Online Appendix for

The Effects of Regulation in the Presence of Multiple Unpriced Externalities: Evidence from the Transportation Sector

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(for reference only; not for publication)

This appendix provides details on the construction of the data and welfare sections, the tabular results for robustness tests using alternate specifications, and figures for alternate polynomial orders. In Appendix A, we provide further details on the data, including the rationale for the choice of the I-10W, background information on the I-10W, and details on the processing of the weather data used in the analysis. In Appendix B we provide the calculations that we use to generate our welfare estimates, discuss parameter values, and present sensitivity analyses of the welfare results. Appendix C provides a proof that the general equilibrium effects of the policy can be upper-bounded by partial equilibrium estimates under reasonable assumptions. Appendix D includes figures for all polynomial orders for the I-10W for all times of day as well as sensitivity analysis figures. Appendix E presents additional tables outlining descriptive statistics of our data, alternate specifications as robustness checks, full coefficient tables, alternate registration and welfare models as well as other supporting analysis.

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Appendix A. Additional data discussion

This appendix provides further details on the datasets discussed in Section III.

Road Selection —The I-10W route near downtown LA was selected for our travel time analysis based on availability of route-level data before 2005, the presence of an HOV lane, and availability of data on competing routes. The I-10W, east of downtown LA (running from West Covina to downtown LA) is the only road that satisfies the criteria outlined above. In addition, the I-10 is also an excellent route to study the impact of CAVS policy on travel time, as it flows through one of the most congested areas of the city, ensuring an incentive for commuters to utilize the HOV lane access, granted by the policy.

HOV lane access on this road requires three or more people per vehicle during the morning peak (5:00 to 9:00 A.M.) and afternoon peak (4:00 to 7:00 P.M.) times.[1] Nearly all other HOV lanes in CA require two or more occupants during peak hours. Because this policy allows hybrid drivers to avoid the cost of carpool formation, the 3+ regulation may affect the decision to switch to a single occupant hybrid for those who currently carpool.[2] For those not carpooling before the policy, the 3+ versus 2+ regulation only has an impact in so far as it creates a

[1] At all other times of day HOV lane access requires two or more occupants per vehicle.

[2] We note that Caltrans car counts of hybrid vehicles and carpools prior to and following implementation of the policy align well with our central estimates, suggesting broken carpools is not a major concern.

larger travel time differential between the HOV and mainline lanes. This differential, however, should not differ greatly across routes, as regulators have set these occupancy requirements to keep HOV lane congestion similar across all roads, implying that despite the 3+ regulation on the I-10 we expect to observe similar effects of the CAVS policy on HOV lanes in other routes.[3] The detector level analysis in Section V supports this assertion, finding that the I-10W detector estimates are similar to estimates from other detectors located within 10 miles of downtown LA.

Of the two directions of travel, the westbound direction of travel was selected for the following reasons. First, data was available for the I-210W, a competing route 5 miles north of the I-10.[4] Travel times for this alternate route allow us to develop a more complete specification of the commuting patterns on the I-10W. Although the I-10 in general has one of the highest detector concentrations of any freeway in general, the detector coverage in the westbound direction is particularly high (3.42 per mile eastbound, 4.51 per mile westbound). This density ensures that the travel times reported by PeMS are not overly dependent upon a small set of detectors.[5]

Background on the I-10—The 17.5-mile section of the I-10W analyzed is shown in Map 1. It runs between the suburb of West Covina and downtown LA. The I-10 was the first highway in the nation to have an HOV lane, with the first 11-mile segment opening in 1973. With the exception of the 3+ occupant requirement

[3] In January 2000, the occupancy regulation was briefly dropped to 2+ during peak hours before extreme congestion required immediate action. An emergency measure was passed in July terminating the experiment in order to return the road to reasonable speeds.

[4] Travel time data on the I-210E is not available until 2006. State highway 60 runs parallel to the I-10 several miles to the south; however data is also not available until 2006.

[5] An additional reason for not considering the eastbound direction of the I-10 is because travel in that direction was drastically affected by an extension to the HOV lane in early 2005. This extension occurred on the easternmost portion of the I-10 route studied below. It appears that this extension may have removed a bottleneck on traffic leaving downtown LA, leading to a dramatic drop in eastbound travel times in early February 2005. However, it did not significantly affect *observed* travel times on the westbound HOV lane.

during peak travel times, this route is fairly representative in terms of size and design for the L.A. region. The road generally has barriers on both sides with a shoulder for stopped vehicles on the right. Entry into the HOV lane from the mainline is limited access at noted points, with a fine of $381 for occupancy violations or for crossing the double-yellow buffer between the HOV lane and mainline lanes. Several park-and-ride lots exist along the I-10 to encourage carpool formation. The Metrolink San Bernardino Line, a regional commuter rail option, tracks a significant portion of the route.

Appendix Table E.2 presents weekday travel time averages for each lane and route, including the I-210W, during the four peak and off-peak periods. The table also reports travel times normalized by the length of the road as well as standard deviations for 2004-2007. Standard deviations in travel time can be interpreted as a measure of lane reliability. Travel times are highest during the morning peak for all lanes, and higher levels of congestion also increase the standard deviation during the morning peak. During the morning peak, travel times are between four and six minutes lower in the HOV lane than the mainline lanes. Travel times on the I-210W are higher than those on the I-10W mainline because the road segment is longer (21.3 miles), although after normalizing by road length, it can be observed that traffic on this route moves at a slightly faster pace. Consistent with theoretical predictions (e.g. Vickrey, 1969), drivers equalize travel costs across these routes with the faster speed on the I-210W compensating for its less direct, peripheral route. Drivers have been shown to value both average travel time as well as the reliability of a route (Small, Winston and Yan 2005). The HOV lane provides higher reliability with smaller variances in travel times compared to the mainline.

Weather—To match weather measures to the travel time data from PeMS, we follow the algorithm used in Auffhammer and Kellogg (2011). First, the

Vincenty distance of each airport weather station to the geographic center of the road segment was calculated. As the closest station to the road segment is Fullerton, the data from this station is matched to the travel time data for the I-10W. After these records have been matched, 2.4% of the travel time records are not matched to a full set of weather measures.[6] These missing weather measures are imputed by regressing the observations where Fullerton was active, for the relevant variable, onto the same variable for the remaining eight stations. The predicted values from that regression were used to replace the missing values. Following this step, weather measures are still missing whenever one of the remaining eight stations is also missing an observation. To estimate the remaining missing values, the above step is repeated with 7 stations, and then 6 and so on. Where variables range from 0 to 1, for example percent cloud cover, a linear regression was performed and predicted values were checked to ensure they remained within that bound. Following this procedure two observations remain unmatched to a full set of weather measures and these observations were dropped. Thus missing values for the primary station are imputed allowing for precise weather measurements to be matched with the full set of hourly travel time observations from PeMS.[7]

Further Detector Discussion—In Section V we present results from the detector data set using local linear regression. As noted, several aspects of the detector data set prevent global analysis as used in the route level. In the route level analysis we found the local and global specifications to provide similar estimates and we therefore expect little would be gained if the global specification could be performed on the detector level data. Three features of the detector level data

[6] For Fullerton, of the 35,064 total observations, 840 had at least one weather measure missing.

[7] As robustness checks two alternate forms of weather aggregation were also tested: the first method weights each station by the inverse distance to the center of the road segment and the second method weights all stations equally. See Table E.9 in Appendix E for more details.

prevent the global analysis. The first challenge is computational. While relatively few observations are used in the final set of regressions, the initial data set is large with over 2.3 million observations for three months. Cleaning a substantially larger data set (around 36 million observations), although feasible, would require significantly more time to perform. The second challenge involves quality control. Prolonged gaps in detector data happen during maintenance shutdowns. We also delete all observations where the percent observed is less than 100 percent (to prevent PeMS interpolation from affecting our estimates), resulting in further gaps. If these gaps occur around the discontinuity the data will not meet the requirements of the regression discontinuity design. A transparent and simple method can be used to exclude these detectors in the local analysis: dropping detectors with a total number of observations less than 50. Detectors with large gaps near the discontinuity will fail to meet this criterion using a 3-month window. Similar rules are difficult to devise for a global design. A detector with large gaps, yet sufficient density near the discontinuity, might be included while a detector having many observations and a modest gap near the discontinuity should not. Lacking a transparent rule, inspection could be used; however, with several hundred detectors it seems to involve excessive researcher discretion. The third problem involves specifying the underlying time trend, which if improperly chosen would lead to bias. Correctly specifying the order of the trend on a large number of detectors is difficult, particularly if detectors have different trends. This problem is compounded by the presence of data gaps. With multiple concerns, we find the problems of analyzing the detector level data with a global specification to outweigh the little expected benefit.

Appendix B. Welfare appendix

This appendix provides further details of the assumptions and calculations of the welfare effects of the CAVS policy derived in Section VI, as well as parameter choices and additional results under alternative econometric specifications and parameter assumptions.

A. Welfare Model

The welfare model captures the change in welfare due to the CAVS policy. As described in Section VI, the welfare effects can be decomposed into a primary welfare gain and a series of interaction effects between the policy and unpriced congestion and emission externalities. These welfare effects are: the *primary welfare gain* (ΔW^{P}), the *cost-side congestion interaction effect* (ΔW^{CSCI}), the *rent effect* (ΔW^{R}), the *system-wide congestion interaction effect* (ΔW^{SWCI}), and the *emissions interaction effect* (ΔW^{EI}).

Our numerical model consists of three types of agents, indexed by *j*: Hybrid drivers (*H*), carpoolers (*C*) and other drivers in the transportation system (*O*), where N_j represents the number of each of these types of agents. Hybrid vehicles emit E_{Hi}, the yearly amount of pollutant *i,* while carpoolers and other drivers emit E_{Fi}, where i indexes emissions of greenhouse gases, NOx, and hydrocarbons. These pollutants have a marginal social damage given by MSD_i. Yearly travel time for each of the three classes of agents is given by TT_j. Value of time is given by VOT_j. Let δ be the fraction of stickered hybrids purchased because of the policy. Changes in welfare due to the policy arise from changes in emissions or travel time. We now describe the numerical calculations that operationalize the theoretical welfare effects presented in Section VI.[8]

Primary Welfare Gain—The *primary welfare gain* represents the benefits associated with emissions reductions from drivers who purchase hybrids because of the policy. In Section VI, the marginal increase in social cost is given by $(E_H - E_R)$. When integrated over the change in the number of HOV lane vehicles, we get the total effect $\int_{C_C}^{C_C+\bar{H}}(E_H - E_R)\, dC_H = \bar{H}(E_H - E_R)$, which is a benefit because $E_H < E_R$. In Figure 4, this is given by the area adbc-ehfg. It should also be noted that this calculation only considers the greenhouse gas reductions associated with commuting on the I-10W. Hybrids achieve mpg_H miles-per-gallon with NOx and hydrocarbon gram-per-mile emissions of NOx_H and HC_H, while the vehicles they replace are assumed to receive the fleet average mpg_F miles-per-gallon with NOx and hydrocarbon gram-per-mile emissions of NOx_F and HC_F. All vehicles are assumed to emit $CO2$ grams-per-gallon of CO_2-equivalent greenhouse gas emissions. All three pollutants are converted from grams into tons via a conversion factor of 1.102 x 10^{-6}. Multiplying by the number of trips per year *T*, and the route length in miles *L* gives the tons of emission savings per year. Thus, taking the number of hybrids entering the HOV lane that were purchased because of the policy times the emissions savings per hybrid times the marginal social damage yields the total *primary welfare gain*:

$$(1)\quad \Delta W^P = \delta N_H\left(\left(\frac{CO2}{mpg_F} - \frac{CO2}{mpg_H}\right)MSD_{GHG} + (NOx_F - NOx_H)MSD_{NOX} + (HC_F - HC_H)MSD_{HC}\right)(1.102x10^{-6})L \cdot T.$$

[8] While Section VI derives the marginal effects from a change in social cost, here we flip the sign to more intuitively represent benefits as positive and costs as negative. For simplicity, we also make several approximating assumptions below.

To determine the number of hybrid vehicles using the HOV lane N_H, we follow Burger and Kaffine (2009) and determine the hourly change in flow in the HOV lane ΔC_t^{HOV} (and thus the number of hybrids moving into the HOV lane) implied by the hourly I-10W travel time estimates in Table 2 from the following equation:

$$(2) \quad \Delta C_t^{HOV} = -\frac{C_t^{HOV} \cdot \beta_t^{TP}}{\varepsilon_t^{SO} \cdot \varepsilon_t^{OC}}$$

where C_t^{HOV} is the baseline average flow in the I-10W HOV lane in July-September 2005 during hour *t*, β_t^{TP} is the hourly travel time estimate from Table 2 (interpreted as a percentage change in travel time due to the CAVS policy), ε_t^{SO} is the elasticity of speed with respect to occupancy and ε_t^{OC} is the elasticity of occupancy with respect to flow.[9] The last two terms translate changes in traffic flow into changes in traffic speeds.[10] To estimate these two elasticities, 66,332 hourly observations of I-10 speed, occupancy, and flow from the PeMS detector dataset during congested periods of the day are used. The congested speed-occupancy elasticity along the HOV lane of the I-10W is estimated to be -0.70, while the occupancy-flow elasticity is estimated to be 1.00.[11] Summing over the number of hybrids entering the HOV lane by hour gives the total number of hybrids using the HOV lane as: $N_H = \sum_t \Delta C_t^{HOV}$.

Cost-side Congestion Interaction Effect—The *cost-side congestion interaction effect* represents the welfare loss as hybrids entering the HOV lane increase

[9] Although we do not globally estimate the marginal travel cost functions, the approach taken here, based on the elasticity estimates of the effect of the policy on travel time, is effectively a local approximation to the true travel cost functions, which we use to locally estimate the congestion changes induced by the policy.

[10] This change must be calculated using occupancy, the percentage of time the detector is covered by a vehicle, to eliminate the hyper-congestion portion of the data where the flow-occupancy curve is backward bending (Small and Chu, 2003).

[11] Burger and Kaffine (2009) find a speed-occupancy elasticity of -0.47 and an occupancy-flow elasticity of 1.28. It should be noted that the analysis here considers only observations in the HOV lane along the I-10, while Burger and Kaffine consider a random sample of mainline detectors across Los Angeles County (12 freeways). Note that these estimates are for congested periods of the day, where traffic flow has surpassed the congestion "threshold". While there may be slight variations in these (congested) elasticities by hour of day, for simplicity they are assumed to be constant.

congestion levels and travel times for existing carpoolers, represented by area fgji in Figure 4. In Section VI, the marginal effect was given by $(3C_C\nu_C + \bar{H}\nu_{\bar{H}})\frac{dT_H^{''''}}{dC_H}$. Integrating over the change in the number of HOV lane vehicles gives the total effect as: $\int_{C_C}^{C_C+\bar{H}}(3C_C\nu_C + \bar{H}\nu_{\bar{H}})\frac{dT_H^{''''}}{dC_H}dC_H = \int_{C_C}^{C_C+\bar{H}}(3C_C\nu_C + \bar{H}\nu_{\bar{H}})dT_H^{'''} \cong (3C_C\nu_C + \bar{H}\nu_{\bar{H}})(T_H(C_C + \bar{H}) - T_H(C_C))$. For simplicity, in the calculation below we ignore the small external congestion cost of hybrids on other hybrids in the HOV lane, focusing on the costs to pre-policy carpoolers. An individual carpool experiences a welfare loss equal to the value of the difference in HOV travel time pre- and post-policy. This will represent an upper-bound on costs, as it is possible that some carpoolers would break their carpool in response to these increased congestion costs.[12]

Multiplying the hourly travel time estimates from Table 2, β_t^{TP}, by the average hourly HOV travel time TT_t^{HOV}, average hourly HOV flow C_t^{HOV}, average carpool vehicle occupancy, P^{HOV}, the value of time for carpoolers VOT_C, and aggregating to the yearly number of trips gives the total *cost-side congestion interaction effect* as:

(3) $\Delta W^{CSCI} = \sum_t[\beta_t^{TP} \cdot TT_t^{HOV} \cdot C_t^{HOV}] \cdot P^{HOV} \cdot T \cdot VOT_C$.

Rent Effect—The *rent effect* represents the rents generated by HOV lane access through the CAVS stickers. Ownership of a stickered hybrid allows access to the HOV lane without incurring the transaction cost of carpool formation. If travel time in the I-10W mainline lane is in equilibrium with other travel options, the rent generated is equal to the difference in travel time between the mainline and

[12] However, as noted in Section IV, our estimates of the number of hybrid drivers entering the HOV lane are consistent with observational vehicle counts conducted by Caltrans, suggesting that while broken carpools are a possibility, the empirical magnitude of this effect is likely very small. Consider a hypothetical scenario where Caltrans observed several thousand hybrids using the HOV lane each hour, while our travel time estimates only suggested a small increase in hybrids of several hundred. This would be evidence of carpools breaking in response to hybrids entering the HOV lane.

HOV lanes, reflected by the area apdq-erhs in Figure 4.[13] The marginal effect in Section VI is $\nu_{\overline{H}}(T_H - T_{ML})$. Integrating over the change in HOV lane vehicles gives the total effect $\int_{C_C}^{C_C+\overline{H}} \nu_{\overline{H}}(T_H - T_{ML})\, dC_H \cong \overline{H}\nu_{\overline{H}}(T_H - T_{ML})$.[14]

The maximum willingness-to-pay for a CAVS sticker is thus the hourly difference in travel times between the HOV, TT_t^{HOV}, and mainline lanes, TT_t^{ML}, multiplied by the value of time for hybrid drivers VOT_H, and aggregated to the yearly level. Multiplying this maximum willingness-to-pay for a sticker times the number of hybrids per hour entering the HOV lane, ΔC_t^{HOV}, gives the total *rent effect* as:

(4) $$\Delta W^R = \sum_t [\Delta C_t^{HOV} \cdot (TT_t^{HOV} - TT_t^{ML})] \cdot T \cdot VOT_H.$$

Estimated changes in travel time in off-peak hours were not consistently positive, and thus we have assumed all congestion interaction effects are zero during these off-peak periods.

