Investigating the Impact of Tolls on High-Occupancy-Vehicle Lanes Using Managed Lanes

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For nearly 40 years, high-occupancy-vehicle (HOV) lanes have been used to combat congestion. These lanes allow only vehicles with multiple occupants and generally offer a free-flow trip, unlike adjacent general purpose lanes. In theory, this encourages additional carpooling, reduces overall vehicle miles of travel, and improves the commute trip. However, as a result of the underutilization of some of these lanes, some HOV lanes are migrating to high-occupancy-toll (HOT) lanes, where HOVs may travel free of charge but lower-occupancy vehicles can pay a toll to use the lane. This research investigated the impacts of offering preferential treatment for HOVs on these lanes. To determine the impact of different HOT lane operating strategies on their travel behavior, freeway travelers in the Houston and Dallas metropolitan areas of Texas were surveyed. A nested logit model was developed to estimate the mode choice for travelers. This model was used to predict the impact of converting an HOV lane to a HOT lane on which all travelers pay a toll. It was found that the overall percentage of HOV2 and HOV3+ vehicles in the traffic stream decreased by only a small amount when a toll was required for them to use the HOV lane. However, that decrease did represent a significant portion of those modes (more than 9%) and resulted in more than a 10% increase in HOT lane revenue. Therefore, elimination of preferential treatment for these vehicle types has significant implications and becomes a difficult policy decision—not just a straightforward choice.

The concept of tolling on managed lanes (MLs) has evolved since the first iterations in the early 1990s. Initially conceived as the permission for previously prohibited vehicles to use high-occupancy-vehicle (HOV) lanes in exchange for the payment of a fee, otherwise known as high occupancy toll (HOT) lanes, managed lanes expanded in scope to include a variety of implementations, generally called express toll lanes (ETL), and are without any inherent policy concerning HOVs.

HOV lanes have a longer history of operation in North America than HOT lanes and ETL facilities. First implemented on Virginia’s Shirley Highway busway facility (I-395) in 1969, HOV lanes provided an incentive to carpool or vanpool. Although the magnitude of travel-time savings offered by HOV lanes has been studied, the role of HOV-lane-related incentives relative to other incentives to carpool has rarely received the same attention. Nationally, since 1993, vehicle miles traveled have increased by 25%, while the percentage use and absolute number of carpools and vanpools for commute trips has declined to a 30-year low: 10,057,000 trips in 2003, down from 11,852,000 in 1993 (1). In the nearly 10-year time frame, HOV lane miles have more than doubled, from approximately 1,300 lane miles in 1995 to more than 2,500 in 2000 and 3,100 in 2005. The majority of these HOV lane miles are located in California (1,000), Georgia (400), and Texas (300) (2). In the HOV corridors, carpooling rates have increased significantly (more than 100%) even as carpool rates nationwide have declined (30%) during the past two decades (3). However, severe congestion in the general purpose lanes has tended to cause animosity on the part of the general public toward HOV lanes if they are underutilized (4). As a means of mitigating the “empty lane syndrome,” HOT lanes have been promoted as an effective way of utilizing the excess capacity without reducing the HOV lanes’ travel time advantages (4).

In addition to HOT lanes, which imply maintenance of HOV operations, ETL concepts have also been promoted as a means of enhancing mobility in congested corridors and regions. First implemented in Orange County, California, as the privately built and operated State Route 91 (SR-91) express toll corridor, ETL facilities provide the same benefits of HOT lanes (exclusive right-of-way with congestion-free trips along the length of the corridor), but they did not originally carry the same implied benefit to carpools and vanpools. During its 10 years of operation, the SR-91 express toll facility has, at times, provided free use by three-people-or-more (HOV-3+) carpools, but at other times required partial toll payment by these users. Although SR-91 is the only ETL facility currently in operation, ETL concepts may be increasingly attractive for those transportation agencies seeking enhanced sources of revenue and ease of enforcement.

As managed lanes are considered throughout more than 25 North American cities, there is a need for research and guidance defining the role of carpools in ETLs and the trade-offs between carpool exemptions and other project objectives. Increasingly, project objectives are reflecting not only mobility concerns but also funding deficiencies and the need to generate revenue. As a result, allowing discounted-toll or toll-exempt users such as carpools requires an evaluation of revenue impacts as well as mobility interests.

The Texas Transportation Institute commissioned the Texas Transportation Institute and University of Texas at Arlington to study the proper role of incentives to carpoolers in managed lane facilities. Using more than 4,600 responses to an adaptive stated-preference
survey of regional travelers in Dallas and Houston, the research
team developed a model for examining the core question of the com-
misioned research: what are the benefits and drawbacks of providing
carpools with discounted or toll-free use of managed lane facilities?
This paper describes the survey’s data collection methodology and
specialized weighting methodology used to analyze the core research
question.

