CLEARING THE AIR BY PROMOTING HYBRIDS?
THE UNINTENDED CONSEQUENCES OF ALLOWING SOLO-HYBRID DRIVES IN HIGH OCCUPANCY LANES[*]

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Abstract

This paper examines the overall welfare effects and distributional impacts of the Clean Air Stickers program in California. In an attempt to promote the penetration of hybrids in the vehicle fleet and reduce greenhouse gas emissions, this program allowed solo drivers of 85,000 low-emission vehicles, predominately hybrid-electric vehicles, to access to high-occupancy vehicle (HOV) lanes. Using a regression discontinuity design, we estimate the effect of the Clean Air Stickers program on HOV lane congestion, mainline congestion, and hybrid vehicle registration. We show that across specifications, travel time in the HOV lane increased significantly, while mainline travel times remained steady. Furthermore, we find no evidence that this policy stimulated registration of hybrid vehicles, and as a consequence, greenhouse gas emissions may have actually increased. Finally, we find that regardless of the effect of the program on new hybrid registration, because congestion costs dominate potential GHG emissions savings, the policy fails to pass a simple benefit-cost test. Even under our most optimistic scenario, the cost per ton of GHG emissions reduction, is substantially larger that the most costly available options to the regulator. Further, by promoting the penetration of the hybrid technology at the expense of increased travel time for carpoolers, this program was highly regressive. We estimate that it costs 9 dollars to transfer one dollar to hybrid owners.

1. Introduction

For various reasons, automobiles and the fuels they use have attracted the attention of researchers, policy analysts and policymakers.[1] Automobiles are responsible for local and global air pollution. Gasoline vehicles, for example, emit carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbons (HC). The transportation sector alone accounts for 40% of gasoline consumption and 20% of greenhouse gas (GHG) emissions (Environmental Protection Agency, 2007).[2] Increases in automobile demand also contribute to traffic congestion, which in most metropolitan areas remains unpriced. Between 1980 and 2003 annual urban congestion delays increased from 16 to 47 hours per driver, while the national cost of wasted time from congestion increased from $12.5 to $63 billion (Shrank and Lomax 2005).[3] Large metropolitan areas, such as Los Angeles, are particularly vulnerable to these various externalities associated with automobile use.[4]

To address these environmental concerns, over the years the U.S. Federal and State governments have introduced various public policies to reduce vehicle use and gasoline consumption, including policies aimed at increasing the share of hybrid vehicles in the vehicle fleet.[5] Policies to promote the purchase of these new hybrid vehicles that feature fuel-efficient technologies are also motivated by the perceived lag in adoption that often results from the lack of acceptability of new technologies by consumers (Greene, 2010; Wolverton and Helfand, 2010).

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[1] For an excellent survey of the various external costs of transportation, see Parry et al (2007).

[2] CO reduces oxygen in the bloodstream causing breathing difficulty and cardiovascular effects; HC and NOx react in the atmosphere to form Ozone (the main component of smog), which affects pulmonary function in children and asthmatics; fine particles (PM 2.5) are small enough to reach lung tissue and studies have documented a causal relationship between particulate exposure and mortality (Dockery et. al. (1993), Schwartz (1994)).

[3] In addition to these two major externalities, there are also increasing concerns related to U.S. dependence on foreign oil and traffic accidents. Dependence on oil and foreign imports exposes the US economy to energy price volatility, raising national security concerns. The US consumes 21 million barrels of oil a day, of which almost 60% is imported (up from 27% in 1985); gasoline is the single most important source of oil use, accounting for 45% of petroleum products (EIA (2006)).

[4] Earlier work by Small and Kazimi (1995) points to an average local pollution costs of 2.3 cents per mile for the Los Angeles region for the year 2000; NOx and HC emissions contribute about equally to these costs, mainly through particulate formation, while CO effects are ignored as their outdoor concentrations are too low to have noticeable health effects. Although meteorological conditions in Los Angeles are especially favorable for pollution formation, Small and Kazimi's estimates are broadly consistent with estimates for other urban areas (e.g. Donald McCubbin and Delucchi 1999, U.S. FHWA 2000).