Another potential rent generated by the CAVS sticker would come from increased reliability, if travel time in the HOV lane experienced less variability than their original route. Even though we omit these benefits from our central estimates, we describe the calculation of the reliability benefits following the procedure in Small, Winston, and Yan (2005). Hourly reliability measures for the I-10W HOV lane and mainline lanes were calculated as the hourly differences between the 50th and 80th percentiles of the travel time distribution. The difference in reliability between the two lanes, R_t, represents the reliability

13 To generate rents larger than this amount, drivers would have to be worse off in their pre-policy choice than in the pre-policy 1-10W mainline.

14 Note we have simplified things slightly as T_H and T_{ML} are functions of the number of HOV lane vehicles, which we ignore in the integration. In the calculation below, we use the travel time differential pre-policy to calculate the welfare benefit to hybrid drivers of HOV lane access.

benefits that hybrids would receive if they moved from the mainline to the HOV lane. The following equation determines the aggregate reliability benefits:

(5) $\sum_t [\Delta C_t^{HOV} \cdot R_t] \cdot T \cdot VOR$

where VOR is the value of reliability.

System-wide Congestion Interaction Effect—The final congestion interaction is the *system-wide congestion interaction effect*, representing the congestion relief benefits for all other drivers in the transportation system due to the CAVS policy. Initially, the calculation of this welfare effect may appear nearly impossible, as hybrid drivers exiting their initial route choice for the I-10W HOV lane can generate a large set of behavioral adjustments in the transportation system, altering congestion levels for a huge number of agents. Nonetheless, as we show in Appendix C, the *system-wide congestion interaction effect* can, under reasonable assumptions, be upper-bounded by the *partial equilibrium congestion interaction effect* ΔW^{PECI}, defined as the congestion relief benefits for I-10W mainline drivers, and given by the area btuc in Figure 4. In Section VI, the marginal effect is given by $-\nu_{ML} N_{ML} \frac{dT_{ML}^{'''\,'}}{dN_{ML}}$. Integrating over the change in the number of HOV lane vehicles gives the total effect as: $\int_{C_C}^{C_C+\bar{H}} -\nu_{ML} N_{ML} \frac{dT_{ML}^{'''\,'}}{dN_{ML}} dC_H = \int_{C_C}^{C_C+\bar{H}} \nu_{ML} N_{ML} dT_{ML}^{'''} \cong \nu_{ML} N_{ML} (T_{ML}(C_C + \bar{H}) - T_{ML}(C_C))$. This is the number of mainline vehicles times the value of the difference in mainline travel time pre- and post-policy.[15]

To actually calculate the upper-bound *partial equilibrium congestion interaction effect*, we evaluate a scenario where all hybrids entering the I-10W

[15] For simplicity we ignore the fact that N_{ML} is a function of the number of HOV lane vehicles and simply use the number of mainline vehicles pre-policy for the calculation below.

HOV lane originated in the I-10W mainline. This scenario is simulated by removing ΔC_t^{HOV} vehicles (the number of hybrids entering the HOV lane from Equation (3)) from the mainline, and calculating the corresponding change in mainline travel time.[16] The remaining mainline drivers would then receive a benefit equal to the difference in mainline travel time pre- and post-policy. The total *partial equilibrium congestion interaction effect,* given an occupancy of P^{ML} for mainline vehicles, is thus given by:

$$(6) \qquad \Delta W^{PECI} = \sum_t \left[\frac{\Delta C_t^{HOV}}{C_t^{ML}} \cdot \epsilon^{SO} \cdot \epsilon^{OC} \cdot TT_t^{ML} \cdot C_t^{ML} \right] \cdot P^{ML} \cdot T \cdot VOT_O.$$

Finally, we note this upper bound on the *system-wide congestion interaction effect* is likely a substantial overestimate of the true congestion relief benefits, as the number of hybrids entering the HOV lane as a result of this policy is dwarfed by the total traffic volume in the area. Therefore, it is likely that there are a sufficient number of drivers on uncongested alternatives such as free-flowing secondary routes and surface streets to fill any route that experiences a decrease in congestion due to the CAVS policy, effectively returning mainline lane travel times to the pre-policy equilibrium.[17] We also note that these benefits upper-bound the welfare gained by any drivers taking new trips (new VMT) in response to hybrids exiting for the HOV lane.[18]

Emissions Interaction Effect—The final interaction effect to consider is the *emissions interaction effect* ΔW^{EI} associated with the increase in emissions from

[16] Note that this calculation only requires the estimated number of hybrids entering the I-10W HOV lane and does not require the (noisy) mainline estimates in Section IV. While the detector level traffic flow analysis in Section V finds that this outcome (decreased mainline traffic flow) is not the observed equilibrium, this simulation allows us to bound the possible congestion relief benefits that may be widely distributed across the city as a result of hybrids moving into the I-10W HOV lane.

[17] This is shown more formally in Appendix C, where the presence of uncongested, outside alternative travel options drives the *system-wide congestion interaction effect* to zero.

[18] To achieve benefits larger than this amount, a new driver would have to be worse off, pre-policy, by not driving than in the pre-policy 1-10W mainline.

induced new VMT, as reflected by the area abvw in Figure 4. Given an elasticity of new VMT, σ, the induced number of trips and thus emissions are calculated, yielding the *emissions interaction effect:*

$$(7) \quad \Delta W^{EI} = \sigma N_H \left(\frac{CO2}{mpg_F} MSD_{GHG} + NOx_F MSD_{NOX} + HC_F MSD_{HC} \right) \cdot (1.102x10^{-6}) L \cdot T.$$

B. Parameter Assumptions

The welfare calculations rely on the estimates from Sections IV-V, additional PeMS and Caltrans data and parameters from the literature presented in Table 5. As noted above, a key input into our calculations is the hourly regression discontinuity estimates of the effects of the CAVS policy effect on peak period travel time from Table 2. Below, we discuss the additional parameters used to supplement our analysis.

Policy and Travel Characteristics—The hourly number of drivers on the I-10W is gathered from PeMS, and we assume that each driver is making 260 trips per year along the 17.5 mile route. Based on Caltrans observations, we assume carpools in the I-10 HOV lane have average occupancy of 3.1 people, carpools in other HOV lanes in California have average occupancy of 2.2 people, and mainline vehicles have average occupancy of 1.1 people. Based on observational evidence from Caltrans, we assume that existing carpoolers did not break their carpools in response to the policy.[19] The CAVS policy was in effect for 5.86 years (August 20th, 2005 to June 30th, 2011) and new vehicles are assumed to last twelve years. We initially assume that all CAVS stickers led to new hybrid purchases and perform sensitivity analysis on this assumption below. To some extent, this is a

[19] Caltrans observers determined the average number of occupants per vehicle in the carpool and mainline lanes in the *2007 HOV Annual Report*, Caltrans District 7.

rather extreme assumption, as Diamond (2009) and Gallagher and Muehlegger (2011) find no evidence that the CAVS policy stimulated hybrid purchases.

Value of Time and Reliability—The value of time is assumed to equal to 93% the wage rate in Los Angeles, based on Small, Winston, and Yan (2005).[20] As the authors note, this is a higher fraction of the wage rate than suggested in other studies, and therefore sensitivity analysis of this parameter is performed in the appendix below. Using 2009 NHTS data we determined the average income for HOV owners, carpoolers and other commuters, which when multiplied by 93% gives a value of time of $32.86 for HOV owners, and a value of time of $20.87 for all other drivers.[21] For the reliability calculations, we use $19.56 as the estimated value of reliability for drivers in Southern California, based on Small, Winston, and Yan (2005).

Elasticity of New VMT—While our estimates in Section V suggest the existence of induced demand, we cannot a priori distinguish between new VMT and other sources of induced demand, requiring us to use estimates from the literature. The elasticity of new VMT with respect to an increase in capacity is assumed to be 0.15, which Hymel, Small and Van Dender (2010) consider the short-run elasticity best supported by the existing literature. In the sensitivity analysis below, we perform sensitivity analysis, varying this elasticity between 0 and 1.

Fuel Economy—We assume hybrid vehicles achieve 45 miles per gallon (the lower bound required to receive an HOV lane sticker), while the vehicles they

[20] Small, Winston and Yan's (2005) value of time was estimated for commuters in Los Angeles County, rendering it especially appropriate.

[21] This is consistent with consumer surveys, such as J.D. Power's 2004 automobile survey, which have found that hybrid drivers tend to be older, whiter, more affiliated with the Democratic Party and wealthier than the average driver (new buyers of hybrid vehicles had average incomes of $100,000 compared to $85,000 for non-hybrid buyers).

replace receive 20 miles per gallon, based on fleet averages.[22] To mimic potential future effects of plug-in hybrid electric vehicles (PHEV), in the sensitivity analysis below we consider alternative values of fuel economy – 96 miles per gallon for the EPA average fuel efficiency of the Chevy Volt and Nissan Leaf.

Emissions per Mile and Social Cost of Emissions— We use the EPA's value of 8,788 grams of greenhouse gases (CO_2 equivalent) per gallon of gasoline for the emissions per gallon by all vehicle types.[23] Based on EPA Tier II standards, NOx emissions from regular vehicles are assumed to be 0.07 grams/mile and hydrocarbon emissions from regular vehicles are assumed to be 0.09 grams/mile. California SULEV standards require hybrid NOx and hydrocarbon emissions to be less than 0.02 grams/mile and 0.01 grams/mile respectively. The discount rate is assumed to be 3%, implying a marginal social damage of greenhouse gas emissions of $21 per ton.[24] Social costs of NOx and hydrocarbons are assumed to be $15,000/ton and $4,100/ton, consistent with Small and Kazimi (1995), Parry and Small (2005) and Parry, Walls, and Harrington (2007).[25]

C. Additional Welfare Results

Section VI presents our central estimates of the distributional and welfare effects of the CAVS policy. Here, we explore the robustness of our central results under alternative econometric specifications and parameter assumptions.

[22] An EPA report, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2009*, finds that average fuel economy in 2004 was 19.3 miles-per-gallon.

[23] See http://www.epa.gov/otaq/climate/420f05001.htm for details on CO_2 calculations.

[24] $21 per ton is the central estimate of the US Interagency Working Group On Social Cost Of Carbon (http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf). It should be noted that the ultimate benefits and costs of the policy (and qualitative conclusions) are relatively invariant to changes in emissions. Larger social cost estimates, such as $85 per ton as suggested by Stern (2006) would only lead to slight changes in the final welfare calculations (see Nordhaus (2007) for discussion on social discounting and why Stern's estimates are inconsistent with real interest and savings rates).

[25] Recent estimates from Muller and Mendelsohn (2007) suggest social costs more than an order of magnitude smaller; given the small contribution of emissions changes to the total welfare effect of the CAVS policy, using these smaller values would result in trivial welfare consequences of changes in local air pollutants.

Econometric Specifications—Table E.25 in Appendix E reports the net welfare effect of the CAVS policy on the I-10W across alternative RD specifications.[26] For each specification, the travel time effect of the policy by hour is estimated as in Table 2, and the welfare effects are calculated as in Table 6. When the *system-wide congestion interaction effect* is excluded, the net welfare effect of the policy is negative across all scenarios regardless of specification, and ranges from -$2 to -$3.9 million dollars. Including the *system-wide congestion interaction effect* still results in negative net welfare across specifications, ranging from -$800,000 to -$1.9 million dollars. Note that the ultimate welfare effect of the policy is more or less invariant with respect to changes in emissions; congestion costs and benefits are orders of magnitude larger than the welfare effects of the changes in emissions.

In general, the various welfare effects are roughly consistent in magnitude to the values presented in Table 6 for an eighth-order polynomial, although the welfare effects under local linear regression tend to be generally smaller. While there is some heterogeneity in the magnitude of the various effects across polynomial orders, the transfer ratio is remarkably stable, varying from 3.31 to 3.46 (5.91-6.13 excluding the *system-wide congestion interaction effect*), with the local linear regression yielding a slightly smaller transfer ratio of 2.62 (4.83). Thus, the results of Section VI, which find that congestion interaction effects are the dominant welfare effect, are robust across econometric specifications.

Alternative Parameter Assumptions (Central results)—Next, we explore the sensitivity of our central results to alternative parameter assumptions. In particular, we examine the distribution of our estimates of the net welfare effect, accounting for econometric uncertainty alone, external model parameter

[26] In addition to the central estimates, the table also displays the welfare calculations using the seventh-ninth order polynomial specifications, the BIC selected specification, and a local linear specification.

uncertainty alone, and both sources of uncertainty jointly. Figure D.11 in Appendix D displays the distribution of net welfare effects, with and without the system-wide congestion interaction effect, where the travel time effect of the CAVS policy from Table 2 is drawn from the estimated distribution.[27] In either case, the vast bulk of the distribution is negative (less than 1% positive), and the 95% confidence interval does not include zero. The top panel of Figure D.12 in Appendix D displays the distribution of net welfare effects where the external model parameters are drawn from uniform distributions, with the value of time ranging from 0.5 to 1.0 of wage rate, fuel economy of fleet vehicles ranging from 10 to 30 mpg, fraction of hybrids with stickers purchased because of the policy ranging from 0 to 1, induced demand ranging from 0 to 1 and the elasticity of new VMT ranging from 0 to 1. Strikingly, regardless of the parameter draw, the net welfare effect is always negative. The bottom panel of Figure D.12 in Appendix D displays the distribution of net welfare effects where both the econometric estimates and the external parameters are varied. Again, the vast bulk of the distribution is negative (less than 1% positive), and the 95% confidence interval does not include zero. Thus, we can strongly conclude that our main result, that the net welfare effect of the CAVS policy was negative, is robust to both econometric and parametric uncertainties.

Alternative Parameter Assumptions (State-wide results)—Finally, we will examine the state-wide cost per ton of greenhouse gas emissions reductions under alternative assumptions regarding the fraction of stickered hybrids purchased because of the policy (δ), the elasticity of new VMT (σ), the value of time as a percentage of the wage rate (VOT), and the fuel-economy of vehicles receiving

[27] While in principle, one could draw from each distribution for each hourly estimate. However, as the hourly estimates are unlikely independent, we draw a single draw from a normal distribution and apply that draw to the estimated distribution of each hourly estimate. In essence, each hourly estimate is either above or below the mean of its distribution by the same amount, which will produce a conservative estimate of the confidence interval of the estimated net welfare effect.

HOV access stickers (MPG). Recall that in Section VI, we reported the state-wide cost per ton of greenhouse gas emission reductions as \$125, under the most favorable assumptions that $\delta = 1$, $\sigma = 0$, $VOT = 93\%$ of the wage rate, and $MPG = 45$.

Before discussing the results of varying these key parameters, we first describe the methodology used to calculate the state-wide cost per ton of emission reductions. While the analysis above calculates the primary welfare gain and interaction effects of the CAVS policy for a one-way commute on the I-10W, here we calculate back-of-the-envelope estimates for the welfare effects across the state of California.[28] However, because the I-10W is a particularly congested freeway, it would be inappropriate to simply scale up the estimated welfare effects calculated above. Thus, we proceed by making two strong assumptions. First, the distribution of effects per sticker throughout the state is assumed to be identical to the estimated heterogeneous distribution of traffic flow effects in Los Angeles from Section V (displayed in Figure 3). Second, the interaction effects are assumed to scale linearly with the estimated traffic flow effect. From above, the net interaction effect for the I-10W is -\$3482 per hybrid for a two-way commute, including the *system-wide congestion interaction effect*. Finally, because this represents the net interaction effect of a hybrid on the 3+ HOV lane of the extremely congested I-10W, the interaction effect per hybrid is adjusted downward to -\$1498 to represent average mainline congestion and the 2+ occupancy requirement on most of the HOV lanes in California.[29] Linearly scaling this value to the traffic flow effect for the I-10W (9.6%), and integrating over the distribution in Figure 3 yields the state-wide interaction effect of the

[28] For the calculations to follow, we consider only the welfare effects of the initial 75,000 stickers distributed under the CAVS program, on the grounds that it is the effect of these initial stickers that is captured in our empirical estimates.

[29] Caltrans observations suggest an average HOV lane vehicle occupancy of 2.2 on 2+ HOV lanes which implies smaller aggregate congestion costs for carpoolers. The average freeway in District 7 has 85% as much flow as the I-10W, implying smaller aggregate congestion relief benefits for all other drivers.

policy. Under central estimates, the state-wide interaction effect of the policy is negative, at -\$67 million dollars annually, with a present value over the policy lifetime of -\$362 million dollars.

We also consider the state-wide, upper-bound on the primary welfare gain and reduction in emissions. Assuming that 75,000 hybrids induced by the policy state-wide drive 12,000 miles per year, this would reduce greenhouse gas emissions by roughly 250,000 tons per year, NOx emissions by 50 tons per year, and hydrocarbon emissions by 60 tons per year under average driving conditions.[30] This gives a hypothetical annual state-wide primary welfare gain of \$6.1 million dollars. Over the lifetime of a hybrid vehicle, this corresponds to present value benefits of \$60 million dollars. Dividing the state-wide interaction effect by the upper-bound reduction in emissions gives the best-case cost per ton of GHG emissions reductions of \$125 per ton, with costs per ton of NOx and hydrocarbon reductions of \$606,000 dollars and \$505,000 dollars.

Several scenarios of the stimulative effects of the CAVS policy on the adoption of new hybrids are considered: $\delta = 1/3$, $2/3$, and 1. The case of $\delta = 1/3$ represents a scenario that accounts for the fact that two-thirds of stickers were received by preregistered hybrids, and thus are assumed to not have stimulated new purchases. Several scenarios that vary the elasticity of new VMT are also considered, with $\sigma = 0.15$, 0.50, and 1.00. $\sigma = 0.15$ represents our central estimate based on the short-run elasticity from Hymel, Small, and Van Dender (2010), $\sigma = 0.50$ is similar to the long-run elasticity from Hymel, Small, and Van Dender (2010), and $\sigma = 1$ is based on Duranton and Turner (2011) who find a long-run elasticity of unity. Value of time scenarios range from 50% of wage rate

[30] To the extent that these hybrids would also be reducing their individual emissions when making other trips, this underestimates the true emissions savings. On the other hand, we also assume that there is no “rebound effect” from increased fuel-efficiency leading to more driving, which would reduce greenhouse gas savings (Small and Van Dender (2007) find the importance of this effect has declined over time). Furthermore, we assume that hybrid purchases replace an average fuel-economy vehicle. To the extent that hybrid drivers already owned fuel-efficient vehicles, greenhouse gas savings would be further reduced.

to 93% of wage rate, and mile-per-gallon standards for vehicles receiving stickers range from 45 MPG (representing hybrid-electric vehicles), 95 MPG (representing newer technologies such as the Chevy Volt and Nissan Leaf), and 145 MPG.