LITERATURE REVIEW

HOV lanes and carpools have an overlapping purpose: encourage
greater person throughput through greater vehicle occupancies. By
encouraging people to rideshare, particularly during peak periods,
person throughput on congested corridors can increase without a
Corporation}
corresponding significant increase in capacity. Since 1969 HOV lanes
have been implemented with the explicit purpose of encouraging the
formation of new carpools and enhancing the performance of transit
through a significant, reliable travel time incentive.

Although distinction is made between regular carpools (recurring,
scheduled carpools) and occasional carpools (situational carpools
only), the basics of carpooling on HOV lanes has remained the same
for 35 years—a minimum of two or three people with common com-
mute patterns share one vehicle for their trip on an exclusive facility.
Carpooling itself requires no public investment because the decision
to carpool remains a private one. However, advocates for govern-
mental and commercial encouragement to carpool rationalize that
“every person added to a carpool means another congestion- and
pollution-causing car is taken off the road” (5). As practice holds, if
commuters are provided with a large enough incentive to switch
from driving alone to carpooling, they may form a carpool either nor-
ally (through a matching service or agreement) or causally (through
situational agreement). Travel time savings from HOV lanes have
constituted a large portion of that incentive.

Studies have shown that there are three main reasons com-
muters switch from driving alone to ridesharing (either carpools
or vanpools):

• Travel time. Research has shown that commuters are likely to
alter their commute choice if it reduces their commute time. Because
driving alone is typically the quickest means from home to work
(or the reverse), total travel time is one factor that makes driving
alone attractive to drivers (6-9). HOV lanes have been shown to
reduce travel time, thereby making carpooling more appealing and
counteracting the disposition toward driving alone (9-11).

• Convenience. Studies have also confirmed that convenience is a
factor in determining mode choice. Driving alone is seen as the most
convenient mode for most commuters. However, this can change if
employers or municipalities have carpooling incentives in place mak-
ing carpooling more suitable for their needs, such as conveniently
located parking spaces reserved for carpoolers (6-8, 12, 13).

• Cost. Although many commuters do not use the most cost-
effective commute choice, it is an influential factor. Cost savings can
be realized simply through the sharing of costs between driver and
passenger(s), although additional financial incentives and subsidies
may be offered by governmental or employer entities or both. This
is true especially with vanpool programs (9, 12, 13). Researchers
note that free or low-cost parking tends to influence a greater use of
single-occupant vehicles (12).

Benefits from carpooling, which HOV lanes endeavor to encour-
age, can be articulated for users and society. User benefits include
personal cost savings and perceived quality of life enhancements.
Many commuters underestimate the true cost of driving alone to and
from work. The cost of commuting may be significantly reduced
when carpoolers or vanpoolers share the costs. This is true especially
in situations with added costs, such as parking fees and tolls, in addi-
tion to fuel (14, 15). Commutes are increasingly becoming too con-
gested and stressful, which can be carried over into professional and
social situations. Carpools enables riders to relax and allows them
to arrive at their destination without the stress of driving (14, 16).

Societal benefits are most typically associated with reduction in
vehicular use (and corresponding reduction in vehicle miles traveled)
and a resulting improvement in air quality. In areas of serious air qual-
ity concerns, carpooling and HOV lanes together constitute important
elements in achieving conformity with air quality targets (17). Cou-
pled with the perception of HOV lanes and carpooling as enabling
broader environmental objectives (including favorable land use and
fuel consumption goals), a significant stakeholder community has
formed around their continued use and promotion.

However, further investigation into current carpooling trends indi-
cates that the majority of carpools are family oriented, a type of car-
pooling called “fampools” (18). Only 26% of surveyed travelers in
Houston in 2001 taking a work tour carpooled involved a non-household
member, compared with 74% involving a family member (19). Critics
have argued that the extensive amount of household-member-only
carpooling for work trips belies the premise behind the investment in
HOV lanes—that it will encourage the formation of carpools between
two drivers, explicitly to take advantage of the travel time savings in
the HOV lanes (18).

That fampooling does not take cars off the street is evident particu-
larly when HOV lanes are used by drivers whose passenger is some-
one who, for a variety of reasons, would not be driving anyway. For
example, it is certainly convenient for a parent driving with a son or
daughter to use the carpool lane, but as long as the son or daughter is
under the legal driving age, this sort of carpool does not spare the road
from an extra car (18).

Fampooling criticism implies that family members who carpool
would do so with or without the presence of HOV lanes and other
incentives. However, a counterargument suggests that familial car-
pools (particularly involving two or more adults) are perfectly legit-
imate to the extent that those family members would otherwise drive
separately.

With the decline in HOV travel in general (but an increase in
HOV travel in areas with HOV lanes), the significant presence of
fampools, the need to maximize the use of existing infrastructure,
and transportation funding shortfalls, it is imperative that the bene-
fits and disbenefits of providing preferential treatment for carpools
on exclusive facilities (such as ETLs) be examined.