[5] The U.S. Senate recently passed a bill that would raise corporate average fuel economy (CAFE) standards for passenger vehicles and mandate the consumption of renewable fuels. In addition, governments at both the federal and state level have implemented a variety of policies aimed at increasing the share of hybrids in the vehicle fleet. Examples of these policies include federal income tax credits, sales tax breaks and exceptions for solo drivers in high occupancy lanes (HOV) on major freeways

A popular policy, recently adopted by several states, consists of allowing solo-hybrid drivers in high occupancy lanes (HOV) in major freeways.[6] In this paper, we rely on a unique real time dataset on travel time and vehicle flow and registration data of new hybrids from California to provide the first comprehensive empirical estimates of the effects of this policy. We focus primarily on its impacts on changes in travel time to carpoolers and hybrid drivers in HOV and drivers in regular lanes, as well as registrations of ultra efficiency vehicles. We use these estimates to determine who benefits from these incentives for hybrids owners by calculating the incidence of the policy across hybrid owners who received the sticker and carpoolers; and we contrast the incidence of the costs of this policy against more standard tax-credit incentives that do not give HOV privileges to hybrid owners. We also compute the GHG emissions resulting from the policy; finally we evaluate the overall benefits of the policy, illustrating the trade-offs between the potential benefits of GHG emissions reductions against unintended increased congestion costs

Allowing solo-hybrid drivers in HOV lanes as a strategy to promote the diffusion of hybrid technologies is appealing to policymakers, given the general perception of it being a 'free' policy. Unlike most tax-credit programs, this policy requires no need for additional revenues. However, as documented in the popular press, the controversies associated with this policy continue to grow and a careful study of its potential unintended consequences is granted. On one hand, proponents of this policy argue that, by promoting the diffusion of cleaner and more fuel-efficient vehicles, these policies effectively addresses urban air pollution issues and contributes to the reduction of GHG emissions. On the other hand, opponents are quick to point to some of the potential unintended consequences of this policy. One such unintended consequence is the potential increase in travel time in HOV lanes, which in turn can create disincentives for carpool formation leading and an exacerbation of congestion. Another opposing argument builds on the fundamental law of highway congestion first documented in Downs (1962) which states that any displacement of vehicles away from the mainlines into the HOV lane would quickly replaced due to latent and induced travel demand, leading to the original flow equilibrium in the mainline and potentially more vehicles overall on the freeway. In turn, such increase in vehicles can potentially lead to higher gasoline consumption and emissions, even if some of these vehicles

[6] Of nearly twenty states with HOV lanes, nine allow hybrid vehicles to drive in HOV lanes including Arizona, Colorado, Florida, New Jersey, New York, Tennessee, Utah and Virginia. An additional six have similar bills in various states of being passed. Some require no special registration, while others require special license plates

were to be replaced by ultra-efficient cars. Finally, others argue that, these policies are ineffective at promoting the diffusion and penetration of new hybrids in the vehicle fleet because they often do not apply exclusively to newly purchased hybrid vehicles. In fact, some argue that, at least in California, these hybrid vehicles were already in excess demand by the time the policy came into place in California. As a consequence, it may have not promoted the diffusion of new hybrids but rather only constitute a transfer to existing owners of hybrid vehicles. Our estimates presented below provide magnitudes of these potential unintended consequences of the Clean Air Vehicle Stickers (CAVS) program in California.

We measure the effects of the CAVS policy in California on travel time by examining the westbound route of the I-10 – one of the busiest freeways in CA and the first to introduce an HOV lane in the U.S. – using hourly travel time data from January 2004 through December 2007 in a regression discontinuity design. Hourly travel time data is gathered from the Freeway Performance Measurement System (PeMS), which obtains 30-second loop detector data on vehicle count and occupancy in real-time from each Caltrans District Transportation Management Center (TMC). Travel times are compared before and after the implementation of the policy, with levels in previous years serving as a comparison group to control for seasonal variation. Using PeMS data on hourly flow counts on detectors across all of Los Angeles County, we present additional evidence to confirm and generalize the travel time results presented for the I-10.