Table E.26 in Appendix E reports the state-wide cost per ton of greenhouse gas reductions while varying the key parameters δ, σ, VOT, and MPG, where δ = 1, σ = 0.15, VOT = 90% of wage rate, and MPG = 45 unless otherwise specified. Reducing the fraction of hybrids stimulated by the policy dramatically increases the cost of the policy, with cost per ton reaching several thousand dollars when $\delta = 1/3$. Similarly, increasing the elasticity of new VMT means more vehicles are induced into driving, offsetting the emission savings from hybrids and increasing the cost of the policy. In fact, for σ > 0.55, emission increases from induced new VMT more than offsets emission reductions, leading to infinite costs of emission reductions. On the other hand, reducing the value of time decreases cost per ton, as the congestion interaction effects become less important in magnitude, though the cost per ton is still substantial at 50% of wage rate. Finally, increasing the fuel-economy of vehicles receiving stickers reduces the cost of the policy at a diminishing rate. Allocating stickers to the new Chevy Volt and Nissan Leaf would have a cost per ton of emissions reduction of $108. Somewhat surprisingly, even if the vehicles receiving stickers were completely emission free, the cost per ton of the policy would still be $97 per ton, reflecting the magnitude of congestion costs per vehicle relative to emissions costs per vehicle. Finally, we note that Table E.26 also reports estimates that exclude the system-wide congestion effect or use long-run estimates from Section V. In both cases, the cost per ton increases relative to the best-case estimates.

Appendix C. Upper bound on system-wide effects

Here, we demonstrate that under reasonable assumptions, the *partial equilibrium congestion interaction effect* is an upper-bound on the *system-wide congestion interaction effect*, as discussed in Appendix B. Consider a scenario where we have a fast and direct route (*m*) such as the I-10 between points A and B, and a number (*n*) of alternative options (*o*) that are either longer in distance, slower to travel, or at a less preferred time of day.

Nash equilibrium versus social optimum—We first compare, in general, the allocation of commuters under Nash equilibrium versus the social optimum. Suppose that travel time on route *i* is given by the following form:

$$(8) \qquad TT_i = \alpha_i + f(C_i)$$

where $f(C_i)$ represents the convex congestion function such that $f'(C_i) > 0$, $f''(C_i) > 0$. We will assume that all *o* routes have identical free-flow and congestion functional forms, and that the direct route is fastest in free-flow, such that $\alpha_m < \alpha_o$.[31] We will assume that there are $\bar{C}$ people wishing to travel from point A to point B, such that $C_m + nC_o = \bar{C}$.

Nash Equilibrium requires that travel time be equilibrated across all routes, such that no driver could improve his well-being by utilizing a different route, and all drivers are allocated. Thus:

$$(9) \qquad \alpha_m + f(C_m) = \alpha_o + f(C_o) \quad \text{and} \quad C_m + nC_o = \bar{C}.$$

[31] In LA, routes with HOV lanes are generally heavily congested, (see Table E.24 in Appendix E), following from the fact that transportation authorities often site HOV lanes on the most congested routes.

Simply rearranging terms yields: $(\alpha_m - \alpha_o) + \big(f(C_m) - f(C_o)\big) = 0$, and because $\alpha_m < \alpha_o$, if follows that $f(C_m) > f(C_o)$ and thus $C_m^* > C_o^*$ under Nash.

How does the social planner's allocation of drivers compare to the Nash outcome? A social planner would choose C_m and C_o in order to minimize aggregate travel time:

$$(10) \quad \min C_m(\alpha_m + f(C_m)) + nC_o(\alpha_o + f(C_o)) \quad \text{st.} \quad C_m + nC_o = \bar{C}.$$

Recognizing that $C_o = \frac{\bar{C} - C_m}{n}$ and differentiating with respect to C_m yields the first-order condition that:

$$(11) \quad (\alpha_m - \alpha_o) + \big(f(C_m) - f(C_o)\big) + C_m f'(C_m) - C_o f'(C_o) = 0$$

If we consider the Nash allocation of commuters, the first two terms disappear, leaving the term $C_m f'(C_m) - C_o f'(C_o)$ which is greater than zero as $C_m^* > C_o^*$. Thus, for the optimal condition to hold, the social planner would remove vehicles from the fast, direct route (relative to the Nash level) and add vehicles to the other routes, such that $C_m^* > C_m^S$ and $C_o^* < C_o^S$.

Thus, the Nash number of vehicles in the fast, direct route exceeds the socially optimal level, and the number of vehicles in the slower, circuitous routes is too small. Consider a partial equilibrium scenario where a fraction of vehicles are removed from the direct route, and drivers do not re-optimize their travel choices. This would clearly constitute a welfare gain for the remaining drivers as travel times improve. Now consider a general equilibrium scenario where this improved travel time caused drivers to re-optimize. Cars would move from the slow, circuitous routes to the direct route, further reducing the number of cars on the circuitous routes relative to the social optimum. Simultaneously, the number of cars on the direct route would also increase, also moving away from the social optimum. Thus, the partial equilibrium welfare gain is eroded as drivers re-optimize, implying that the partial equilibrium welfare gain will upper-bound the general equilibrium welfare gain.

Nash equilibrium versus social optimum (linear)—To solidify the above results, suppose that travel time on route *i* is given by the following linear form:

(12) $TT_i = \alpha_i + f(C_i) = \alpha_i + b_i C_i$

where α_i is free-flow speed, and $b_i C_i$ is the increase in travel time due to congestion from cars C_i using route *i*.

Nash Equilibrium requires that travel time be equilibrated across all routes, such that no driver could improve his well-being by utilizing a different route, and all drivers are allocated. Thus:

(13) $\alpha_m + b_m C_m = \alpha_o + b_o C_o$ and $C_m + nC_o = \bar{C}$.

Calculating the equilibrium number of cars on each type of route, we have:

(14) $C_m^* = \frac{\bar{C}b_o + (\alpha_o - \alpha_m)n}{b_o + b_m n}$ and $C_o^* = \frac{\bar{C}b_m + \alpha_m - \alpha_o}{b_o + b_m n}$.

Not surprisingly, as long as $\alpha_m < \alpha_o$, there will be more vehicles using the direct, fast route *m*.

We begin by comparing the Nash Equilibrium solution above with the optimal allocation of cars between *m* and *o*. A social planner would choose C_m and C_o in order to minimize aggregate travel time:

(15) $\min C_m(\alpha_m + b_m C_m) + nC_o(\alpha_o + b_o C_o)$ st. $C_m + nC_o = \bar{C}$.

Solving for the optimal number of cars on each route we have:

(16) $C_m^S = \frac{2\bar{C}b_o+(\alpha_o-\alpha_m)n}{2(b_o+b_m n)}$ and $C_o^S = \frac{2\bar{C}b_m+\alpha_m-\alpha_o}{b_o+b_m n}$.

Comparing the Nash Equilibrium with the social optimum we have:

(17) $C_m^* - C_m^S = \frac{n(\alpha_o-\alpha_m)}{2(b_o+b_m n)} > 0$ and $C_o^* - C_o^S = \frac{\alpha_m-\alpha_o}{2(b_o+b_m n)} < 0$

and we see that there are too many cars in *m* and too few cars in *o* under the Nash Equilibrium. Thus, removing cars from the *m* route will provide some congestion relief, which we explore below.

We now consider two scenarios: First, a partial equilibrium where hybrid drivers leave *m,* no other drivers adjust and the remaining drivers on *m* receive congestion relief. Second, a general equilibrium where hybrid drivers leave *m,* all other drivers adjust, moving the system to a new equilibrium.

What is the partial equilibrium welfare gain from removing a fraction φ of drivers C_m^* from *m*? For simplicity, we measure the welfare gain by the change in travel time times the number of drivers, which is given by:

(18) $$\Delta W^{PECI} = (1-\varphi)C_m^*[(\alpha_m + b_m C_m^*) - (\alpha_m + b_m(1-\varphi)C_m^*)] = \frac{b_m[\bar{C}b_o+(\alpha_o-\alpha_m)n]^2(1-\varphi)\varphi}{(b_o+b_m n)^2}$$

or the remaining drivers times the difference between mainline travel times pre and post removal of vehicles.[32]

Now suppose we remove $\varphi \cdot C_m^*$ from route *m*, and let all drivers readjust to the new general equilibrium. The new Nash Equilibrium is given by:

(19) $\alpha_m + b_m C_m = \alpha_o + b_o C_o$ and $C_m + nC_o = \bar{C}$ - φC_m^*.

[32] To convert into dollar terms, one can simply multiply the aggregate change in travel time by the value of time VOT, as in Appendix B.

which can be solved to yield C_m^{GE} and C_o^{GE} , similar to Equation (17). The total welfare effect in this general equilibrium case is:

$$(20) \qquad \Delta W^{SWCI} = (C - \varphi C_m^*)[(\alpha_m + b_m C_m^*) - (\alpha_m + b_m(1-\varphi)C_m^*)] = \frac{b_m b_o(\bar{C}b_o + (\alpha_o - \alpha_m)n)\varphi[(\alpha_m - \alpha_o)n\varphi + \bar{C}(b_o + b_m n - b_o\varphi)]}{(b_o + b_m n)^3}.$$

If the *partial equilibrium congestion interaction effect* is an upper bound on the *system-wide congestion interaction effect*, then $\Delta W^{PECI} - \Delta W^{SWCI} > 0$.

$$(21) \qquad \Delta W^{PECI} - \Delta W^{SWCI} = \frac{b_m n(\bar{C}b_o + (\alpha_o - \alpha_m)n)\varphi(\alpha_o - \alpha_m)((b_o + b_m n) - b_m(\bar{C}b_o + (\alpha_o - \alpha_m)n)\varphi)}{(b_o + b_m n)^3}$$

A priori, this expression cannot be precisely signed. Nonetheless, we can say something about this difference under "reasonable" conditions. In particular, consider a situation analogous to the I-10W where we have many alternative routes to the direct I-10W route, and the number of hybrids removed from mainline traffic is small relative to the total number of cars.

First, suppose that *n,* the number of other routes, is very large. Then Equation (21) becomes:

$$(22) \qquad \lim_{n\to\infty} \Delta W^{PECI} - \Delta W^{SWCI} = \frac{(a_m - a_o)^2(1-\varphi)\varphi}{b_m} > 0$$

Further intuition can be gained by looking at the limits of Equations (18) and (20) which are: $\lim_{n\to\infty} \Delta W^{PECI} = \frac{(a_m - a_o)^2(1-\varphi)\varphi}{b_m} > 0$ and $\lim_{n\to\infty} \Delta W^{SWCI} = 0$. Thus, as the number of alternative routes increases, the partial equilibrium effect remains positive, while the system-wide effect goes to zero.

Next, suppose that the fraction of drivers removed from the mainline is relatively small, such that $0 < \varphi \ll 1$. If φ is small, then any higher order terms are approximately zero, such that:

$$(23)\quad \Delta W^{PECI} - \Delta W^{SWCI}|_{\varphi \ll 1} = \frac{b_m n(\bar{C}b_o + (\alpha_o - \alpha_m)n)\varphi(\alpha_o - \alpha_m)(b_o + b_m n)}{(b_o + b_m n)^3} > 0.$$

Thus, as long as the number of hybrids removed from mainline lanes is small relative to total traffic levels, the partial equilibrium effect is an upper-bound on the system-wide effect.[33]

Thus, we have shown that ΔW^{PECI} represents an upper-bound on ΔW^{SWCI} if: A) Free-flow travel time on mainline routes with HOV lanes present are faster than free-flow travel time on other routes, and B) *Any* one of the following hold: i) The number of alternative routes is large; ii) The number of vehicles removed from mainline lanes is small; or iii) An uncongested outside alternative exists.[34] These represent sufficient conditions establishing I-10W mainline congestion relief benefits as an upper-bound on welfare benefits for all other drivers in the freeway system.

[33] We have assumed a linear functional form for analytical tractability. To ensure that the results to follow are not driven by this assumption, a Monte Carlo analysis was conducted using a quadratic functional form of Equation (14). For all 10,000 runs, the partial equilibrium effect always exceeded the general equilibrium effect, with parameters drawn from the following distributions: $a_m \in [10,15]$, $a_o \in [20,25]$, $b_m, b_o \in [1.2 * 10^{-7}, 1.6 * 10^{-7}]$, $n \in [8,14]$, $\varphi \in [0.01,0.05]$ and $\bar{C} = 50{,}000$.

[34] While not formally proven here, the presence of an uncongested alternative route implies that drivers will simply divert from the uncongested option to the lanes vacated by hybrids. As Vickrey (1969, p. 257) notes in discussing the enlargement of a bottleneck in the presence of an uncongested, circuitous option, "An enlargement of the bottleneck under these conditions will, if it falls short of being able to accommodate all of the traffic, simply result in enough traffic being diverted from the circuitous route to the enlarged bottleneck route to maintain the queue at the former level. The enlargement may thus produce no improvement in travel times at all, at least during periods of peak traffic." Note, this case also includes new VMT created by the capacity expansion. Drivers induced into the freeway system will gain at most the partial equilibrium welfare gain. Were these drivers able to gain more, they would have used the I-10W before the policy.

APPENDIX REFERENCES

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Appendix D. Additional Figures

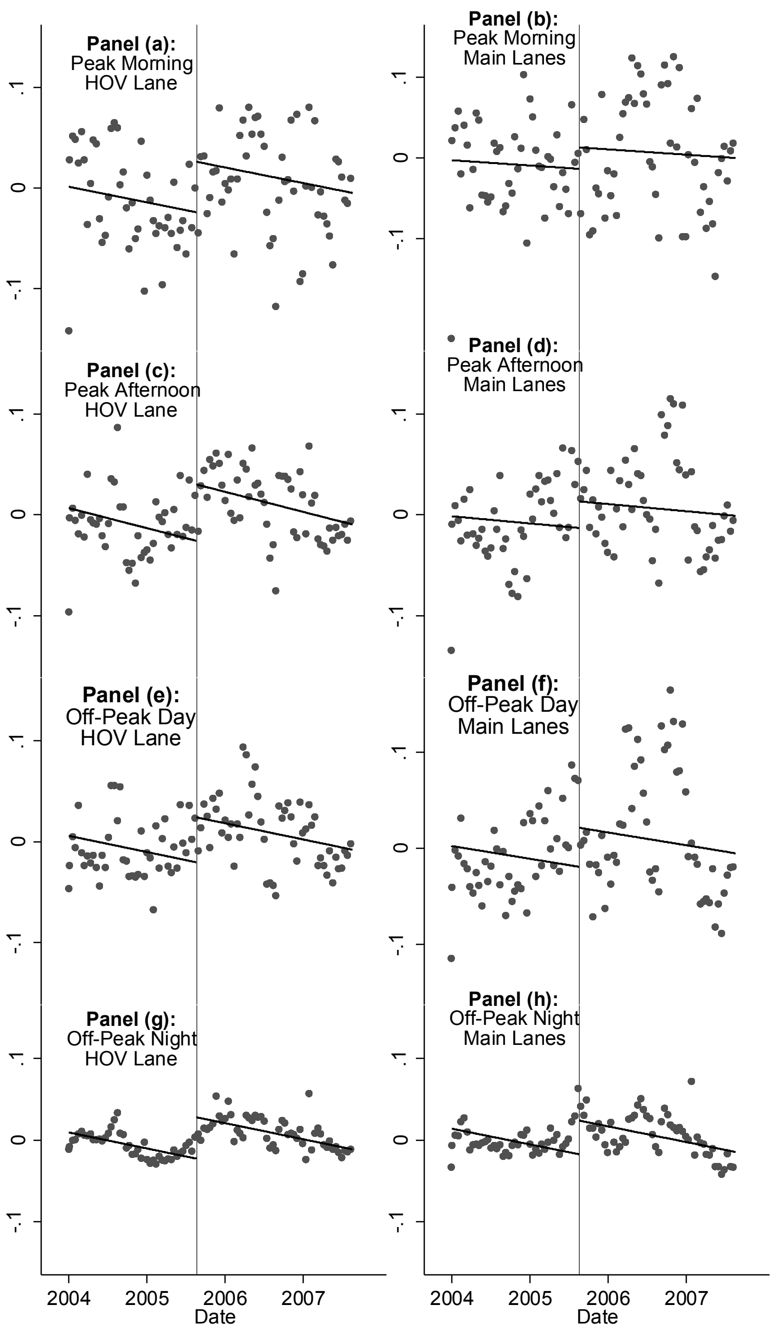


FIGURE D.1. INTERSTATE 10 W TRAVEL TIME: FIRST ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and an first-order polynomial on date.