DATA COLLECTION

To better estimate the potential impacts of eliminating or reducing
the preferential treatment of HOV’s on HOV lanes, a survey of travelers
was undertaken. The survey was performed in two Texas metro-

transportation areas (Houston and Dallas) that have high levels of congestion and
numerous HOV lanes. The survey focused on people who regularly
taveled on one or more of these cities’ major roadways. A list of
31 major roadways and tollways in the two cities, including all those
with HOV lanes, was developed for use in the survey. Thus, many
of the respondents already traveled on a roadway with a toll or an
HOV lane, and the rest traveled on roadways on which an HOV, HOT, or managed lane might be added at a future date.
The survey was administered via the Internet in both English and Spanish from May to July 2006. Many Houston and Dallas transportation organizations helped in announcing and providing Internet links to the survey. A couple of local news stations also announced the survey, helping to generate 4,280 responses via the Internet. Additional survey efforts were required because those 4,280 respondents did not accurately reflect the socioeconomic characteristics of people in Houston and Dallas. Survey crews administered paper- and laptop-based surveys at community centers and driver’s license offices in low-income and minority neighborhoods. This effort garnered an additional 354 surveys, many from underrepresented groups. Unfortunately, the 4,634 total respondents still did not reflect the ethnic and economic makeup of the two cities, so a weighting process was undertaken (see the next section).

SURVEY DATA ANALYSIS

Replicate Weighting Process

The sampling design for this survey of ML travelers was simple random sampling (SRS) followed by poststratification. Because of the data collection method, the statistical formulas and methods developed for survey analyses on SRS data were inappropriate. SRS would imply that for each stratum, the proportion of respondents in the sample was the same as the proportion in the population. The sample proportions for this survey were not equal to population proportions for each stratum, necessitating a weighting process using replicate weights.

In SRS, the sampling weights are fixed depending on the proportions of each stratum in the population. If the sampling plan is not SRS, the sampling weights (pweights) developed poststratification depend on the given sample size. In other words, the sampling weights are random. They cannot be used like fixed weights to conduct tests of proportions or for testing other hypotheses. The reason is that a non-SRS methodology results in higher standard errors (SEs) for the estimates. An assumption of fixed weights (with SRS) would imply lower SEs. Thus, using fixed weights may lead to some results from non-SRS surveys being found statistically significant when in fact they are not.

To address that issue, replicate weights were calculated using poststratification weights as the input. Income (four groups), ethnicity (four groups), and toll-use road (two groups) were used as the criteria for computing the poststratification weights (pweight). The formula for the pweight calculation is

\[
pweight = \frac{\text{pop}_i}{\text{sample}_i} \quad (1)
\]

where

\[
\text{pop}_i = \text{percentage of population in stratum } i,
\text{sample}_i = \text{percentage in survey sample in stratum } i,
\text{stratum}_i = \text{group (or stratum) of the survey}.
\]

For example, one stratum could be Caucasians with annual household incomes less than $25,000 who traveled on a toll road.

The poststratification weights for the survey were computed using an iterative procedure. The final pweights were used to adjust the survey sample from each city (Houston and Dallas) to match that city’s population (based on the 2005 American Community Survey data and average annual daily traffic volumes) in all 16 strata (four income groups by four ethnic groups).

Next, replicate weights were used to calculate a better approximation of the standard error of the full sample estimates. The method used to calculate replicate weights begins with dividing the sample into subsamples. The same 16 subsamples or strata (per city) were used with the replicate weights as were developed for the pweights. Next, the estimate of interest is calculated from the subsample and the full sample. The difference between the estimates of interest in the full sample and each of the subsamples is used to determine the standard error of the estimate.

For example, assume \( \hat{\theta} \) is the full-sample estimate of some population parameter \( \theta \), for example, the mean. The variance estimation \( \sigma^2(\hat{\theta}) \) is given by

\[
\sigma^2(\hat{\theta}) = \frac{c \sum_{g=1}^{G} (\hat{\theta}_g - \hat{\theta})^2}{G - 1} \quad (2)
\]

where

\[
\hat{\theta}_g = \text{estimate of } \theta \text{ based on the observations included in the } g \text{th replicate (subsample)};
G = \text{total number of subsamples (or replicates formed)};
c = \text{constant depending on the replication method (20); for Jackknife-n, } c = 1; \text{ and}
g = \text{replicate number}.
\]

Different methods of creating subsamples yield different kinds of replicate weights. Because this survey of ML travelers had more than two primary sampling units per stratum (Houston road, Dallas road, neither of the given roads in Houston or Dallas, or missing location), the Jackknife-n (JK-n) method was the only appropriate method. For the JK-n method, the formula for variance estimation is modified as shown in Equation 3.

\[
\sigma^2(\hat{\theta}) = \frac{c \sum_{g=1}^{G} h_g (\hat{\theta}_g - \hat{\theta})^2}{G - 1} \quad (3)
\]

where \( h_g \) is the factor specific to JK-n methodology and \( f_g \) is the finite population correction factor.