We also examine the effects of the policy on the diffusion of hybrid vehicles by analyzing weekly data on new vehicle registrations in Los Angeles County. This confidential data was obtained from the California Department of Motor Vehicles' and consists of a weekly count of all newly registered hybrid vehicles by make and model, spanning from the first quarter of 2003 to the last quarter of 2007.

Finally, we rely on our estimates of the effects of the CAVS policy on travel time on HOV and mainline lanes, and the diffusion of hybrids to perform a back-of-the-envelope calculation of the welfare effects and distribution of the costs and benefits of the policy to both hybrid owners and carpoolers. For the back-of-the-envelope cost-benefit analysis, we include calculations for both travel time and GHG emissions.

This paper makes significant contributions to a growing literature on hybrid vehicles. Earlier work examined the determinants of the demand for hybrid vehicles, documenting the correlation between Prius ownership and Green Party registration and other measures of environmental preferences (Kahn, 2007a,b). More recently, researchers have applied reduced form methods (e.g. Gallagher and Muehlegger (2007) and Diamond (2009)) as well as structural methods (Bresteanu and Li (2009)) to estimate the effects of various federal and state incentives on sales of hybrid vehicles. Our paper differs from these studies in three important ways. First, while Diamond (2009) and Gallagher and Muehlegger (2007) rely on annual and quarterly data respectively, we use weekly registration data. The greater frequency of our data allows for more precision when identifying the effects of the policy. Second, unlike Diamond (2009) who examined the effects of an HOV-exemption policy in Virginia, our focus is on California, an area of the country notably known for its greener preferences. There is also anecdotal evidence of excess demand for hybrids and capacity constraints facing producers in Los Angeles. To the extent that the effectiveness of the policy is linked with such factors, we provide additional evidence of the circumstances under which such policies are likely to be more or less successful. Third, and perhaps most important, while examining the effects of incentives on hybrid sales none of these studies considers the potential unintended consequences of these incentives. Ours is the first study to systematically measure both the intended effects – that is effects on registrations – as well as the unintended effects of the policy, measured by changes in travel time in the HOV and mainlines.

Our paper also complements recent work by Sallee (2010) who examined the incidence of the tax incentives for Toyota Prius and concluded that consumers fully captured both the state and federal incentives, even though Toyota faced a binding capacity constraint. In the spirit of Sallee (2010), we examine the incidence of the CAVS policy. However, our focus is not on the incidence between consumers and producers. Instead we focus on the incidence between hybrid owners that were given the sticker and carpoolers. As a consequence, we are able to speak to the potential regressivity of the CAVS policy and calculate the cost of transferring a dollar to hybrid owners from carpoolers through this policy. As we deepen our understanding of the incidence of these types of policies across consumers, we also fill an important gap in policy evaluation because knowing who benefits from these types of policies is necessary not only to evaluate the current policy, but also to inform future legislative action. This is particularly important as these types of policies are often renewed due to their popularity, despite the potentially undesirable distributional consequences.[7]

Finally, our paper also relates to earlier work that examined the welfare effects of environmental and transportation policies in a second best setting (e.g. Bovenberg and Goulder (1996) and Parry and Small (2005)). When deriving the second best optimal gasoline tax, Parry and Small (2005) stressed the role that pre-existing distortions, such as unpriced congestion and air pollution, play in calculating the optimal gasoline tax. Here, when examining the welfare effects of the CAVS policy, we quantify the relative importance of travel time and congestion costs vis-à-vis the potential benefits that come through reductions in GHG emissions.

The rest of the paper is organized as follows: section 2 discusses the determinants of travel time, section 3 presents the data and section 4 describes the estimation strategy; section 5 examines the effects of the policy on travel time while 6 examines the effects of the policy on flow. Section 7 considers the diffusion and penetration of new hybrids. Using estimates from section 5, 6, and 7, in section 8 we perform back-of-the-envelope calculations of the efficiency effects and distribution of costs and benefits of the policy to carpoolers and hybrid drivers, incorporating GHG emissions. Finally, section 9 concludes.

