Moderate</td>
<td>N/A</td>
</tr>
<tr>
<td>Houston (Hardy Toll Road)</td>
<td>Moderate</td>
<td>N/A</td>
</tr>
</tbody>
</table>

N/A = Not available / none found.

increase in toll rate reasonable and preferable to alternatives, resulting in a low $E_{T\text{rate}}$.

In contrast, $E_{T\text{variable}}$ accounts for a change in traffic due to route change, mode change, or abandoned trip, plus a change in the time of travel. On several of the roads employing variable tolls (I-15, SR 91, and Singapore) additional incentives in the form of reduced or eliminated tolls were available to those drivers who switched to a high occupancy vehicle mode. As well, to change route on either I-15 or SR 91 from the tolled to the free lanes was very easy, but often came at the cost of increased travel times due to traffic congestion. Therefore, high elasticities for each of these facilities were expected.

In the Lee County project there was no additional incentive for HOV use, transit was not convenient for many travelers, and the alternative bridge crossings were inconvenient. Studies showed that the introduction of the variable toll had no impact on route or mode of travel (Burris, 2002). In addition, while traffic congestion was quite severe on both I-15 and SR 91, there was basically no congestion on the toll bridges in Lee County. Therefore, drivers did not have the additional incentive to change their times of travel due to congestion avoidance. For all of these rea-
The toll-price component of travel demand elasticity

...sons it is not surprising that $E_{T\text{variable}}$ is generally smaller in Lee County than on SR 91 and I-15. In the Singapore case, drivers had already spent 14 years developing car pools and taking mass transit to avoid the toll. Transit and carpooling was probably very inconvenient (or at least not worth the expense) for the remaining drivers in low-occupancy vehicles. Therefore, the low elasticity in Singapore was not surprising.

In general, $E_{T\text{variable}}$ is more elastic than the other components of travel cost. The larger $E_{T\text{variable}}$ may indicate motoryst’s increased abilities to change their times of travel rather than alter their use of fuel, change their parking behaviors, their route of travel, etc.

CONCLUSION

As expected, the toll-price elasticity of travel demand was greater for a facility with a variable rate toll than a flat-rate toll. The toll-price elasticity of a flat-rate toll was comparable to the price elasticities of other components of travel cost such as parking and travel time. The empirical evidence from toll facilities with variable toll rates was sparse and contained a great deal of variability. This variability could likely be explained by the differences in both the characteristics of the toll facility and of the driving population. However, the extent to which each is responsible for the variation in elasticities will require further research.

REFERENCES