The finite population correction factor \( f_g \) is estimated using Equation 4 (21). In both Houston and Dallas this value was extremely close to 1.

\[
FPC = \left[ \frac{(N - n)}{(N - 1)} \right]^{1/2} \quad (4)
\]

where \( N \) is total population and \( n \) is total sample size.

The number of replicates, \( G \), is equal to

\[
G = \sum_{h=1}^{L} n_h \quad (5)
\]

where \( L \) equals number cf strata (16 in this case) and \( n_h \) (varies from 2 to 4) equals number of primary sampling units in stratum \( h \). \( G \) totaled 39 for this survey.

The methodology for replicate weight creation is given in detail in WesVar Manual (21): "For computation of first replicate weight, the full sample of observations in the first stratum and first primary sampling unit (PSU) are given a weight of zero and the weights associated with the other PSU in the same stratum are adjusted by

\[
\frac{n_h}{(n_h - 1)}
\]
[in this case often 2] to account for reducing the sample. The weights for observations in all the other strata are not changed. The remaining replicates for the stratum (weights and \( \theta \)) are formed in the same manner by systematically dropping each of the remaining PSUs for that stratum and computing the replicate weights in a manner similar to computation of the first replicate weight." Then each stratum is done in a similar manner.

**Descriptive Analysis of the Data**

Next, descriptive statistics were developed using the replicate weights and the fixed (or \( P \)) weights. This information was used to help determine what variables would most likely be included in the mode choice model (discussed below) and to provide some insight into the impact of using replicate weights. The analysis divided the sample into two groups: (a) respondents who selected a managed lane option in at least one of the four stated preference questions (approximately 71% of respondents) and (b) respondents who never chose an ML option. The results of this analysis are provided in Table 1. Significant \( p \)-values indicate that respondents with that characteristic selected an ML option significantly more or less than respondents with the other characteristics. For example, travelers with a trip purpose of "other" were significantly less likely to choose an ML option than all other travelers combined.

As shown in Table 1, the means calculated using the replicate and fixed weights are the same; it is the standard deviations that change. In general, the standard deviations calculated by the replicate weighting method were larger, and therefore the probability ( \( p \)-values) was also larger, indicating a lower likelihood that the differences observed were statistically significant. In the categories listed in Table 1, 13 were found to be significantly different using \( P \) weights, but the correct method, using replicate weights, found only six significant differences. The differences were not surprising, and respondents more likely to choose an ML option:

- Were not on a trip purpose categorized as "other,”
- Were younger than 65 years old,
- Were traveling on a Dallas toll road,
- Had one vehicle per household, and
- Had a household income between $25,000 and $49,999 or greater than $100,000.

**Mode Choice Model Development**

A mode choice model based on respondents’ answers to the stated preference questions was then developed. All six mode options were available in the model:

- Single-occupant vehicle (SOV) on the managed lanes (MLs),
- Two-person vehicle (HOV2) on the MLs,
- Three-or-more-person vehicle (HOV3+) on the MLs,
- SOV on the general purpose lanes (GPLs),
- HOV2 on the GPLs, and
- HOV3+ on the GPLs.

Although transit was available in many of these corridors, it was not included as a mode choice. It was felt that an additional mode would add too much complexity to the choice set, and previous research showed transit riders to be loyal to the bus mode (19).

Nested and random parameter logit models were estimated for mode choice modeling using the maximum likelihood method in LIMDEP. Several utility equations with varied combinations of parameters were examined. The utility function of the nested logit model shown in Table 2 was found to have best fit and explanatory ability. The nest is shown in Figure 1. One side of the nest contains respondents who chose a toll option, including SOV on the MLs and most of the HOV2s on the ML. The other side of the nest includes non-toll-paying travelers on the GPLs and most of the HOV3+ travelers on the MLs. Because of the random features built into the stated preference questions, 1,078 stated preference questions of 17,176 included HOV2s who paid no toll on the ML or HOV3+ travelers who paid a toll on the ML. These were removed before model estimation for this nest. Driving alone on the GPLs was taken to be the base mode.

All variables used in the model were significant at the 95% confidence level (see Table 2). Apart from its statistical significance, each variable in the model was examined for its sign and magnitude. All parameters used in the model seemed reasonable on the basis of the literature review and the survey descriptive statistics. For example, work-related trips and adults living alone were less likely to carpool. Conversely, Caucasians with higher incomes were more likely to use the MLs as an SOV, whereas middle-class incomes were much less likely to break up and use the ML as an SOV. From the model, the value of time for travelers was found to be $12.60 per hour. This value seems reasonable as compared with other studies and national guidance, in which the value generally is in the $15/h range.