2. Background on the Policy

A. California's Clean Air Vehicle Stickers Program

Beginning August 10, 2005 in California, for a small fee of $8 dollars, owners of hybrid vehicles achieving 45 miles-per-gallon (mpg) or better were able to apply for a special sticker that allowed them access to HOV lanes regardless of the number of occupants in the vehicle. The original state bill allowed the issuance of 75,000 stickers, which was eventually increased to 85,000.[8]

The stated goal of the Clean Air Vehicle Stickers (CAVS) policy was to stimulate the demand for highly fuel-efficient vehicles, particularly of ultra-low-emission vehicles (ULEV),

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[7] This often occurs, as in the case of Virginia, despite DOT assessments that the policy has significantly impaired HOV travel times. Virginia, which did not place a limit on the number of vehicles that would be allowed to participate, has seen significant increases in HOV traffic due to Hybrid cars. A Jan. 4, 2005 report by VDOT stated, "The most recent traffic counts indicate that the HOV lanes on I-95 are already operating at unacceptable levels of service at over 1,900 vehicles per lane per hour."

[8] While the state bill (Assembly Bill 2628 (AB 2628)) was passed on September 23, 2004 by the California legislature and slated to go into effect on January 1, 2005, Federal action was required as the HOV lanes in question were on Federal Interstates. The transportation bill (H.R. 3) signed into law on August 10, 2005 included a provision by Congressman Brad Sherman which authorized an exemption for states to allow cars with only a single occupant into the HOV lanes

such as the Honda Insight, Honda Civic Hybrid and Toyota Prius. Within 10 days of the signing of the bill, more than 12,000 applications for stickers were put into the DMV.[9] By February 2007, all 85,000 stickers had been issued, and hybrid drivers were unable to acquire new stickers.[10] On August 30th, 2010, Governor Schwarzenegger approved SB 535 to extend the current CAVS HOV program through June 30th, 2011. SB 535 also introduced an updated HOV program to allow for 40,000 stickers for electric, hydrogen fuel cell and plug-in hybrid vehicles. This program will begin on January 1st, 2012 and is set to expire on January 1st, 2015.

B. Similar policies in other states

Nine other states have passed legislation granting access to HOV lanes for hybrid vehicles (Arizona 2007, Colorado 2008, Florida 2008, Georgia 2004, New Jersey 2006, New York 2006, Tennessee 2009, Utah 2009, and Virginia 2000), and similar legislation has been proposed in Connecticut, Hawaii, Massachusetts, Michigan, Minnesota and Texas.[11] The particulars of each policy vary substantially by state in terms of number of stickers (or special license plates) available, fees, and specific freeway restrictions. Arizona and Colorado have restricted the number of available license plates and stickers to 10,000 and 2,000 respectively, while the remaining states allow unlimited distribution. While New York, New Jersey and Tennessee require no payment in exchange for HOV privileges for hybrids, most states require a small fee ($5-$25 dollars). New York and New Jersey only allow HOV access on the Long Island Expressway and the New Jersey Turnpike, while the remaining states allow for statewide access.

3. Data

Travel time in major highways in California is collected by the Freeway Performance Measurement System (PeMS), a joint effort by the California Department of Transportation (Caltrans), the University of California, Berkeley, and, the Partnership for Advanced Technology on the Highways (PATH). PeMS obtains 30-second loop detector data in real-time from each

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[9] "Drivers race for carpool permits for hybrids: At 1,000 applicants a day, some predict gas-saver gridlock," by Lynda Gledhill, *SF Chronicle*, 8/20/2005. http://www.sfgate.com/cgi-bin/article.cgi?file=/c/a/2005/08/20/HYBRID.TMP

[10] The stickers themselves stay with the hybrid, and both car and sticker could be transferred to a new owner.

[11] Although legislation allowing hybrid access have been passed in Georgia, to date, hybrids have not been allowed access to the HOV lane.

Caltrans District Transportation Management Center (TMC).[12] Each detector compiles data on traffic flow and lane occupancy, which are then used to calculate traffic speed.[13] We will use both travel time on a single route (I-10W) and detector level traffic flow to estimate the effect of the CAVS policy.