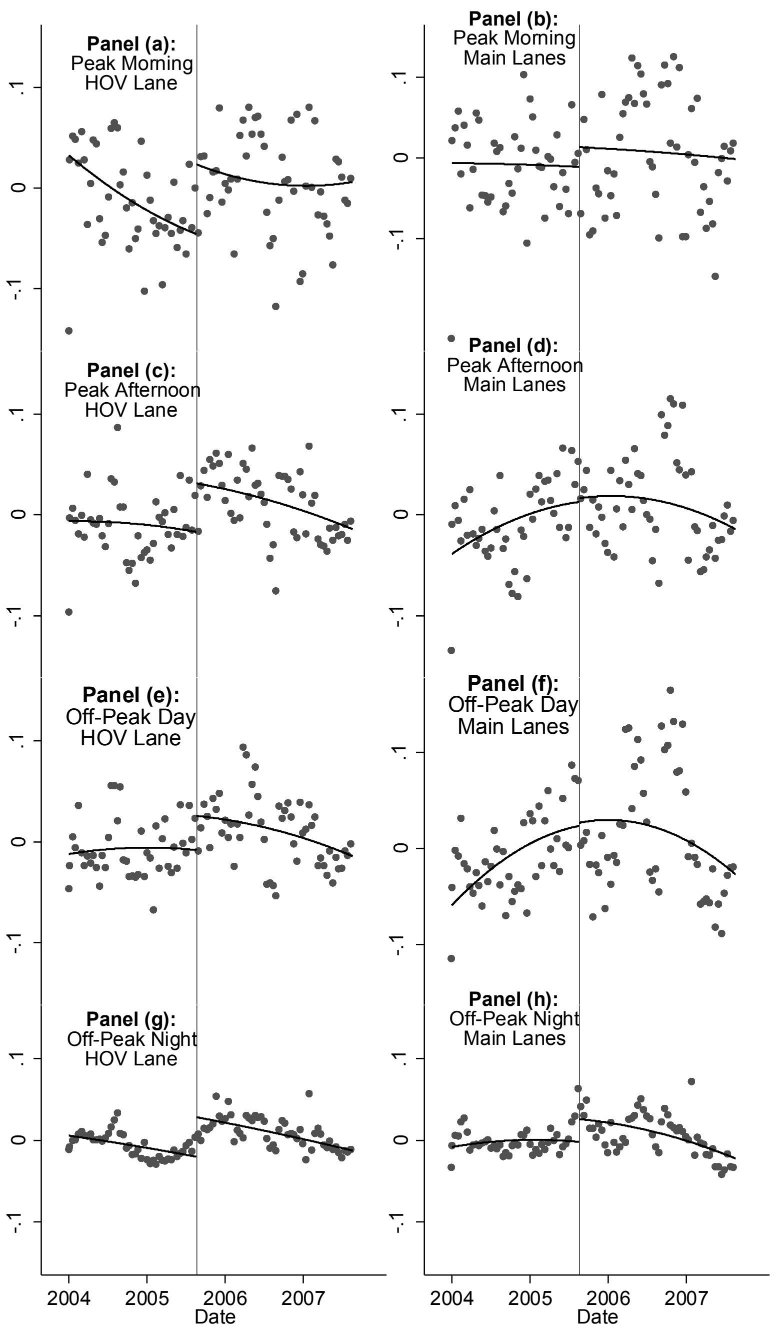


FIGURE D.2. INTERSTATE 10 W TRAVEL TIME: SECOND ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a second-order polynomial on date.

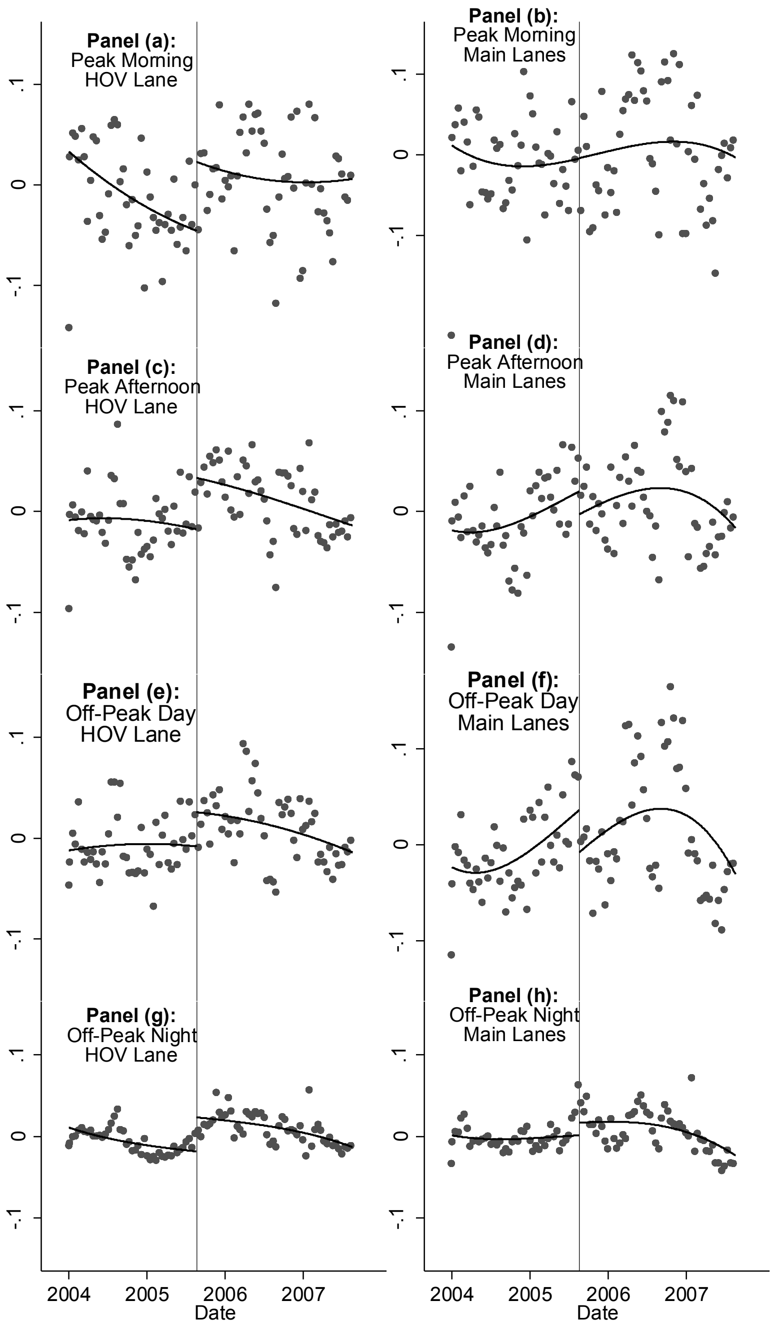


FIGURE D.3. INTERSTATE 10 W TRAVEL TIME: THIRD ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a third-order polynomial on date.

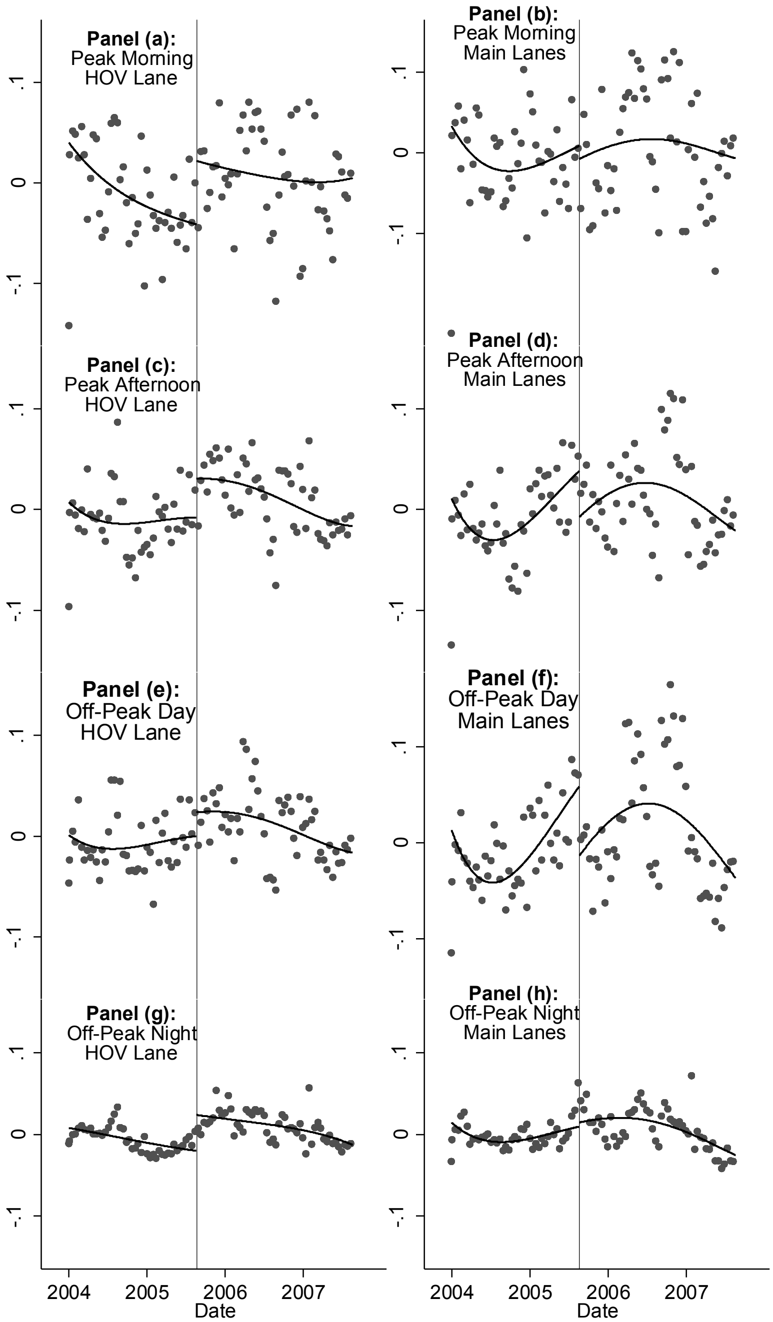


FIGURE D.4. INTERSTATE 10 W TRAVEL TIME: FOURTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a fourth-order polynomial on date.

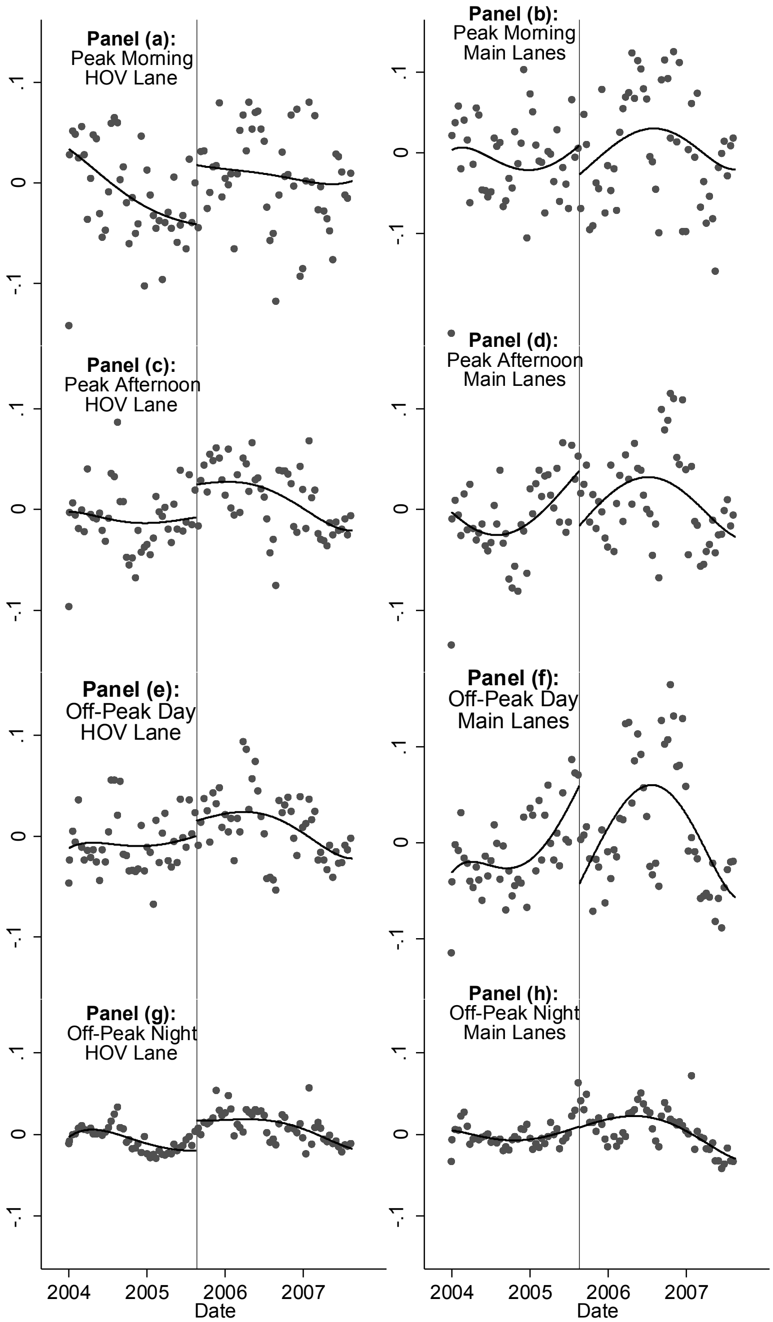


FIGURE D.5. INTERSTATE 10 W TRAVEL TIME: FIFTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a fifth-order polynomial on date.

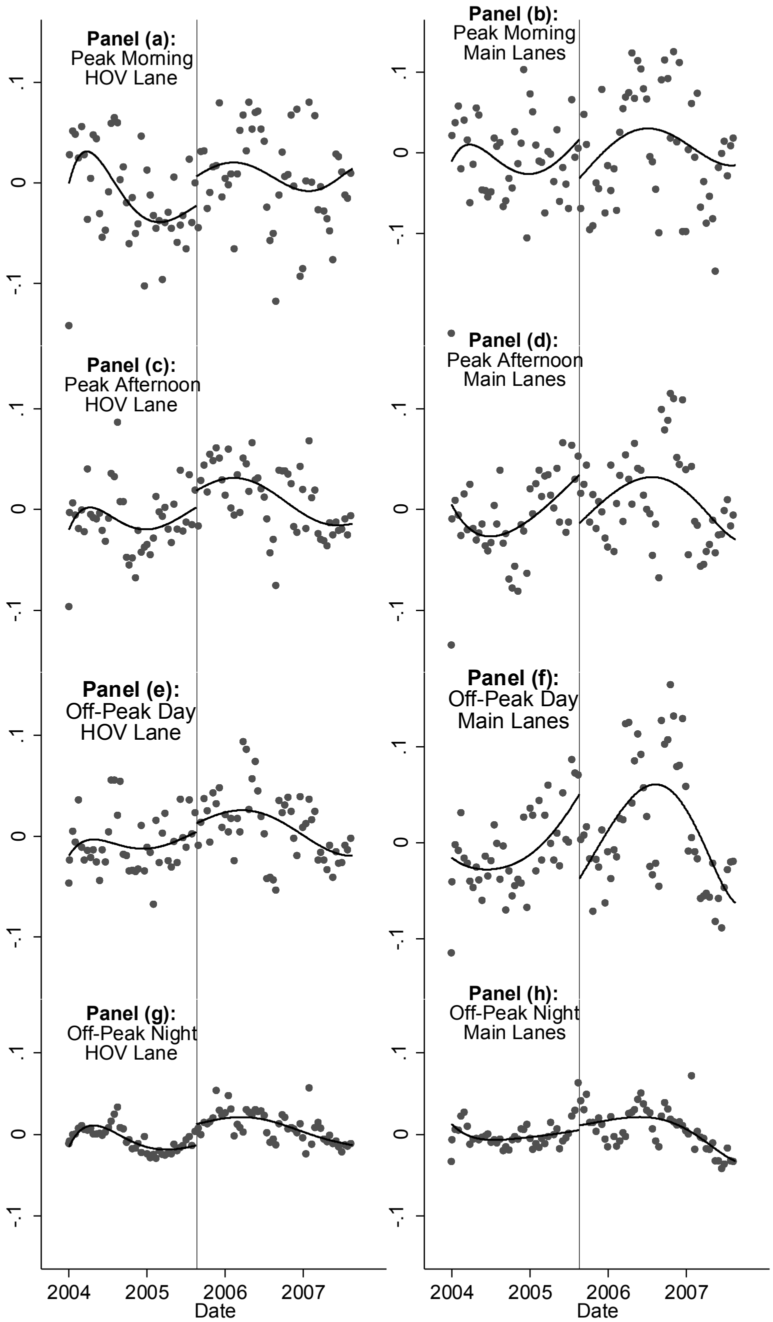


FIGURE D.6. INTERSTATE 10 W TRAVEL TIME: SIXTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a sixth-order polynomial on date.

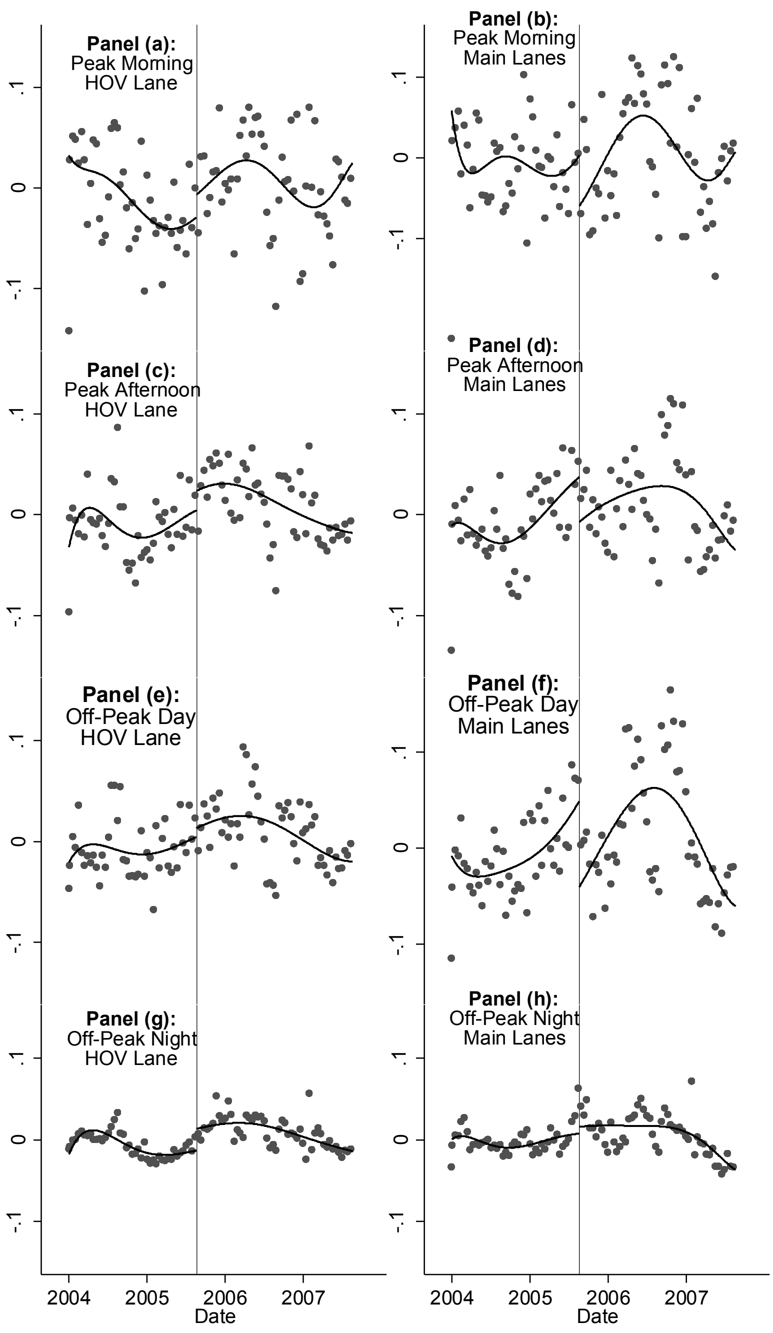


FIGURE D.7. INTERSTATE 10 W TRAVEL TIME: SEVENTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a seventh-order polynomial on date.