**HOV LANE VERSUS MANAGED LANE SIMULATION**

This survey of travelers and the mode choice model developed in the previous section were designed to better understand the impact of preferential treatment for carpools on managed lanes. This section of the paper presents one example of how these data may be used to accomplish that objective. In this section, the mode choice model was applied to Katy Freeway automobile travelers, and their mode choices due to varying toll levels were investigated.

**Katy Freeway Travelers as the Test Group**

Katy Freeway was chosen as an example corridor to use in this simulation because this freeway already has an HOV lane and many of the travelers along the freeway already carpool. This provided a significant number of carpool respondents (130) of the many total survey respondents (498) who regularly traveled that freeway. This high percentage of carpools was useful when the model was applied. If the percentage of carpools was too small, the model may not have properly estimated the impact of tolls and travel times on this group’s mode choice.

However, to simulate the impact of preferential toll treatment on carpools on Katy Freeway another set of weights was developed. These weights adjusted the average weights by the ratio of surveyed to actual SOV, HOV2, and HOV3+ travelers on the Katy corridor during the 3-h peak period. Survey respondents who traveled by automobile on the Katy Freeway were primarily in SOVs (73.9%), followed by HOV2 carpools (17.5%), and then HOV3+ carpools (8.6%). Actual percentages of these groups on Katy Freeway were obtained from average vehicle occupancy counts on the main lanes, frontage roads, and HOV lane. The actual percentage of vehicles on
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>$N$</th>
<th>Replicate Weights Choose ML (%)</th>
<th>$p$-Value (%)</th>
<th>$P$ Weights Choose ML (%)</th>
<th>$p$-Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trip Purpose</strong></td>
<td></td>
<td></td>
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<tr>
<td>Commute</td>
<td>2,364</td>
<td>71.6</td>
<td>0.40</td>
<td>71.6</td>
<td>0.40</td>
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<tr>
<td>Recreational</td>
<td>651</td>
<td>74.8</td>
<td>0.26</td>
<td>74.8</td>
<td>0.18</td>
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<td>Work-related</td>
<td>582</td>
<td>69.4</td>
<td>0.33</td>
<td>69.4</td>
<td>0.30</td>
</tr>
<tr>
<td>School</td>
<td>154</td>
<td>77.0</td>
<td>0.31</td>
<td>77.0</td>
<td>0.29</td>
</tr>
<tr>
<td>Other*</td>
<td>93</td>
<td>52.5</td>
<td>0.01*</td>
<td>52.5</td>
<td>0.04*</td>
</tr>
<tr>
<td><strong>Road</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Houston: Beltway 8 (only Houston toll road in list)</td>
<td>106</td>
<td>79.3</td>
<td>0.13</td>
<td>79.3</td>
<td>0.03*</td>
</tr>
<tr>
<td>Houston: all other roads listed</td>
<td>2,178</td>
<td>72.2</td>
<td>0.35</td>
<td>72.2</td>
<td>0.32</td>
</tr>
<tr>
<td>Dallas: George Bush Turnpike and Dallas North Tollway (only Dallas toll roads in list)</td>
<td>219</td>
<td>80.0</td>
<td>0.00*</td>
<td>80.0</td>
<td>0.00*</td>
</tr>
<tr>
<td>Dallas: all other roads listed</td>
<td>1,203</td>
<td>67.1</td>
<td>0.10</td>
<td>67.1</td>
<td>0.01*</td>
</tr>
<tr>
<td>No road selected</td>
<td>182</td>
<td>78.7</td>
<td>0.22</td>
<td>78.7</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Time of Travel (multiple answers allowed)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early a.m. (midnight–6 a.m.)</td>
<td>513</td>
<td>68.8</td>
<td>0.29</td>
<td>68.8</td>
<td>0.26</td>
</tr>
<tr>
<td>Peak a.m. (6 a.m.–9 a.m.)</td>
<td>2,190</td>
<td>72.1</td>
<td>0.37</td>
<td>72.1</td>
<td>0.36</td>
</tr>
<tr>
<td>Midday (9 a.m.–4 p.m.)</td>
<td>1,080</td>
<td>71.9</td>
<td>0.40</td>
<td>71.9</td>
<td>0.40</td>
</tr>
<tr>
<td>Peak p.m. (4 p.m.–6:30 p.m.)</td>
<td>1,929</td>
<td>73.2</td>
<td>0.24</td>
<td>73.2</td>
<td>0.16</td>
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<tr>
<td>Late p.m. (6:30 p.m.–midnight)</td>
<td>649</td>
<td>74.4</td>
<td>0.29</td>
<td>74.4</td>
<td>0.23</td>
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<tr>
<td><strong>Typical Trip Length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short (0–3 miles)</td>
<td>140</td>
<td>65.4</td>
<td>0.31</td>
<td>65.4</td>
<td>0.24</td>
</tr>
<tr>
<td>Medium (4–9 miles)</td>
<td>582</td>
<td>70.4</td>
<td>0.38</td>
<td>70.4</td>
<td>0.34</td>
</tr>
<tr>
<td>Long (10–20 miles)</td>
<td>1,736</td>
<td>72.1</td>
<td>0.39</td>
<td>72.1</td>
<td>0.38</td>
</tr>
<tr>
<td>Very long (more than 21 miles)</td>
<td>1,206</td>
<td>72.7</td>
<td>0.37</td>
<td>72.7</td>
<td>0.34</td>
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<tr>
<td><strong>Pay to Park at Destination</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Yes</td>
<td>599</td>
<td>68.1</td>
<td>0.26</td>
<td>68.1</td>
<td>0.17</td>
</tr>
<tr>
<td>No</td>
<td>3,266</td>
<td>72.4</td>
<td>0.26</td>
<td>72.4</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Number of People in the Vehicle</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One</td>
<td>2,374</td>
<td>70.5</td>
<td>0.27</td>
<td>70.5</td>
<td>0.20</td>
</tr>
<tr>
<td>Two</td>
<td>515</td>
<td>76.3</td>
<td>0.20</td>
<td>76.3</td>
<td>0.08</td>
</tr>
<tr>
<td>Three or more</td>
<td>239</td>
<td>77.1</td>
<td>0.30</td>
<td>77.1</td>
<td>0.19</td>
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<tr>
<td>Vanpool, train, bus, or motorcycle</td>
<td>572</td>
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<td><strong>Number of Trips per Week</strong></td>
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<td>1 or 2</td>
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<td>3 to 5</td>
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<td>68.4</td>
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<td>10</td>
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<td>72.5</td>
<td>0.38</td>
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<tr>
<td>More than 10</td>
<td>568</td>
<td>72.8</td>
<td>0.39</td>
<td>72.8</td>
<td>0.38</td>
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<td><strong>Travel Companion (only for carpoolers)</strong></td>
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<tr>
<td>Coworker (nearby office)</td>
<td>164</td>
<td>78.4</td>
<td>0.39</td>
<td>78.4</td>
<td>0.37</td>
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<tr>
<td>Adult family member</td>
<td>338</td>
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<td>0.24</td>
<td>72.9</td>
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<tr>
<td>Child</td>
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<td>78.8</td>
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<tr>
<td>Other</td>
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<td>86.1</td>
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(continued on next page)
### TABLE 1 (continued) Descriptive Statistics of Survey Respondents