A. Travel time on the I-10W

Because commuters are primarily concerned with the time it takes to commute along a predetermined route, our initial analysis focuses on travel time over a single freeway route.[14] Routes are defined as a segment of the freeway system from a fixed starting point to a fixed destination and are predetermined by PeMS. A route level measure of travel time combines information from multiple detectors (usually on a single freeway) that a commuter would typically drive.[15] PeMS computes travel time over a section of freeway by dividing the length of the detector segment by the calculated traffic speed at that detector. PeMS computes route level travel time by summing across the travel time on the detector segments that form the route. The unit of observation for the route level travel time analysis is the PeMS-reported hourly travel time in the HOV and mainline lanes.[16]

Route selection

In selecting the ideal route for the route level travel time analysis, we have used the following criteria: data availability for routes before 2005, the presence of an HOV lane, and data on competing routes. All freeways for which PeMS has data for several years prior to the CAVS policy (August 2005) were considered. This early data is crucial for confidently establishing pre-policy travel times, which will serve as a counterfactual in the analysis. Freeways with an HOV lane were identified from Caltrans reports, PeMS' listing of HOV

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[12] PeMS collects data for the following districts: Districts 3 (Sacramento), 4 (San Francisco), 5 (Santa Barbara), 6 (Fresno), 7 (Los Angeles), 8 (Riverside), 9 (Stockton), 11 (San Diego), and 12 (Orange County).

[13] Lane Occupancy is the fraction of time the detector is "on" due to the presence of a vehicle <this is still rather confusing. Are we talking about the time the detector is 'on' during a 30-second period>. We never said how speed is calculated.

See PeMS FAQ for more information: http://pems.eecs.berkeley.edu/?dnode=Help&content=help_faq.

[14] By contrast, the detector level data only provides a snapshot of traffic at a single spatial point.

[15] For example, drivers commuting to downtown LA from West Covina typically use the I-10 route, those commuting from Thousand Oaks to downtown LA use US Hwy 101; drivers in San Francisco commute to San Jose using US Hwy 101.

[16] Each hourly observation from PeMS represents the average travel time for the route during that hour based on the 30-second raw detector data. <still very confusing>

detectors, and visual inspection with Google Maps.[17] Although HOV lanes are present in many districts in California, 70% are located in the five counties of the Los Angeles Metropolitan Area.[18] Based on these criteria, the I-10W east of downtown LA satisfies the criteria outlined above, with the I-210W serving as a gauge of traffic on a competing route. The 17.5 mile section of the I-10W analyzed is shown in Map 1, running between the suburb of West Covina and terminating in downtown LA. With the exception of a three-plus occupant requirement during peak travel times in the HOV lane, this route is fairly representative in terms of size and design for the L.A. region.

Basic descriptive statistics

The data set obtained from PeMS reports the hourly travel times along the I-10W route for the HOV lane and each of the four mainline lanes. Values for the four mainline lanes were averaged to create the travel time in the mainline. A maximum symmetric window of data before and after the policy is desirable, however, the length is limited by I-210W data availability. Thus the time span from January 2004 through December 2007 is considered. Finally, as weekend travel demand is substantially different from weekday demand, weekend observations are removed from the initial analysis resulting in a total of 34,980 hourly observations by lane.

Table 1 presents weekday travel time averages for each lane and route, including the I-210W, during the four peak and off-peak periods.[19] The table also reports travel times normalized by the length of the road as well as standard deviations for 2004-2007. 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 transportation theory, drivers equalize

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[17] See *2007 HOV Annual Report*, Caltrans District 7 for information on HOV lanes and Table A.1 in Appendix A for more information on various routes.

[18] See: http://www.metro.net/projects_studies/hov/faqs.htm; while it would be important to conduct similar analysis for other districts, in particular San Francisco due to substantial hybrid demand, PeMS does not separately calculate travel time for HOV and mainline lanes on District 4 freeways. <good>

[19] Morning peak is defined by Caltrans as 5 A.M. to 9 A.M. and afternoon peak as 4 P.M. to 7 P.M. The mid-day off-peak corresponds to 10 A.M. to 4 P.M. and the night off-peak from 8.P.M. to 4 A.M.

travel costs across these routes with the faster speed on the I-210W compensating for its less direct, peripheral route.