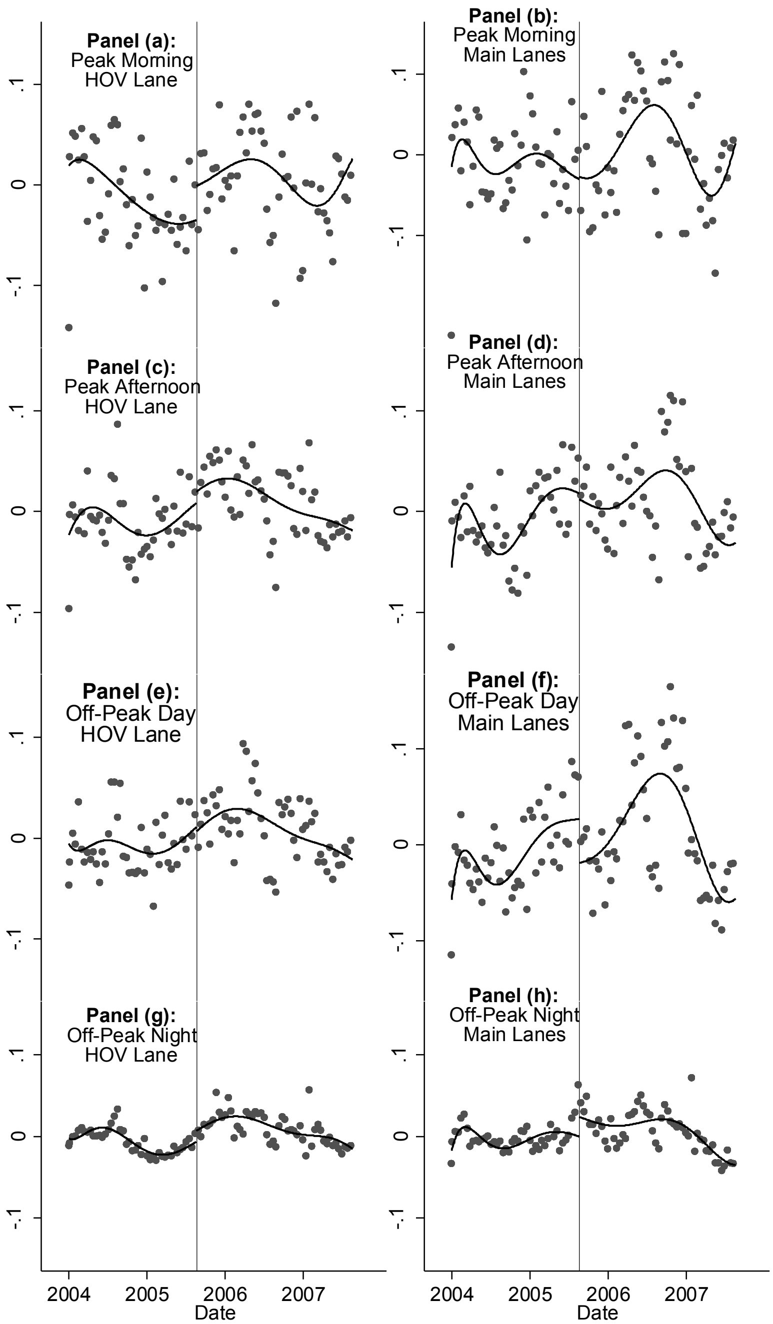


FIGURE D.8. INTERSTATE 10 W TRAVEL TIME: EIGHTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and an eighth-order polynomial on date.

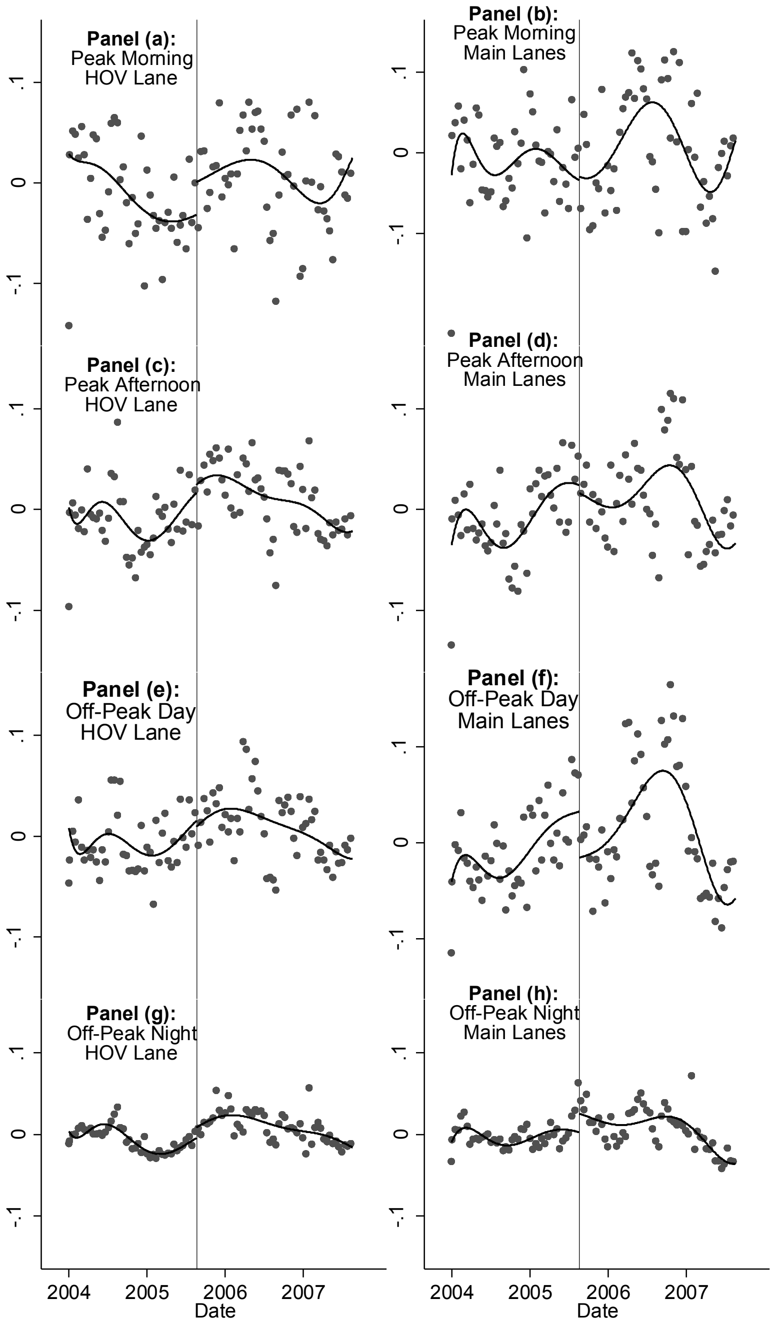


FIGURE D.9. INTERSTATE 10 W TRAVEL TIME: NINTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a ninth-order polynomial on date.

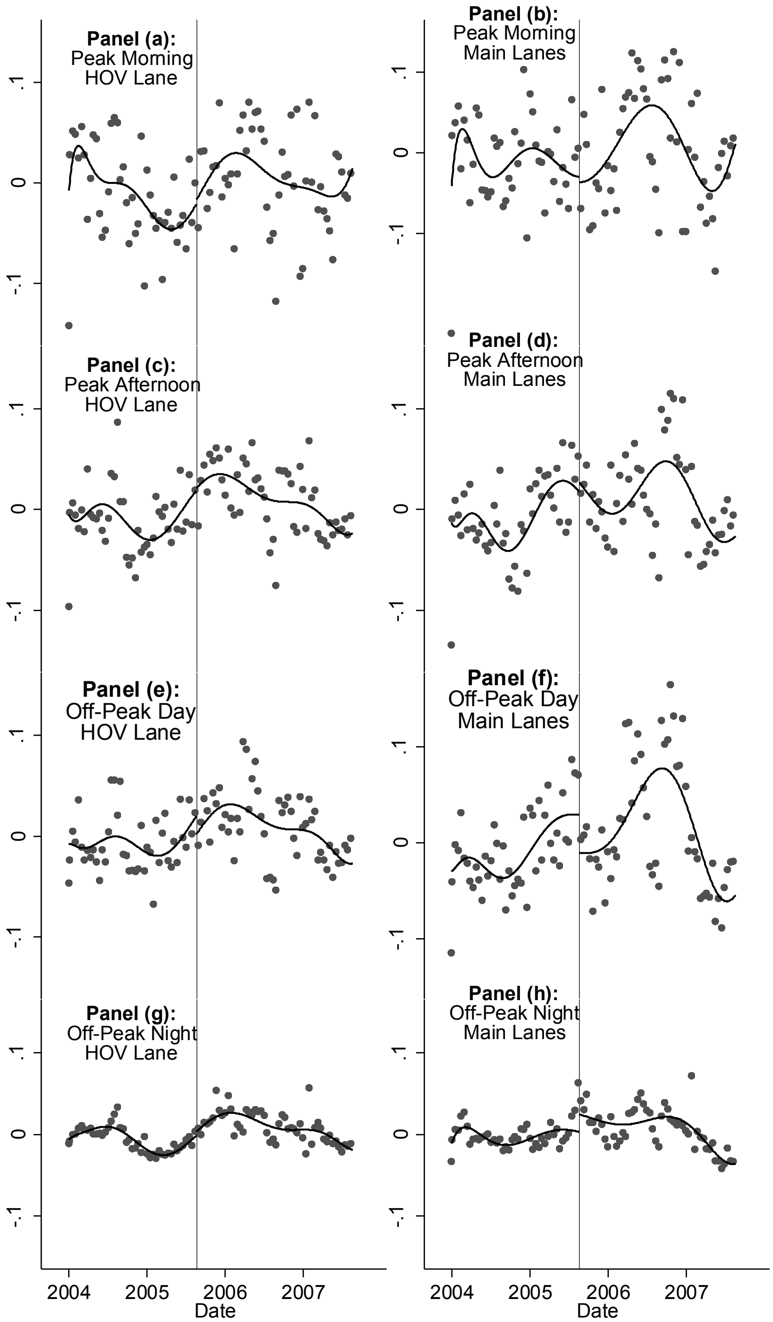
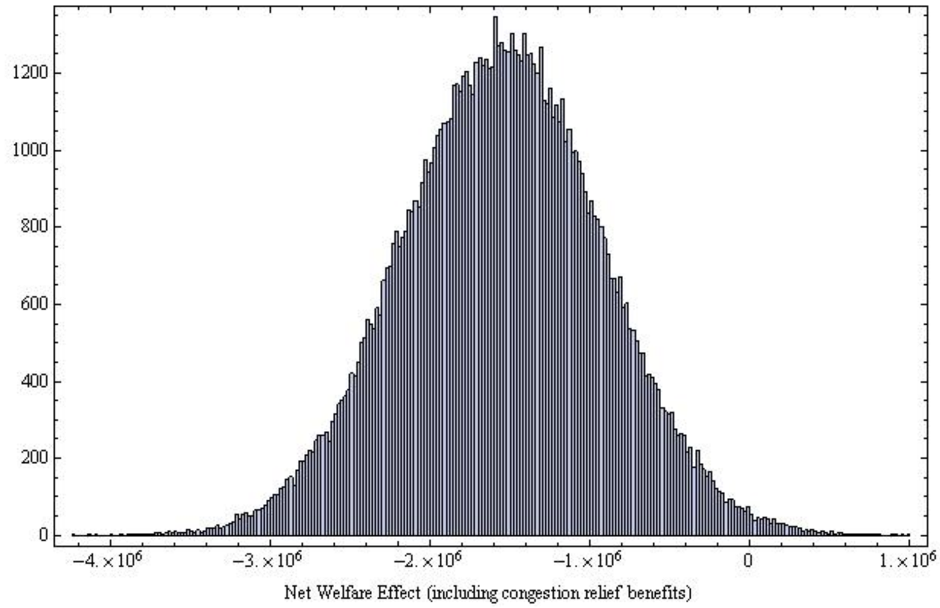


FIGURE D.10. INTERSTATE 10 W TRAVEL TIME: TENTH ORDER

Notes: Values plotted are biweekly averaged hourly residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover. Fitted lines are the predicted values obtained after regressing the residuals on hybrid exemption policy dummies and a tenth-order polynomial on date.



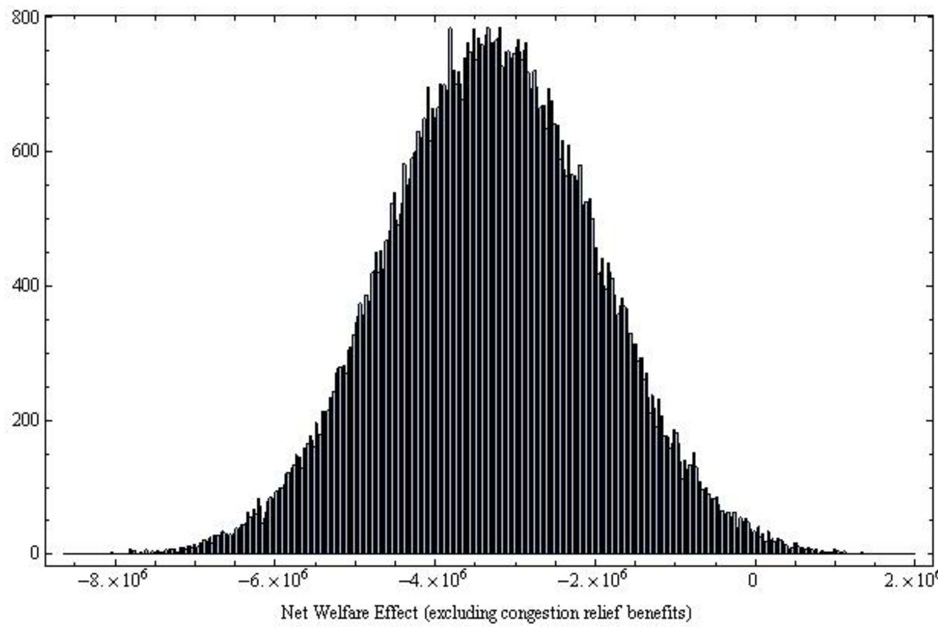


FIGURE D.11. DISTRIBUTION OF NET WELFARE EFFECT – ECONOMETRIC UNCERTAINTY

Notes: Histogram of net welfare estimates, including and excluding system-wide congestion relief benefits, based on confidence interval of econometric estimates in Table 2.

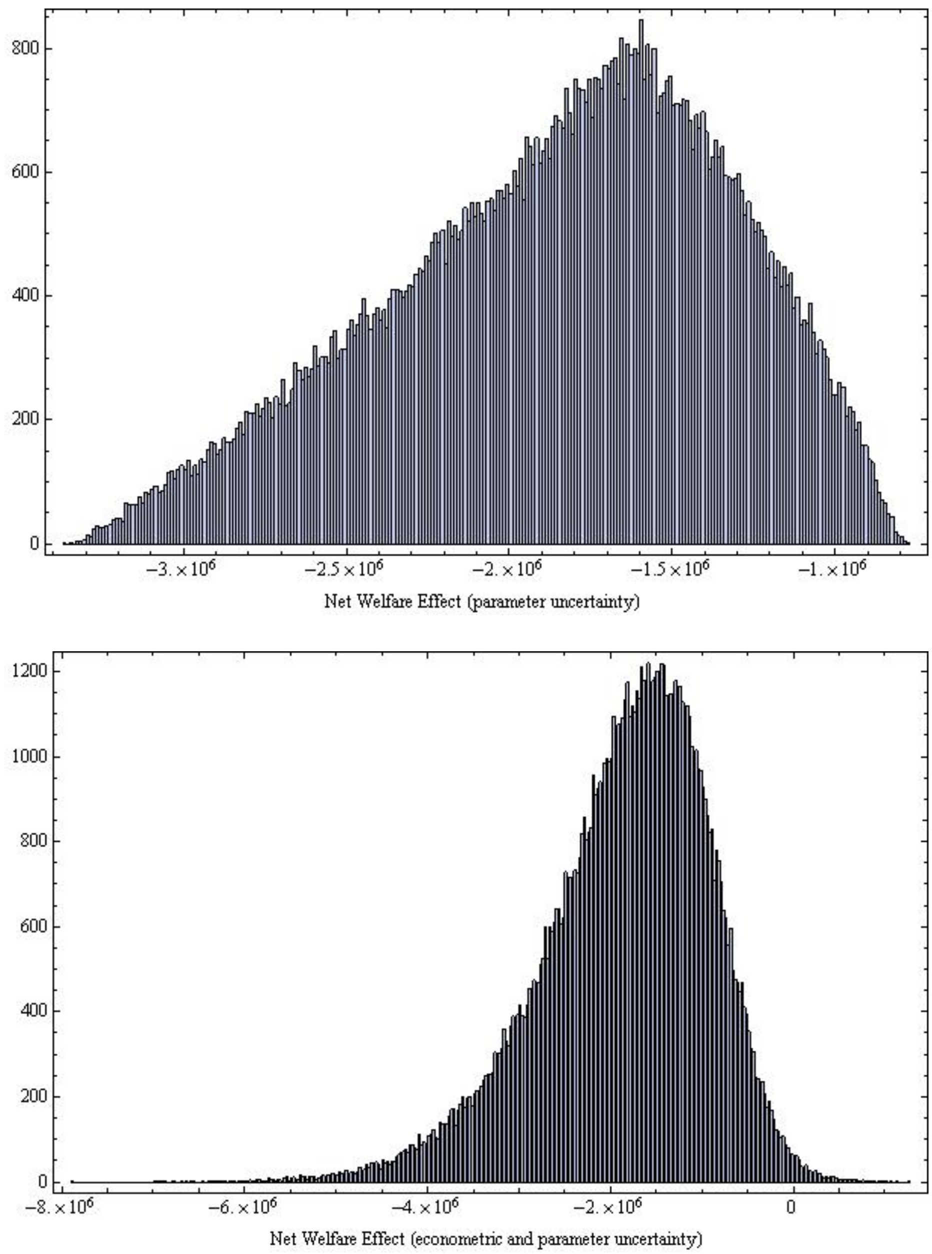


FIGURE D.12. DISTRIBUTION OF NET WELFARE EFFECT – ECONOMETRIC AND PARAMETRIC UNCERTAINTY

Notes: Histogram of net welfare estimates, based on confidence interval of econometric estimates in Table 2 and external model parameters drawn from uniform distributions, where value of time ranges from 0.5 to 1.0 of wage rate, fuel economy of fleet vehicles ranges from 10 to 30 mpg, fraction of hybrids with stickers purchased because of the policy ranges from 0 to 1, induced demand ranges from 0 to 1, and the elasticity of new VMT ranges from 0 to 1.