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<th>Characteristic</th>
<th>N</th>
<th>Replicate Weights</th>
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<th>P-Weights</th>
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<th>p-Value (%)</th>
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<tr>
<td></td>
<td></td>
<td>Choose ML (%)</td>
<td>p-Value (%)</td>
<td>Choose ML</td>
<td>p-Value (%)</td>
<td></td>
<td></td>
</tr>
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<td>16 to 24 years old</td>
<td>481</td>
<td>79.9</td>
<td>0.12</td>
<td>79.9</td>
<td>0.02*</td>
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<td>25 to 34 years old</td>
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<td>0.15</td>
<td>75.1</td>
<td>0.05*</td>
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<td>35 to 44 years old</td>
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<td>45 to 54 years old</td>
<td>784</td>
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<td>0.06</td>
<td>64.6</td>
<td>0.00*</td>
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<td>55 to 64 years old</td>
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<tr>
<td>More than 65 years old*</td>
<td>94</td>
<td>50.5</td>
<td>0.03*</td>
<td>50.5</td>
<td>0.00*</td>
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<tr>
<td>Gender</td>
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<td>Male</td>
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<td>73.0</td>
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<td>Female</td>
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<td>Caucasian</td>
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<td>Afro-American</td>
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<td>Household Type</td>
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<td>Single adult</td>
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<td>0.39</td>
<td>70.9</td>
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<td>Unrelated adults (e.g., roommates)</td>
<td>273</td>
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<td>0.15</td>
<td>79.5</td>
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<tr>
<td>Married without child</td>
<td>704</td>
<td>73.9</td>
<td>0.28</td>
<td>73.9</td>
<td>0.21</td>
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<tr>
<td>Married with child</td>
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<td>71.3</td>
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<td>Other</td>
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<td>One</td>
<td>776</td>
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<td>0.10</td>
<td>66.8</td>
<td>0.04*</td>
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<td>Two</td>
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<td>0.33</td>
<td>73.2</td>
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<td>Three</td>
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<td>0.39</td>
<td>72.4</td>
<td>0.39</td>
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<td>Four</td>
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<td>0.20</td>
<td>75.0</td>
<td>0.18</td>
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<td>Five or more</td>
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<td>One</td>
<td>1,097</td>
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<td>0.03*</td>
<td>67.2</td>
<td>0.02*</td>
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<td>Two</td>
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<td>Three or more</td>
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<tr>
<td>Technical</td>
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<td>Administrative</td>
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<td>Sales, service, manufacturing, student, and self-employed</td>
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<td>76.7</td>
<td>0.05*</td>
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<td>Stay-home, unemployed, retired, and others</td>
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<td>67.4</td>
<td>0.30</td>
<td>67.4</td>
<td>0.22</td>
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<td>Education</td>
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<tr>
<td>High school graduate or less</td>
<td>654</td>
<td>69.5</td>
<td>0.31</td>
<td>69.5</td>
<td>0.31</td>
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<tr>
<td>Some college, vocational</td>
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<td>0.33</td>
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<td>College graduate</td>
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<td>Postgraduate degree</td>
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<td>70.9</td>
<td>0.38</td>
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<td>Less than $24,999</td>
<td>978</td>
<td>74.3</td>
<td>0.18</td>
<td>74.4</td>
<td>0.23</td>
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<tr>
<td>$25,000 to $49,999</td>
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<td>66.4</td>
<td>0.01*</td>
<td>66.4</td>
<td>0.01*</td>
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<tr>
<td>$50,000 to $99,999</td>
<td>1,150</td>
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<td>0.40</td>
<td>71.7</td>
<td>0.40</td>
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<tr>
<td>More than $100,000*</td>
<td>700</td>
<td>76.0</td>
<td>0.01*</td>
<td>76.0</td>
<td>0.01*</td>
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*aStatistically significant at 95%.
Katy Freeway in each category was very similar to the percentage of responding travelers in each category. However, when one takes into account the multiple occupants in many vehicles, the actual percentage of travelers on Katy Freeway was approximately 62.4% SOV, 26.5% HOV2, and 11.1% HOV3+. This resulted in weights of 0.84 for SOVs (62.4/73.9), 1.52 for HOV2, and 1.28 for HOV3+. Note that transit riders were not included in this analysis.