Figure 1 plots the average travel time for the HOV and mainline lanes of the I-10W across the hours of the day. The figure reveals substantial variation in travel times over the course of the day, with maximum travel time levels of over 35 minutes in the mainline reached during the morning peak. This figure also underscores the large differential between mainline and HOV lane travel times during the morning peak, with a maximum difference of nearly 10 minutes at 7 A.M. Because of this variation, we suspect that the policy will have heterogeneous effects throughout the day, and as a consequence, we also examine the effects of the CAVS policy on travel time during the various hours of the morning peak. While this route level data allows us to explore the heterogeneity of the CAVS policy across various times of the day, it does not allow for exploration of the effect across various areas of the city. To explore the spatial effects of the policy and to gauge the generality of the results on the I-10W, we next consider a detector level dataset of traffic flow spanning the LA area.

B. Detector level data

We estimate the effect of the CAVS policy during peak hours using a comprehensive dataset of 677 detectors.[20] These detectors record hourly observations of traffic flow on 18 freeways in Los Angeles. The wide spatial distribution of the final set of detectors used in the analysis can be noted in Map 1. Relative to the route level analysis, the detector level analysis has advantages and disadvantages. Although these detectors can provide insight into how the CAVS policy affected traffic flow across the city, they only represent traffic patterns, flow and speed, at specific locations and not the factor that affects commuter welfare: travel time across actual commuter routes. Moreover the large size of the dataset (2.3 million observations for only three months of data) makes analysis computationally expensive.[21] Despite these disadvantages, this dataset provides the advantage of generalizing our findings to freeways other than the I-10W, and the increased power from the larger dataset allows for more precise estimates of the effect of the CAVS policy.

[20] As discussed below, peak hour in the detector level analysis refers to the period of day when a given detector experiences maximum flow.

[21] Specifically, the larger dataset constrains us to use local linear regression discontinuity techniques for the analysis, whereas the travel time analysis incorporates both local linear and global polynomial techniques. See below for further discussion.

Hourly traffic flow is collected by PeMS and is counted separately for HOV and mainline lanes. Three months of data, July-September 2005, provide hourly traffic flow observations for 1,750 detectors across 18 freeways, including all freeways with HOV lanes. Not all of the 1,750 detectors are used in our final analysis. Detectors located at on- and off-ramps are deleted from the analysis. Each detector is also required to have at least 1,000 hourly observations in total and at least 50 observations for each regression after all deletions.[22] As is the case for the I-10W, many arterial routes have a dominant commuting pattern such that only one peak time of day may experience congestion. Although we estimate the effect of the CAVS policy for each detector during both peak periods, we report the policy effect during the peak period with maximum traffic flow during the three-month period.[23] This ultimately yields 677 individual detector level estimations of the effect of the CAVS policy on traffic flow, 200 of which are located in HOV lanes.

C. Other covariates

Weather data

The PeMS data is supplemented with hourly measures of weather from the National Weather Service at nine airports in the Los Angeles area.[24] These measures include rainfall in inches, visibility in miles, cloud cover as a percentage of the sky, temperature in degrees Fahrenheit and wind speed in miles per hour. The Fullerton station is closest to the I-10W, and data from this station is matched to the travel time data.[25]

Because rainfall, visibility and sunlight glare can have effects on traffic speeds, variables to control for these factors are included in our main specifications. In the central specification, linear and quadratic terms of hourly rainfall in inches are included. Visibility in miles is also

[22]These deletions include hours outside of the specified peak period, weekend observations and observations labeled as less than 100 'percent observed.' Where detectors are not properly functioning, PeMS imputes missing values. By dropping all observations where 'Percent Observed' is less that 100, all data with PeMS imputation are removed from the analysis.

[23] This method implies that for nearly all of the detectors that comprise the I-10W route above, the morning peak is selected as the most congested time of day, as expected. Detectors for which the maximum traffic flow occurs outside the peak periods are also excluded, as a detector with maximum flow occurring at 2 A.M. is of questionable quality.

[24] These include Chino, Fullerton, Hawthorne, Hollywood, Long Beach, Los Angeles, Ontario, Santa Monica and Van Nuys.