Appendix E. Additional Tables

TABLE E.1—ROUTE LEVEL DATA AVAILABILITY

	Highway	HOV Lane	Start of Data
Los Angeles-Long Beach			
Starting Location 101-S/Los Angeles/Aliso St	I-710	No	2000
Ending Location 710-S/Willow St			
Los Angeles-Santa Clarita			
Starting Location 101-N/Los Angeles St	I-5	No	2000
Ending Location 5-N/Valencia Blvd			
Los Angeles-Santa Monica			
Starting Location 10-W/Maple Ave	I-10	Partial	2000
Ending Location 10-W/4th St			
Los Angeles-Simi Valley			
Starting Location 101-N/Los Angeles St	I-405	Partial	2000
Ending Location 118-W/Tapo Canyon Rd			
Los Angeles-Thousand Oaks			
Starting Location 101-N/Los Angeles St	U.S. 101	No	2000
Ending Location 101-N/Moorpark Rd			
Los Angeles-West Covina			
Starting Location 101-S/Los Angeles/Aliso St	I-10	Yes	2000
Ending Location 10-E/Vincent Ave			

Source: PeMS

TABLE E.2— YEARLY TRAVEL TIME AT PEAK AND OFF-PEAK BY LANE AND ROAD

	Year			
Panel A. Morning peak				
I-10 W (HOV)	2004	2005	2006	2007
Mean (Total)	22.58	22.72	23.68	24.17
Mean (per mile)	1.29	1.30	1.35	1.38
Standard Deviation	4.20	4.13	4.64	5.36
I-10 W (ML)				
Mean (Total)	27.11	28.20	30.02	34.40
Mean (per mile)	1.55	1.61	1.72	1.70
Standard Deviation	7.39	8.04	9.15	9.76
I-210				
Mean (Total)	31.56	33.59	33.30	24.30
Mean (per mile)	1.48	1.58	1.56	1.61
Standard Deviation	10.54	10.90	10.05	10.36
Panel B. Afternoon peak				
I-10 W (HOV)	2004	2005	2006	2007
Mean (Total)	17.84	18.11	18.22	17.63
Mean (per mile)	1.02	1.03	1.04	1.01
Standard Deviation	1.89	2.18	1.84	1.89
I-10 W (ML)				
Mean (Total)	18.30	18.94	19.05	17.79
Mean (per mile)	1.05	1.08	1.09	1.02
Standard Deviation	2.27	2.87	2.82	2.18
I-210				
Mean (Total)	21.36	21.86	22.40	21.94
Mean (per mile)	1.00	1.03	1.05	1.03
Standard Deviation	3.89	3.74	3.48	2.80
Panel C. Mid-day off-peak				
I-10 W (HOV)	2004	2005	2006	2007
Mean (Total)	17.94	18.29	18.31	17.73
Mean (per mile)	1.02	1.05	1.05	1.01
Standard Deviation	1.99	2.49	1.89	1.84
I-10 W (ML)				
Mean (Total)	19.22	20.25	20.82	18.76
Mean (per mile)	1.10	1.16	1.19	1.07
Standard Deviation	2.75	4.18	3.43	2.72
I-210				
Mean (Total)	20.96	22.16	22.37	22.33
Mean (per mile)	0.98	1.04	1.05	1.05
Standard Deviation	2.55	3.48	2.42	2.94
Panel D. Night off-peak				
I-10 W (HOV)	2004	2005	2006	2007
Mean (Total)	15.72	15.66	16.01	15.68
Mean (per mile)	0.90	0.89	0.91	0.90
Standard Deviation	0.43	0.53	0.59	0.49
I-10 W (ML)				
Mean (Total)	16.29	16.45	16.46	15.97
Mean (per mile)	0.93	0.94	0.94	0.91
Standard Deviation	0.92	0.98	0.59	1.02
I-210				
Mean (Total)	19.37	20.13	20.33	21.08
Mean (per mile)	0.91	0.95	0.95	0.99
Standard Deviation	1.20	1.18	1.31	7.30

Notes: Travel time reported in minutes. Per mile values are normalized by road length and can be interpreted as minutes per mile. Weekends and holidays, as well as the day before and after a holiday, are dropped.

TABLE E.3—YEARLY TRAVEL TIME BY LANE AND ROAD

Panel A. I-10 W

	Year							
	2004		2005		2006		2007	
	ML	HOV	ML	HOV	ML	HOV	ML	HOV
Mean	19.6	18.1	20.3	18.2	20.8	18.6	19.8	18.3
	(1.12)	(1.03)	(1.16)	(1.04)	(1.19)	(1.06)	(1.13)	(1.05)
Standard Deviation	5.5	3.4	6.2	3.6	6.9	3.7	7.1	4.2
Minimum	14.9	14.7	14.9	14.7	14.9	14.8	14.6	15
	(0.85)	(0.84)	(0.85)	(0.84)	(0.85)	(0.84)	(0.83)	(0.88)
10th Percentile	15.7	15.5	15.8	15.3	15.8	15.6	15.4	15.4
	(0.90)	(0.88)	(0.90)	(0.87)	(0.90)	(0.89)	(0.88)	(0.88)
Median	17.5	16.6	18	16.9	18.2	17.1	17.2	16.7
	(1.00)	(0.95)	(1.03)	(0.97)	(1.04)	(0.98)	(0.99)	(0.95)
90th Percentile	27.5	23.4	29.1	23.4	30.3	24.1	30	24.4
	(1.57)	(1.34)	(1.66)	(1.34)	(1.73)	(1.38)	(1.71)	(1.40)
Maximum	55.3	40.6	66.1	48	63.6	49.9	105.7	47.6
	(3.16)	(2.32)	(3.78)	(2.74)	(3.63)	(2.85)	(6.04)	(2.72)
Observations	6000	6000	5986	5987	5928	5928	5832	5832

Panel B. I-210 W

	Year			
	2004	2005	2006	2007
	ML	ML	ML	ML
Mean	22.6	23.7	23.8	24.3
	(1.06)	(1.11)	(1.12)	(1.14)
Standard Deviation	7	7.5	7	7.3
Minimum	17.6	17.6	17.5	19.8
	(0.83)	(0.83)	(0.82)	(0.93)
10th Percentile	18.5	19.3	19.3	19.8
	(0.87)	(0.90)	(0.91)	(0.93)
Median	20.1	21	21.4	21.6
	(0.94)	(0.98)	(1.00)	(1.02)
90th Percentile	30.9	33.2	32.8	34.3
	(1.45)	(1.56)	(1.54)	(1.61)
Maximum	76.8	86.7	75.1	70.9
	(3.61)	(4.07)	(3.53)	(3.33)
Observations	6000	5987	5928	5807

Notes: Values in parenthesis are normalized by road length and can be interpreted as minutes per mile. Weekends and holidays as well as the day before and after a holiday are dropped.

TABLE E.4— OLS REGRESSION ESTIMATES WITH VARIOUS TIME WINDOWS - FIXED EFFECT ROBUSTNESS

	I	II	III	IV	V	VI
Period Beginning	01/01/2004 -	08/20/2004-	01/01/2005-		05/20/2005-	
Period Ending	12/31/2007	08/20/2006	12/31/2005		11/20/2005	
Panel A. Morning and Afternoon peak effects						
	Morning peak					
Policy (HOV)	0.070***	0.071***	0.100***	0.087***	0.090***	0.084***
	(0.013)	(0.020)	(0.012)	(0.019)	(0.013)	(0.032)
Observations	4944	2485	1250	1250	625	625
Policy (Mainline)	0.046**	-0.017	0.069**	0.028	0.062*	0.040
	(0.019)	(0.029)	(0.033)	(0.030)	(0.034)	(0.048)
Observations	4944	2485	1250	1250	625	625
	Afternoon peak					
Policy (HOV)	0.067***	0.073***	0.010	0.095***	0.007	0.092***
	(0.009)	(0.013)	(0.011)	(0.011)	(0.014)	(0.033)
Observations	3952	1984	996	996	496	496
Policy (Mainline)	0.049***	0.001	-0.007	0.042***	-0.013	0.038
	(0.015)	(0.013)	(0.021)	(0.011)	(0.019)	(0.026)
Observations	3952	1984	996	996	496	496
Panel B. Mid-day and Night off-peak effects						
	Mid-day off-peak					
Policy (HOV)	0.053***	0.060***	0.029	0.010	0.024	0.014
	(0.010)	(0.014)	(0.018)	(0.011)	(0.018)	(0.018)
Observations	5928	2977	1495	1495	745	745
Policy (Mainline)	0.059***	0.002	0.000	-0.044***	-0.010	-0.057*
	(0.021)	(0.022)	(0.042)	(0.015)	(0.038)	(0.034)
Observations	5927	2976	1494	1494	744	744
	Night off-peak					
Policy (HOV)	0.044***	0.047***	0.0218***	0.0417***	0.018***	0.021***
	(0.004)	(0.006)	(0.007)	(0.004)	(0.007)	(0.006)
Observations	8894	4469	2246	2246	1121	1121
Policy (Mainline)	0.012*	-0.010	0.019	0.001	0.011	-0.022
	(0.007)	(0.007)	(0.013)	(0.005)	(0.011)	(0.014)
Observations	8894	4469	2246	2246	1121	1121
Day of Wk-Mon FE	Yes	Yes	Yes	No	Yes	No
Day of Week FE	No	No	No	Yes	No	Yes

Notes: Values shown are the coefficients from 16 separate regressions of log(travel time) by lane on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.22 to 0.78 in HOV lane, and 0.26 to 0.80 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.5—SUMMARY STATISTICS AND FULL COEFFICIENTS

		I	II	III	IV	V
					Morning peak	
	Description	Mean	Minimum	Maximum	HOV	Mainline
Policy (date)	Aug. 20th, 2005				0.088	0.059
Polynomial	8th order				Yes	Yes
Day of week-					Yes	Yes
Hour of day					Yes	Yes
Log(Gas price)	Reg. reformulated (cents)	258.580[a]	163.20[a]	345.80[a]	-0.114	-0.132
I-210 W—lagged	Speed on I-210W	23.65	17.44	86.69	0.009	0.013
Rainfall	Hourly precip. (inches)	0.00	0.00	0.80	1.343	1.561
Rainfall squared		0.00	0.00	0.64	-2.196	-2.427
Visibility	Visibility (miles)	8.54	0.19	10.00	-0.006	-0.002
Visibility squared		78.31	0.04	100.00	0.000	0.000
Maximum cloud	Cover≥80	0.27	0.00	1.00	-0.013	-0.019
High cloud cover	80>Cover≥60	0.00	0.00	1.00	-0.064	-0.076
Moderate cloud	60>Cover≥40	0.03	0.00	1.00	0.000	0.007
Low cloud cover	40>Cover≥20	0.03	0.00	1.00	-0.002	-0.008
Minimal cloud	20>Cover	0.67	0.00	1.00	Omitted	Omitted
Gusts	Wind gusts>20	0.01	0.00	1.00	-0.107	-0.154
High winds	Average hourly	0.00	0.00	1.00	0.076	0.103
Cold	40≥Temp.	0.01	0.00	1.00	-0.030	-0.043
Moderate heat	95≥Temp.≥80	0.09	0.00	1.00	0.027	0.012
High heat	Temp.>95	0.00	0.00	1.00	Omitted	Omitted
Observations		23834	23834	23834	4944	4944

Notes: Values shown in columns IV and V are the coefficients of regressions of log(travel time) by lane on the regressands. (Note that columns IV and V contain more weather covariates than the central specification.) Weekends and holidays, as well as the day before and after a holiday, are dropped. Observation intervals are hourly for all variables except for gas price, which is reported weekly.

[a] Minimum, mean and maximum values are in levels however the regression analysis uses logged values.

TABLE E.6—FULL COEFFICIENTS AT MORNING AND AFTERNOON PEAK

	I	II	III	IV	V	VI	VII	VIII
	Morning peak				Afternoon peak			
	HOV	Mainline	HOV	Mainline	HOV	Mainline	HOV	Mainline
Policy	0.090	0.060	0.070	0.046	0.057	0.059	0.067	0.049
Polynomial	Yes	Yes	No	No	Yes	Yes	No	No
Day-Month	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hour of day	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Log(Gas price)	-0.116	-0.136	-0.093	-0.019	-0.251	-0.372	-0.221	-0.238
I-210W—lagged	0.009	0.013	0.009	0.013	0.005	0.006	0.005	0.007
Rainfall	1.277	1.458	1.226	1.599	0.779	1.877	0.792	1.916
Rainfall squared	-2.124	-2.311	-2.073	-2.482	-1.617	-4.600	-1.631	-4.704
Visibility	-0.006	-0.001	-0.007	-0.002	0.007	-0.006	0.006	-0.006
Visibility squared	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001
Max cloud cover	-0.013	-0.018	-0.013	-0.022	0.005	0.019	0.008	0.020
High cloud cover	-0.044	-0.068	-0.034	-0.069	0.027	-0.028	0.033	0.004
Med cloud cover	0.000	0.007	0.003	0.005	-0.005	-0.001	-0.002	0.003
Low cloud cover	-0.001	-0.007	-0.002	-0.008	-0.012	-0.020	-0.011	-0.017
Polynomial	Yes	Yes	No	No	Yes	Yes	No	No
Gusts	No	No	No	No	No	No	No	No
High winds	No	No	No	No	No	No	No	No
Cold	No	No	No	No	No	No	No	No
Moderate heat	No	No	No	No	No	No	No	No
High heat	No	No	No	No	No	No	No	No
Observations	4944	4944	4944	4944	3952	4156	4156	4156

Notes: Values shown are the coefficients from regressions of log(travel time) by lane on the regressands and an 8^{th} order polynomial. Weekends and holidays, as well as the day before and after a holiday, are dropped. Specifications shown are the baseline specification. Observation intervals are hourly for all variables except for gas price, which is reported weekly.

TABLE E.7—FULL COEFFICIENTS AT MID-DAY AND NIGHT OFF-PEAK

	I	II	III	IV	V	VI	VII	VIII
	Mid-day off-peak				Night off-peak			
	HOV	Mainline	HOV	Mainline	HOV	Mainline	HOV	Mainline
Policy	0.027	-0.008	0.053	0.059	0.016	0.016	0.044	0.012
Polynomial	Yes	Yes	No	No	Yes	Yes	No	No
Day of week-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hour of day	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Log(Gas price)	-0.250	-0.381	-0.215	-0.274	-0.033	-0.017	-0.116	-0.100
I-210W—	0.009	0.012	0.009	0.012	0.008	0.018	0.005	0.013
Rainfall	1.016	1.410	1.033	1.422	0.327	0.301	0.384	0.400
Rainfall squared	-1.930	-2.513	-1.944	-2.479	-0.342	-0.284	-0.395	-0.398
Visibility	-0.006	-0.010	-0.005	-0.006	-0.003	-0.004	-0.003	-0.003
Visibility	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000
Max cloud	-0.016	-0.013	-0.013	-0.008	0.002	0.004	0.002	0.002
High cloud	-0.052	-0.020	-0.051	-0.027	0.007	0.027	0.008	0.016
Med cloud	-0.015	-0.017	-0.014	-0.018	-0.005	-0.004	-0.004	-0.005
Low cloud	-0.007	-0.002	-0.005	-0.002	0.001	0.002	0.002	0.001
Polynomial	Yes	Yes	No	No	Yes	Yes	No	No
Gusts	No	No	No	No	No	No	No	No
High winds	No	No	No	No	No	No	No	No
Cold	No	No	No	No	No	No	No	No
Moderate heat	No	No	No	No	No	No	No	No
High heat	No	No	No	No	No	No	No	No
Observations	5928	5927	5928	5927	8894	8894	8894	8894

Notes: Values shown are the coefficients of regressions of log(travel time) by lane on the regressands and an 8^{th} order polynomial. Weekends and holidays, as well as the day before and after a holiday, are dropped. Specifications shown are the baseline specification. Observation intervals are hourly for all variables except for gas price, which is reported weekly.