With the use of the new weights, the mode choice model was used to estimate the mode choice for these Katy Freeway travelers under many toll scenarios. For all scenarios, the travel times for the different modes were kept constant. The travel times were based on typical travel times during the peak period on the Katy Freeway general purpose lanes (27 min) and the HOV lane (12 min) along the 11 plus miles of Katy Freeway with a barrier-separated HOV lane. To account for the additional time to collect and drop off carpoolers or spent waiting for the carpool driver, the survey data were examined. On the basis of the survey data, HOV2 carpools using Katy Freeway took an average of an additional 5.5 min, and HOV3+ carpools required an average of 6.0 additional minutes. This extra time was added to the travel times for those modes in the model.

This had the potential to introduce considerable error in the results owing to the distribution of carpool formation times. Approximately 50% of Katy Freeway respondents indicated that the carpool took no extra time (see Figure 2). For those travelers, adding the average carpool formation time could improperly increase the disutility of using that mode. However, the authors tested this theory and found

![Figure 1 Nest Structure](image-url)
only small differences in outcome when reducing the carpool formation time for many carpoolers in the simulation runs. That result may be due to the fact that 89.3% of Katy Freeway carpoolers who required no extra carpool formation time were flagpoles and were therefore likely to choose carpooling even with added travel time disincentive.

**Scenarios Modeled**

The first scenario examined allowed HOV3+ vehicles to travel free of charge on the MLs. SOVs paid a price as noted in Figure 3, and HOV2s paid half the SOV price. Travel times on the MLs and GPLs were set as noted above. The mode choice for Katy Freeway survey respondents was then predicted by the use of the mode choice model described in the previous section. The percentage of travelers choosing each mode is shown in Figure 3. As expected, as the toll increases for SOVs the percentage of those vehicles on the MLs decreases.

Somewhat surprising is the change is rather small—indicating an insensitivity to price. Very little change in HOV2 and HOV3+ modes was observed. The percentage of travelers on the MLs ranged from 38.3 to 38.9.

The next scenario (Scenario 2) investigated the removal of the price discount for HOV2s. The toll for SOVs was set at $8 and HOV3+ vehicles traveled toll free. The toll for HOV2s varied from $2 to $10 (see Figure 4). As expected, when the toll for HOV2 vehicles increased their use of the ML decreased, from 8.9% of vehicles to 7.3%. At the same time, there was a small increase in SOVs on the MLs. In total, only a small decrease in average vehicle occupancy (AVO) was found as a result of increasing the HOV2 ML toll. The percentage of travelers on the MLs ranged from 38.3 to 38.5. When similar models from Scenarios 1 and 2 were compared (in which SOV toll = $8 and HOV3+ toll = $0), when the HOV2 toll increased from $4 to $8 the use of HOV2 on the ML dropped from 8.4% to 7.6%. Although this represents just over 0.5% of total trips, it is a 9.5% reduction in this mode...
choice. The total number of carpools (HOV2 and HOV3+) on both the GPLs and MLs dropped from 23.7% to 23.0%, a drop of 3.0%.