TABLE E.8—GLOBAL POLYNOMIAL REGRESSION DISCONTINUITY ESTIMATES: COVARIATE SENSITIVITY

	I	II	III	IV	V	VI
Panel A. Morning peak and afternoon peak effects						
	Morning peak					
Policy (HOV)	0.056**	0.094***	0.088***	0.094	0.061**	0.093***
	(0.027)	(0.032)	(0.027)	(0.028)	(0.026)	(0.028)
Observations	4950	5199	4944	4945	4944	4944
Policy (Mainline)	0.011	0.069	0.059	0.064	0.026	0.064
	(0.044)	(0.051)	(0.044)	(0.046)	(0.042)	(0.044)
Observations	4950	5199	4944	4945	4944	4944
	Afternoon peak					
Policy (HOV)	0.053**	0.055**	0.059***	0.059***	-0.007	0.057***
	(0.021)	(0.023)	(0.022)	(0.022)	(0.018)	(0.021)
Observations	3956	4156	3952	3952	3952	3952
Policy (Mainline)	0.053	0.059*	0.062*	0.062*	-0.036	0.060*
	(0.033)	(0.036)	(0.034)	(0.036)	(0.027)	(0.034)
Observations	3956	4156	3952	3952	3952	3952
Panel B. Mid-day and Night off-peak effects						
	Mid-day off-peak					
Policy (HOV)	0.011	0.028	0.023	0.035*	-0.038	0.028
	(0.019)	(0.021)	(0.020)	(0.021)	(0.024)	(0.020)
Observations	5935	6234	5928	5928	5928	5928
Policy (Mainline)	-0.030	-0.003	-0.014	0.002	-0.107**	-0.007
	(0.046)	(0.050)	(0.049)	(0.049)	(0.047)	(0.048)
Observations	5934	6233	5927	5927	5927	5927
	Night off-peak					
Policy (HOV)	0.006	0.017**	0.015**	0.016**	0.007	0.016**
	(0.006)	(0.007)	(0.007)	(0.007)	(0.006)	(0.007)
Observations	8904	9352	8894	8895	8894	8894
Policy (Mainline)	-0.005	0.020	0.017	0.016	0.012	0.017
	(0.018)	(0.022)	(0.022)	(0.022)	(0.019)	(0.022)
Observations	8904	9352	8894	8895	8894	8894
Polynomial order	8	8	8	8	8	8
Month-day-of-week	Yes	Yes	Yes	Yes	Yes	No
Month and day-of-week	No	No	No	No	No	Yes
I-210 West lagged	No	Yes	Yes	Yes	Yes	Yes
Basic weather covariates	Yes	Yes	Yes	No	Yes	Yes
Other weather covariates	No	No	Yes	No	No	No
Drop holidays	Yes	No	Yes	Yes	Yes	Yes
Gas price	Yes	Yes	Yes	Yes	No	Yes

Notes: Values shown are the coefficients from 48 separate regressions of log(travel time) by lane on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.27 to 0.70 in HOV lane, and 0.35 to 0.76 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.

** Significant at the 5 percent level.

* Significant at the 10 percent level.

TABLE E.9—REGRESSION DISCONTINUITY ESTIMATES: FURTHER ROBUSTNESS

	I	II	III	IV
	Remove dates	Separate	Remove dates	Separate
	Morning peak		Mid-day off-peak	
Policy (HOV)	0.078**	0.094***	0.019	0.038***
	(0.037)	(0.014)	(0.028)	(0.012)
Observations	4894	4944	5868	5928
Policy (Mainline)	0.028	0.031	-0.063	0.004
	(0.054)	(0.021)	(0.049)	(0.020)
Observations	4894	4944	5927	5927
	Afternoon peak		Night off-peak	
Policy (HOV)	0.078***	0.058***	0.013	0.058***
	(0.027)	(0.010)	(0.009)	(0.004)
Observations	3912	3952	8804	8894
Policy (Mainline)	0.055	0.008	-0.011	0.018***
	(0.043)	(0.015)	(0.020)	(0.007)
Observations	3912	3952	8804	8894
Date of policy	Remove 16	8/20/05	Remove 16	8/20/05

Notes: Values shown are the coefficients from 16 separate regressions of log(travel time) by lane on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.34 to 0.70 in HOV lane, and 0.37 to 0.76 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped. 'Remove dates' uses the standard single polynomial with a transition period removed - 8/20/2005 to 9/5/2005. 'Separate' fits a separate polynomial to each side of the discontinuity allowing the policy to interact with the unobservables. The 'separate' specification allows the polynomial to have different coefficients before and after the policy.

*** Significant at the 1 percent level.

** Significant at the 5 percent level.

* Significant at the 10 percent level.

TABLE E.10—DIFFERENCE-IN-DIFFERENCES ESTIMATES

	I	II	III	IV
Comparison years	2004 - 2005	2005 - 2006	2004 - 2005	2005 - 2006
	Morning peak		Mid-day off-peak	
Policy (HOV)	0.088***	0.105***	0.046***	0.075***
	(0.020)	(0.032)	(0.014)	(0.020)
Observations	2499	2485	2995	2977
Policy (Mainline)	-0.033	-0.001	-0.041**	-0.044
	(0.030)	(0.050)	(0.020)	(0.034)
Observations	2499	2485	2994	2976
	Afternoon peak		Night off-peak	
Policy (HOV)	0.087***	0.081***	0.055***	0.050***
	(0.011)	(0.017)	(0.004)	(0.007)
Observations	1996	1984	4496	4469
Policy (Mainline)	0.005	-0.038	0.009*	0.006
	(0.013)	(0.027)	(0.005)	(0.013)
Observations	1996	1984	4496	4469

Notes: Values shown are the coefficients from 16 separate regressions of log(travel time) by lane on a policy indicator, that is active in the period of each year following the policy date; a treatment year dummy, that is active in 2005; an interaction of the two variables, that is active in the post-policy period of 2005; and a set of covariates. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R2 ranges from 0.31 to 0.72 in HOV lane, and 0.37 to 0.76 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.11—RD WITH VARIOUS WINDOW LENGTHS

	I	II	III	IV	V
Comparison years	6 Months	9 Months	12 Months	15 Months	18 Months
			Morning Peak		
Policy (HOV)	0.038	0.033	0.047**	0.114***	0.128***
	(0.024)	(0.027)	(0.024)	(0.023)	(0.026)
Observations	1245	1870	2485	3114	3719
Policy (Mainline)	0.010	-0.004	0.021	0.054	0.065
	(0.049)	(0.055)	(0.047)	(0.040)	(0.046)
Observations	1245	1870	2485	3114	3719
			Afternoon peak		
Policy (HOV)	-0.045	-0.012	0.002	0.058**	0.067***
	(0.025)	(0.020)	(0.020)	(0.025)	(0.026)
Observations	992	1492	1984	2488	2972
Policy (Mainline)	-0.072	-0.020	-0.006	0.031	0.048
	(0.034)	(0.028)	(0.027)	(0.029)	(0.035)
Observations	992	1492	1984	2488	2972
			Mid-day off-peak		
Policy (HOV)	-0.029	0.014	0.004	0.022	0.042
	(0.018)	(0.022)	(0.025)	(0.022)	(0.022)
Observations	1489	2239	2977	3733	4458
Policy (Mainline)	-0.066	-0.010	-0.017	-0.031	-0.007
	(0.043)	(0.044)	(0.044)	(0.051)	(0.053)
Observations	1488	2238	2976	3732	4457
			Night off-peak		
	0.015	0.014**	0.010	0.020***	0.029***
	(0.008)	(0.007)	(0.006)	(0.008)	(0.009)
Observations	2237	3362	4469	5603	6692
Policy (Mainline)	0.010	0.018	0.013	0.013	0.027
	(0.016)	(0.015)	(0.014)	(0.021)	(0.024)
Observations	2237	3362	4469	5603	6692

Notes: Values shown are the coefficients from 40 separate regressions of log(travel time) by lane on the regressands. Observations are all those with a date that falls within the specified window of time before and after the policy. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.27 to 0.70 in HOV lane, and 0.35 to 0.76 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.12—REGRESSION DISCONTINUITY ESTIMATES: GLOBAL POLYNOMIAL, NEWEY-WEST STANDARD ERRORS

	I	II	III	IV	V	VI
Panel A. Morning and Afternoon peak effects						
Polynomial Order	*6*	7	8	9	10	BIC
	Morning peak					
Policy (HOV)	0.088***	0.084***	0.090**	0.090***	0.116***	0.116***
	(0.018)	(0.018)	(0.019)	(0.019)	(0.019)	(0.019)
Observations	4944	4944	4944	4944	4944	4944
Policy (Mainline)	-0.011	-0.022	0.060**	0.060**	0.070**	0.060**
	(0.025)	(0.027)	(0.028)	(0.029)	(0.029)	(0.028)
Observations	4944	4944	4944	4944	4944	4944
	Afternoon peak					
CAVS policy (HOV)	0.063***	0.066***	0.057***	0.057***	0.067***	0.062***
	(0.013)	(0.013)	(0.014)	(0.014)	(0.015)	(0.013)
Observations	3952	3952	3952	3952	3952	3952
Policy (Mainline)	-0.001	0.004	0.059***	0.059***	0.055**	0.059***
	(0.018)	(0.017)	(0.021)	(0.021)	(0.021)	(0.021)
Observations	3952	3952	3952	3952	3952	3952
Panel B. Mid-day and Night off-peak effects						
Polynomial order	6	7	8	9	10	BIC
	Mid-day off-peak					
Policy (HOV)	0.048***	0.050***	0.027**	0.027*	0.041***	0.041***
	(0.013)	(0.013)	(0.013)	(0.014)	(0.014)	(0.014)
Observations	5928	5928	5928	5928	5928	5928
Policy (Mainline)	-0.064***	-0.063***	-0.008	-0.009	-0.007	-0.009
	(0.021)	(0.021)	(0.025)	(0.025)	(0.026)	(0.025)
Observations	5927	5927	5927	5927	5927	5927
	Night off-peak					
Policy (HOV)	0.033***	0.033***	0.016***	0.016***	0.022***	0.022***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Observations	8894	8894	8894	8894	8894	8894
Policy (Mainline)	-0.008	-0.005	0.016*	0.017*	0.023**	0.023**
	(0.008)	(0.007)	(0.009)	(0.009)	(0.009)	(0.009)
Observations	8894	8894	8894	8894	8894	8894

Notes: Values shown are the coefficients from 48 separate regressions of log(travel time) by lane on the regressands. Newey-West standard errors with a one-week lag are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.34 to 0.70 in HOV lane, and 0.41 to 0.76 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.13—LOCAL LINEAR REGRESSION DISCONTINUITY ESTIMATES

	I	II	III	IV	V
Panel A. Morning and Afternoon peak					
Kernel (days)	50	60	70	80	90
	Morning peak				
Policy (HOV)	0.071***	0.072***	0.065**	0.060**	0.058**
	(0.017)	(0.016)	(0.021)	(0.024)	(0.028)
Observations	330	405	480	545	615
Policy (Mainline)	0.054*	0.055	0.046	0.042	0.043
	(0.030)	(0.037)	(0.043)	(0.045)	(0.049)
Observations	330	405	480	545	615
	Afternoon peak				
Policy (HOV)	0.001	-0.002	-0.004	-0.001	0.002
	(0.016)	(0.012)	(0.011)	(0.011)	(0.012)
Observations	264	324	384	436	492
Policy (Mainline)	0.000	-0.005	-0.008	-0.002	0.000
	(0.014)	(0.013)	(0.013)	(0.014)	(0.017)
Observations	264	324	384	436	492
Panel B. Mid-day and Night off-peak effects					
Kernel (days)	50	60	70	80	90
	Mid-day off-peak				
Policy (HOV)	0.000	0.001	-0.002	-0.005	-0.006
	(0.023)	(0.019)	(0.016)	(0.015)	(0.016)
Observations	396	486	576	654	738
Policy (Mainline)	-0.021	-0.020	-0.021	-0.023	-0.024
	(0.036)	(0.032)	(0.029)	(0.028)	(0.028)
Observations	396	486	576	654	738
	Night off-peak				
Policy (HOV)	0.011	0.012*	0.010*	0.009	0.010*
	(0.008)	(0.007)	(0.006)	(0.006)	(0.006)
Observations	594	729	864	981	1107
Policy (Mainline)	0.012	0.015	0.017*	0.018*	0.018*
	(0.010)	(0.010)	(0.009)	(0.009)	(0.010)
Observations	594	729	864	981	1107

Notes: Values shown are the coefficients from 40 separate regressions of log(travel time) by lane on the regressands. An Epanechnikov kernel is used varying the bandwidth (in days) as listed. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.28 to 0.78 in HOV lane, and 0.29 to 0.8 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.14—LOCAL LINEAR REGRESSION DISCONTINUITY ESTIMATES: COVARIATE SENSITIVITY

	I	II	III	IV	V
Panel A. Morning and Afternoon peak effects					
			Morning peak		
Policy (HOV)	0.069***	0.071***	0.082***	0.071***	0.075***
	(0.023)	(0.015)	(0.019)	(0.026)	(0.016)
Observations	405	405	405	405	405
Policy (Mainline)	0.051	0.054	0.069**	0.055	0.061*
	(0.045)	(0.037)	(0.032)	(0.051)	(0.035)
Observations	405	405	405	405	405
			Afternoon peak		
Policy (HOV)	0.005	-0.005	0.004	-0.005	-0.004
	(0.017)	(0.012)	(0.017)	(0.014)	(0.014)
Observations	324	324	324	324	24
Policy (Mainline)	0.003	-0.011	-0.012	-0.015	-0.004
	(0.016)	(0.014)	(0.021)	(0.014)	(0.015)
Observations	324	324	324	324	324
Panel B. Mid-day and Night off-peak effects					
			Mid-day off-peak		
Policy (HOV)	-0.015	-0.003	-0.021	0.019	0.001
	(0.017)	(0.017)	(0.022)	(0.014)	(0.020)
Observations	486	486	486	486	486
Policy (Mainline)	-0.048	-0.027	-0.055	-0.003	-0.017
	(0.032)	(0.025)	(0.040)	(0.029)	(0.028)
Observations	486	486	486	486	486
			Night off-peak		
Policy (HOV)	0.009*	0.012*	0.012**	0.012*	0.012*
	(0.005)	(0.007)	(0.006)	(0.007)	(0.007)
Observations	729	729	729	729	729
Policy (Mainline)	0.004	0.015	0.011	0.010	0.025*
	(0.006)	(0.010)	(0.009)	(0.009)	(0.015)
Observations	729	729	729	729	729
Kernel bandwidth: days	60	60	60	60	60
I-210W lagged	No	Yes	Yes	Yes	Yes
Basic weather covariates	Yes	Yes	Yes	No	Yes
Other weather	No	Yes	No	No	No
Weekday FE	Yes	Yes	Yes	Yes	No
Gas price	Yes	Yes	No	Yes	Yes

Notes: Values shown are the coefficients from 48 separate regressions of log(travel time) by lane on the regressands. Epanechnikov kernel and 60 day bandwidth are used in all regressions. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.25 to 0.76 in HOV lane, and 0.19 to 0.78 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.15—LOCAL LINEAR REGRESSION DISCONTINUITY ESTIMATES: FURTHER ROBUSTNESS

	I	II	III	IV
	True Date	Placebo		Weekend
Panel A. Morning and Afternoon peak.				
	Morning peak			
Policy (HOV)	0.072***	0.008	-0.019	0.031***
	(0.016)	(0.017)	(0.026)	(0.011)
Observations	405	410	400	160
Policy (Mainline)	0.055	0.002	-0.010	-0.012
	(0.037)	(0.025)	(0.037)	(0.020)
Observations	405	410	400	160
	Afternoon peak			
Policy (HOV)	-0.002	-0.020	-0.009	0.000
	(0.012)	(0.024)	(0.021)	(0.081)
Observations	324	328	320	128
Policy (Mainline)	-0.005	-0.025	-0.042	-0.040
	(0.013)	(0.027)	(0.030)	(0.087)
Observations	324	328	320	128
Panel B. Mid-day and Night off-peak.				
	Mid-day off-peak			
Policy (HOV)	0.001	0.009	0.014	0.050
	(0.019)	(0.026)	(0.017)	(0.051)
Observations	486	492	480	192
Policy (Mainline)	-0.020	0.011	0.013	0.010
	(0.032)	(0.030)	(0.033)	(0.058)
Observations	486	492	480	192
	Night off-peak			
Policy (HOV)	0.012*	-0.001	0.004	0.026
	(0.007)	(0.007)	(0.007)	(0.017)
Observations	729	738	720	288
CAVS policy (Mainline)	0.015	-0.002	-0.009	-0.003
	(0.010)	(0.006)	(0.010)	(0.028)
Observations	729	738	720	288
Policy Date	8/20/05	8/20/04	8/20/06	8/20/05

Notes: Values shown are the coefficients from 32 separate regressions of log(travel time) by lane on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.30 to 0.83 in HOV lane, and 0.33 to 0.85 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped. Epanechnikov kernel and 60 day bandwidth are used in all regressions. 'Weekend' specifications include only observations from weekends. 'Placebo' specifications use only weekday observations with policies starting one year before the true policy, the date of the true policy, and one year after the true policy.
*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.16—LOCAL LINEAR REGRESSION DISCONTINUITY ESTIMATES: FURTHER ROBUSTNESS

	I	II	III	IV	V
Panel A. Morning and Afternoon peak effects					
	Weather Aggregation		Kernel		Remove Days
	Morning peak				
Policy (HOV)	0.069***	0.063***	0.073***	0.072**	0.073***
	(0.017)	(0.020)	(0.013)	(0.034)	(0.026)
Observations	405	405	405	4724	385
Policy (Mainline)	0.050	0.050	0.058*	0.058	0.050
	(0.040)	(0.048)	(0.031)	(0.052)	(0.050)
Observations	405	405	405	4724	385
	Afternoon peak				
Policy (HOV)	-0.015	-0.014	0.000	0.016	-0.024
	(0.014)	(0.013)	(0.012)	(0.016)	(0.015)
Observations	324	324	324	3776	308
Policy (Mainline)	-0.023	-0.022	-0.002	0.007	-0.018
	(0.017)	(0.013)	(0.012)	(0.020)	(0.016)
Observations	324	324	324	3776	308
Panel B. Mid-day and Night off-peak effects					
	Weather Aggregation		Kernel		Remove Days
	Mid-day off-peak				
Policy (HOV)	0.009	0.010	-0.002	-0.004	-0.010
	(0.016)	(0.016)	(0.018)	(0.016)	(0.018)
Observations	486	486	486	5664	462
Policy (Mainline)	0.000	0.004	-0.021	-0.026	-0.042
	(0.023)	(0.018)	(0.031)	(0.031)	(0.027)
Observations	486	486	486	5663	462
	Night off-peak				
Policy (HOV)	0.014**	0.013**	0.011	0.015***	0.017**
	(0.006)	(0.007)	(0.007)	(0.006)	(0.007)
Observations	729	729	729	8499	693
Policy (Mainline)	0.016*	0.015*	0.014	0.019	0.014
	(0.009)	(0.009)	(0.009)	(0.015)	(0.011)
Observations	729	729	729	8499	693
Kernel shape	Epa	Epa	Triangle	Gaussian	Epa
I-210W lagged	Yes	Yes	Yes	Yes	Yes
Basic weather covariates	Yes	Yes	Yes	Yes	Yes
Other weather covariates	No	No	No	No	No
Weekday FE	Yes	Yes	Yes	Yes	Yes
Gas price	Yes	Yes	Yes	Yes	Yes
Weather aggregation	1	2	3	3	3