The final scenario (Scenario 3) examined the removal of the price discount for HOV3+ vehicles. The toll for SOVs was again set at $8, and HOV2 vehicles paid $4. The toll for HOV2s varied from $0 to $8 (see Figure 5). As expected, when the toll for HOV3+ vehicles increased, their use of the ML decreased, from 6.9% of vehicles to 5.3%. At the same time, there were very small increases in HOV2 travel on the GPLs and MLs and no change in HOV3+ vehicles on the GPLs. In total, the AVO decreased from 1.33 (with a $0 toll for HOV3+) to 1.30 when HOV3+ vehicles paid $8 for the MLs. Again, when like scenarios are compared (the SOV ML toll is $8, and the HOV2 toll is $4), when the HOV3+ toll jumped from $0 to $4, the use of HOV3+ on the ML dropped from 6.9% to 6.0%. Although that represents approximately 0.5% of total trips, it is a 13% reduction in this mode choice.

These results are similar to the scant empirical data that exist. A limited examination of carpool traffic on State Route 91 express lanes when the toll was removed showed an inelastic response from carpoolers, in the range of −0.2 to −0.3. Similarly, the toll for HOT lane travel on Katy Freeway was reduced by 50% in April 2003. This resulted in a very inelastic response, with an elasticity of −0.13.

These small changes in carpool volumes with respect to carpool price changes are similar to those found in this analysis.

Summary of Modeling Results

On the basis of these findings, the impact of tolls on the number of HOV2 and HOV3+ vehicles was relatively small when compared with the entire traffic stream. However, the impact on the percentage of travelers choosing each of these modes was measurable. For example, the small number of HOV2 and HOV3+ vehicles that no longer use the ML when the toll increases represents a significant portion of those particular modes. In the examples pulled out above, the decrease in these modes on the ML exceeded 9%. In addition, this decrease was not compensated for by a similar increase in HOV2 and HOV3+ use on the toll-free GPLs. In the examples above, most of the “toll off” HOVs switched to SOVs for both the ML and the GPL.

To examine the revenue implications of a simplistic ML facility, the examples pulled from above are used. Also, assume an ML facility with three GPLs and two MLs and a peak-hour directional demand of 10,000 passenger cars. The toll rates described above would yield close to appropriate traffic distribution on the MLs and GPLs based...
on this model. In Scenario 1 (with SOV toll of $8, HOV2 toll of $4, and HOV3+ toll of $0) the peak-hour revenues are $21,848 (2310 x $8 + 842 x $4 + 690 x $0). In Scenario 2 (with SOV toll of $8, HOV2 toll of $8, and HOV3+ toll of $0) the peak-hour revenues are $25,136 (2,379 x $8 + 763 x $8 + 694 x $0), a 15.0% increase. In Scenario 3 (with SOV toll of $8, HOV2 toll of $4, and HOV3+ toll of $4) the peak-hour revenues are $24,436 (2,325 x $8 + 853 x $4 + 604 x $4), an 11.2% increase with respect to revenue generated in Scenario 1 modeling.

CONCLUSIONS

This research examined the potential impacts of removing or reducing the preferential treatment for carpools in HOV lanes. The impetus for this is the potential for additional revenue from selling the capacity on the HOV lanes. However, this benefit must be weighed against the negative impacts on the number of travelers who choose to carpool.

To investigate this potential impact, a survey of Houston and Dallas travelers was undertaken. Despite efforts to obtain a survey sample that was representative of the populations of the two cities, the survey sample contained too few minority and low-income respondents. To adjust results to better reflect the population, a replicate weighting process was used. When responses were analyzed by this weighting process, the same mean values but different standard deviations were obtained when compared with a simple weighting process. This provided more reliable results when the data were examined for significant differences. The survey responses were also used to develop a mode choice model.

This mode choice model was used to predict the impact of converting an HOV lane to a HOT lane, where all travelers pay a toll. The model found that travelers were relatively insensitive to price. It was found that the overall percentage of HOV2 and HOV3+ vehicles in the traffic stream decreased by only a small amount when a toll was required for them to use the HOV lane. However, this did represent a significant portion of those modes (more than 9% in the specific scenarios examined) and did result in increased HOT lane revenue (more than 10% in the specific scenarios examined). Therefore, elimination of preferential treatment for these vehicle types has significant implications and becomes a difficult policy decision—not just a straightforward choice.

ACKNOWLEDGMENTS

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REFERENCES