Notes: Values shown are the coefficients from 32 separate regressions of log(travel time) by lane on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.25 to 0.78 in HOV lane, and 0.27 to 0.80 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped. Epanechnikov kernel (Epa) and 60 day bandwidth are used in all regressions. Weather Aggregation: 1) station values are averaged according to inverse distance to the road center. 2) station values are averaged using equal weights from all stations. 3) Values from station closest to the road segment with imputation according to Auffhammer and Kellogg (2011). Dates removed from 8/20/2005 to 8/25/2005.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.17—LOCAL LINEAR REGRESSION DISCONTINUITY ESTIMATES: NEWEY-WEST STANDARD ERRORS

	I	II	III	IV	V
Panel A. Morning and Afternoon peak effects					
Kernel (Days)	50	60	70	80	90
	Morning peak				
Policy (HOV)	0.071***	0.072***	0.065***	0.060***	0.058***
	(0.020)	(0.019)	(0.019)	(0.020)	(0.021)
Observations	330	405	480	545	615
Policy (Mainline)	0.054**	0.055**	0.046*	0.042	0.043
	(0.027)	(0.027)	(0.027)	(0.029)	(0.030)
Observations	330	405	480	545	615
	Afternoon peak				
Policy (HOV)	0.001	-0.002	-0.004	-0.001	0.002
	(0.013)	(0.012)	(0.012)	(0.012)	(0.012)
Observations	264	324	384	436	492
Policy (Mainline)	0.000	-0.005	-0.008	-0.002	0.000
	(0.016)	(0.015)	(0.015)	(0.015)	(0.015)
Observations	264	324	384	436	492
Panel B. Mid-day and Night off-peak effects					
Kernel (Days)	50	60	70	80	90
	Mid-day off-peak				
Policy (HOV)	0.000	0.001	-0.002	-0.005	-0.006
	(0.019)	(0.018)	(0.017)	(0.017)	(0.017)
Observations	396	486	576	654	738
Policy (Mainline)	-0.021	-0.020	-0.021	-0.023	-0.024
	(0.026)	(0.023)	(0.022)	(0.021)	(0.021)
Observations	396	486	576	654	738
	Night off-peak				
Policy (HOV)	0.011***	0.012***	0.010***	0.009***	0.010***
	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)
Observations	594	729	864	981	1107
Policy (Mainline)	0.012	0.015**	0.017**	0.018***	0.018***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Observations	594	729	864	981	1107

Notes: Values shown are the coefficients from 40 separate regressions of log(travel time) by lane on the regressands. Newey-West standard errors with a one-week lag are in parentheses. Covariates include logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.28 to 0.78 in HOV lane, and 0.29 to 0.80 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped. An Epanechnikov kernel is used in all regressions.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.18—DAILY MAXIMUM EVENT

	I	III
	Morning peak	Mid-day off-peak
Policy (HOV)	0.083**	0.031
	(0.040)	(0.046)
Observations	989	988
Policy (Mainline)	0.028	-0.024
	(0.051)	(0.084)
Observations	989	987
	Afternoon peak	Night off-peak
Policy (HOV)	0.078***	0.009
	(0.029)	(0.015)
Observations	988	989
Policy (Mainline)	0.088*	-0.002
	(0.048)	(0.035)
Observations	988	989

Notes: Values shown are the coefficients from 8 separate regressions of the daily maximum of log(travel time) by lane on the regressands. Estimates use only the maximum travel time during the specified time of day. Standard errors, clustered by week, are in parentheses. Covariates include an 8^{th} order polynomial in date, logged gas price, travel time for the I-210W, dummies for day of the week-month, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. R^2 ranges from 0.32 to 0.61 in HOV lane, and 0.39 to 0.64 in mainline lanes. Weekends and holidays, as well as the day before and after a holiday, are dropped.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.19—AVERAGE TREATMENT EFFECT BY DISTANCE FROM CBD: SILVERMAN RULE BANDWIDTH SELECTION

	I	II	III	IV	V
	All detectors				I-10W
Distance from CBD	0-10	10-20	20-30	0-30	‡
Policy (HOV)	0.084***	0.055***	-0.089	0.043*	0.103***
	(0.025)	(0.019)	(0.151)	(0.024)	(0.007)
Detectors[1]	50	124	26	200	14
Observations[2]	12,320	29,834	6,066	48,220	4,219
Flow[3]	1056	973	824	974	1033
Average Bandwidth	8.46	8.62	8.36	8.54	8.65
Policy (Mainline)	0.027**	0.009	-0.002	0.013	0.000
	(0.011)	(0.019)	(0.025)	(0.012)	(0.037)
Detectors[1]	152	254	71	477	27
Observations[2]	36,120	59,209	15,509	110,838	6,869
Flow[3]	5729	5859	5144	5712	5761
Average Bandwidth	8.55	8.52	8.17	8.48	8.76
Increased flow in HOV[4]	88	53	-74	42	106
Simulated flow change in mainline[5]	-0.015	-0.009	0.014	-0.007	-0.018

Notes: Values shown are the means of policy coefficients on detectors within the stated number of miles from the city center for the indicated lane from local linear regressions of log traffic flow on the regressands. Standard errors of the means, clustered by route-direction, are in parentheses and are calculated using 5,000 bootstrap samples. Covariates for detector regressions include logged gas price, dummies for day of the week, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. Weather aggregation method 2 is used: simple averaging across all stations. Weekends are dropped from the analysis. A Gaussian kernel is used and bandwidth is selected using the Silverman Rule of Thumb for individual detector regressions. Detector-level regressions include only those observations where Percent Observed is 100%. A minimum of 50 observations per detector are required after all deletions. Effect reported for peak time of day when maximum traffic flow occurs.

[a] Detectors is the number of detectors within the listed distance from the CBD that comprise each average treatment effect.

[b] The total number of observations entering the detector level regressions.

[c] Flow is the number of cars passing the average detector entering the regressions.

[d] The implied increase in flow on the average HOV lane detector, i.e. the CAVS policy multiplied by flow.

[e] The implied percentage decrease in flow that would be observed if the hybrids entering the HOV lane had originated in the mainline lanes.

[f] Route I-10W consists of detectors between post miles 35.239 and 18.489. These range between 3.3 and 19.2 miles from downtown LA.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.20— AVERAGE TREATMENT EFFECT BY DISTANCE FROM CBD: PRECISE ESTIMATE SELECTION

	I	II	III	IV	V
	All detectors				I-10W
Distance from CBD	0-10	10-20	20-30	0-30	3.3-19.2[f]
Policy (HOV)	0.091***	0.058**	0.011	0.060***	0.103***
	(0.018)	(0.024)	(0.076)	(0.020)	(0.005)
Detectors[a]	50	124	24	198	14
Observations[b]	8,297	20,662	3,883	32,842	2,799
Flow[c]	1056	973	825	976	1033
Policy (Mainline)	0.018	0.006	0.024	0.013	0.004
	(0.012)	(0.019)	(0.017)	(0.012)	(0.040)
Detectors[a]	151	253	70	474	27
Observations[b]	24,380	40,784	10,571	75,735	4,671
Flow[c]	5738	5882	5141	5727	5761
Increased traffic flow in HOV[d]	96	56	9	59	106
Simulated flow change in mainline[e]	-0.017	-0.010	-0.002	-0.010	-0.018

Notes: To eliminate the most imprecisely estimate effects, detectors are deleted from the analysis where the detector level regression has a standard error on the CAVS policy variable in excess of 0.5. Values shown are the means of policy coefficients on detectors within the stated number of miles from the city center for the indicated lane from local linear regressions of log traffic flow on the regressands. Standard errors of the means, clustered by route-direction, are in parentheses and are calculated using 5,000 bootstrap samples. Covariates for detector regressions include logged gas price, dummies for day of the week, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. Weather aggregation method 2 is used: simple averaging across all stations. Weekends are dropped from the analysis. Epanechnikov kernel and 30-day bandwidth are used in all regressions. Detector-level regressions include only those observations where Percent Observed is 100%. A minimum of 50 observations per detector are required after all deletions. Effect reported for peak time of day when maximum traffic flow occurs.

[a] Detectors is the number of detectors within the listed distance from the CBD that comprise each average treatment effect.

[b] The total number of observations entering the detector level regressions.

[c] Flow is the number of cars passing the average detector entering the regressions.

[d] The implied increase in flow on the average HOV lane detector, i.e. the CAVS policy multiplied by flow.

[e] The implied percentage decrease in flow that would be observed if the hybrids entering the HOV lane had originated in the mainline lanes.

[f] Route I-10W consists of detectors between post miles 35.239 and 18.489. These range between 3.3 and 19.2 miles from downtown LA.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.21— AVERAGE TREATMENT EFFECT BY DISTANCE FROM CBD: IMBENS AND KALYANARAMA ESTIMATION

Regressand/Lane		I	II	III
	Distance from CBD	0-10	10-20	20-30
CAVS policy/ HOV		0.108***	0.091***	0.116***
		(0.012)	(0.011)	(0.038)
	Detectors	47	114	17
CAVS policy/ Mainline		0.057***	0.063***	0.063***
		(0.006)	(0.004)	(0.010)
	Detectors	136	226	56

Notes: Values shown are the means of policy coefficients on detectors within the stated number of miles from the city center for the indicated lane from local linear regressions of log traffic flow on the regressands. Standard errors of the means, clustered by route-direction, are in parentheses and are calculated using 5,000 bootstrap samples. Covariates for detector regressions include logged gas price, dummies for day of the week, dummies for hour of the day, quadratics in rainfall and visibility, and five dummies for sky cover. Weather aggregation method 2 is used: simple averaging across all stations. Weekends are dropped from the analysis. Uniform kernel and bandwidth selected by criteria outlined in Imbens and Kalyanarama (2010) are used in all regressions. For all detectors the bandwidth selected is less than 2 days implying the average flow of 5 days closest to the discontinuity are used. Detector-level regressions include only those observations where Percent Observed is 100%. Effect reported for peak time of day when maximum traffic flow occurs.

[a] Detectors is the number of detectors within the listed distance from the CBD that comprise each average treatment effect.

*** Significant at the 1 percent level.
** Significant at the 5 percent level.
* Significant at the 10 percent level.

TABLE E.22—PLAUSIBILITY CHECK ON EFFECT SIZES

	I	II
	Morning peak	Afternoon peak
Citywide traffic flow		
HOV	132,279	131,838
Mainline	1,212,433	1,054,993
I-10 West		
HOV	9,971	5,566
Mainline	47,330	39,344
Percent on I-10 West		
HOV	7.54%	4.22%
Mainline	3.90%	3.73%
Daily L.A. commuters by car, truck, or van[1]	3,296,964	3,296,964
Percent of commuters tracked by PeMS	40.79%	36.00%
Implied pre-existing Hybrids in HOV lanes covered by PeMS[2]	6,054	5,343
Implied pre-existing Hybrids on I-10 West[3]	456	226
Daily total	682	
Caltrans I-10W HOV lane car counts (morning only)[4]	~385	—
Total stickers allocated to counties close to I-10[5]	6,880	
Daily total estimates from table D.22 — global polynomial	904	
Daily total estimates from table D.22 — local linear	528	

Notes: Flows are calculated using the following algorithm. First the maximum flow across detectors on each route-direction (e.g. I-10W) is established by hour and day. This is the minimum number of cars on each route-direction by day and hour. The hourly-route-direction values are averaged across days and then summed over hours. 1. Source: U.S. Census Bureau. 2000. Total cars may be lower as 582,020 individuals carpool. 2. Assumes 14,843 ULEVS before policy. It is an overestimate if not all adopt CAVS sticker; underestimate if ULEV drivers not using freeways before policy begin using major highways because of the policy. 3. Assumes ULEVs are distributed across city evenly. May underestimate if hybrids are more common than average along the I-10, or overestimate if less common. 4. 2007 HOV Annual Report, Caltrans District 7. Hourly count (77 hybrids) multiplied by five hours of peak traffic. A similar two hour count found 167 hybrids implying a five hour total of 418. 5. This calculation finds the closest freeway with an HOV lane to each zip code in the counties surrounding L.A. For those zip codes where the I-10W was the closest freeway, the stickers ultimately allocated to that zip code are totaled.

TABLE E.23—CITY-WIDE FLOW

		I		II	
		Morning peak		Afternoon peak	
Route	Direction	HOV	Mainline	HOV	Mainline
2	E		16,660		32,500
2	W		26,309		17,104
5	N		45,692		35,876
5	S		52,350		37,583
10	E	2,945	38,242	5,602	39,368
10	W	9,971	47,330	5,566	39,344
14	N	1,760	11,944	5,345	21,582
14	S	6,424	24,641	2,358	10,365
57	N	2,298	27,474	4,856	26,546
57	S	4,590	27,537	2,326	24,413
60	E	1,884	34,986	4,280	32,668
60	W	5,591	41,406	5,146	31,274
71	N		9,749		7,078
71	S		5,284		4,678
91	E	3,826	36,836	5,067	35,318
91	W	4,671	37,492	4,585	31,693
101	N		39,606		37,948
101	S		42,387		35,298
105	E	3,609	31,023	6,703	29,650
105	W	9,835	36,132	7,772	28,742
110	N	10,919	41,973	7,902	31,073
110	S	5,724	41,918	10,105	38,300
118	E	1,264	30,259	3,236	25,147
118	W	8,833	30,343	3,780	28,987
134	E	1,470	26,558	3,450	30,008
134	W	3,151	33,404	2,619	24,520
170	N	1,076	19,369	3,716	21,193
170	S	3,118	27,040	1,866	19,354
210	E	5,261	33,142	6,430	33,032
210	W	8,763	42,964	6,078	31,284
405	N	6,424	46,444	4,865	39,043
405	S	6,786	46,192	5,894	39,058
605	N	4,165	38,773	5,891	32,281
605	S	7,918	41,694	6,399	37,873
710	N		34,340		30,723
710	S		44,941		34,087
Sum		132,279	1,212,433	131,838	1,054,993
Total flow			1,344,712		1,186,832

Notes: Flows are calculated using the following algorithm. First the maximum flow across detectors on each route-direction (e.g. I-10W) is established by hour and day. This is the minimum number of cars on each route-direction by day and hour. The hourly-route-direction values are averaged across days and then summed over hours.

TABLE E.24—AVERAGE SPEED CHANGE FROM 2 A.M. TO 8 A.M. ON CENTRAL FREEWAYS

Route	Speed differential	HOV lane
10	-15.8	Yes
110	-15.4	Yes
60	-13.7	Yes
2	-12.8	No
105	-12.4	Yes
405	-12.4	Yes
5	-11.2	No
710	-11.2	No
91	-11.0	Yes
101	-10.6	No
605	-9.5	Yes

Notes: Speed changes are calculated by averaging speeds across detectors at 2 A.M. and 8 A.M. and differencing. Route 71 excluded due to insufficient data. 2 A.M. values are used to determine speeds during free flow. Larger differentials indicate traffic slows more due to congestion.

TABLE E.25—WELFARE EFFECTS OF THE CAVS POLICY FOR THE I-10 WEST: ROBUSTNESS

	Polynomial Order				
	7th	8th	9th	BIC	LLR
Panel A Welfare Effects					
Primary welfare gain	\$27,455	\$28,127	\$28,241	\$33,321	\$16,436
Cost-side congestion interaction effect	-\$3,843,660	-\$3,990,620	-\$4,003,590	-\$4,717,590	-\$2,478,170
Rent effect	\$623,582	\$671,882	\$672,415	\$787,292	\$510,716
System-wide congestion interaction effect	\$1,668,850	\$1,744,620	\$1,749,480	\$2,059,020	\$1,129,130
Emissions interaction effect	-\$7,067	-\$7,240	-\$7,269	-\$8,577	-\$4,231
Net welfare effect of the CAVS policy for the I-10W	-\$1,530,840	-\$1,553,225	-\$1,560,715	-\$1,846,530	-\$826,126
Excluding system-wide congestion interaction effect	-\$3,199,690	-\$3,297,846	-\$3,297,846	-\$3,905,560	-\$1,955,250
Panel B Distributional Effects					
Carpoolers using I-10W HOV lane (daily)	21,943	21,943	21,943	21,943	21,943
Hybrids using I-10W HOV lane (daily)	883	904	908	1071	528
Congestion cost per carpooler	-\$170	-\$176	-\$176	-\$176	-\$109
Rent per sticker[a]	\$707	\$743	\$743	\$735	\$967
Transfer ratio	3.46	3.31	3.32	3.35	2.62
Excluding system-wide congestion interaction effect	6.13	5.91	5.91	5.96	4.83

Notes: Central estimates - peak hours. Present value calculated over the policy or hybrid vehicle lifetime. Transfer ratio defined as the cost of transferring \$1 dollar to hybrid drivers. Author calculations.

[a] Calculation represents benefits of HOV lane access per sticker. Two-thirds of stickers went to hybrids purchased prior to the policy, whose drivers likely received this full benefit. However, the benefits associated with the remaining stickers may have been appropriated by agents other than hybrid drivers.

TABLE E.26— STATE-WIDE COST OF REDUCTIONS IN GREENHOUSE GAS EMISSIONS

		$/ton	$/ton[a]	$/ton[b]
Fraction of stickered hybrids purchased because of the policy	δ = 1/3	$1,969	$6,280	$2,542
	δ = 2/3	$314	$1003	$406
	δ = 1	$171	$545	$221
Elasticity of new VMT	σ = 0.15	$171	$545	$221
	σ = 0.50	$1,247	$3,978	$1,609
	σ = 1.00	∞[c]	∞[c]	∞[c]
Value of time	VOT = 50% of wage	$95	$302	$123
	VOT = 70% of wage	$133	$424	$172
	VOT = 93% of wage	$171	$545	$221
Fuel-efficiency of vehicles receiving sticker	MPG = 45	$171	$545	$221
	MPG = 95	$108	$346	$140
	MPG = 145	$97	$310	$126

Notes: State-wide cost per ton estimates for greenhouse gas emissions. Unless noted, δ = 1, σ = 0.15, VOT = 93% of wage rate, and MPG = 45.
Source: Author calculations.
[a] Excludes *system-wide congestion interaction effect*
[b] Using long-run estimates
[c] Emissions from induced VMT are sufficient to completely offset emissions reductions from hybrids, resulting in infinite costs of emission reductions