[25] For the Fullerton station, of the 35,064 total observations, 840 had at least one weather measure missing. These missing weather measures are imputed from the other stations in the Los Angeles area, following the algorithm used in Auffhammer and Kellogg (2010). See Appendix C for further detail.

included as linear and quadratic terms and ranges between 10 miles on clear days to 0.2 miles on the foggiest. Cloud cover, ranging from 0 to 100 percent, is divided into five, equally spaced indicator variables. Because cloud cover reduces sunlight, these indicator variables control for the potential that sunlight glare may affect driving patterns. Several robustness checks also include measures of temperature, (prolonged) wind speed and wind gusts. Temperature is included as three indicator variables, below 80 degrees, 80 to 100 degrees, and above 100 degrees. Wind is included as an indicator variable for sustained wind speeds above 20 miles per hour and similarly an indicator for wind gusts indicates gusts above 20 miles per hour.

Gasoline price data

Data on weekly retail gasoline prices for Los Angeles from 2004 to 2007 were obtained from the Energy Information Administration. Regular reformulated (nominal) prices in cents were logged. During the period of study, the price of regular reformulated gasoline in L.A. ranged from a low of $1.60 per gallon in January 2004 to a high of $3.46 per gallon in May 2007. These values were not deflated for the analysis because the time span is relatively narrow and deflation would introduce discontinuities into the data.

4. Empirical strategy

We begin by describing the empirical strategy utilized to estimate the effect of the CAVS policy on travel time on the I-10W. In the main specification, logged hourly travel time in lane *i* on date t, TT_t^i,[26] is regressed on $1(Hybrid)$, an indicator variable for observations after the implementation of the CAVS policy,[27] a vector of covariates X_t and a flexible polynomial in date $f(Date_t)$:

$$TT_t^i = \alpha^i + \beta^i \cdot 1(Hybrid_t) + \gamma^i \cdot X_t + f(Date_t) + \varepsilon_t^i \qquad (1)$$

The coefficient of interest is β^i, which is the percent effect of the CAVS policy on travel time in lane *i*. The vector of covariates X_t includes indicator variables for month of the year interacted

[26] In the main specification, hourly observations within each peak or off-peak period are grouped by date creating a panel with a fixed effect for each hour.

[27] Policy date is taken to be August 20th, 2005, which is when the stickers first became available. The sensitivity of our results to this date choice is tested with robustness checks. Because all CAVS stickers were not immediately released on this date, it is possible that our estimates of the effect of the policy on travel time are biased towards zero, yielding conservative estimates of the policy. As discussed in the results below, plausibility checks of our estimates are performed, which suggest that the magnitude of this downward bias is not substantial.

with day of the week, and indicators for hour of the day. Additional controls include weather variables (rainfall, visibility, and cloud cover in the central specification), logged gas prices, and travel time on competing routes (I-210W). Because drivers optimize across routes, travel time on the I-210W is lagged by one hour to avoid endogeneity concerns.[28] As a point of comparison, Equation (1) is first estimated without $f(Date_t)$ using standard ordinary least squares (OLS) methods for various time windows around the implementation of the policy. As these estimations are potentially biased, Equation (1) is then estimated using a regression discontinuity design, employing both global polynomial and local linear methods.

OLS estimation

The effect of the policy is first estimated using OLS without $f(Date_t)$. Two different time windows are considered: the full data set (Jan 2004-Dec 2007), and a 2-year window (Aug 2004-Aug 2006). In the spirit of Davis (2008), we narrow the time window around the policy date in order to disentangle the effect of the CAVS policy on travel time from the effect of other time-varying factors.[29] The potential for omitted time-varying factors to confound our estimation make observations substantially before or after the implementation of the policy less informative about the effect of the policy on travel time. Without controlling for these time-varying factors, the error term may be correlated with time, and thus with 1(Hybrid), producing biased estimates of β^i.

RD: Global polynomial

The regression discontinuity design addresses the bias introduced by unobserved time-varying factors by considering an arbitrarily narrow window of time around the implementation of the policy. Within the narrow window surrounding the policy start date, the CAVS program began allowing large numbers of hybrids into HOV lanes, leading to a step change in travel time. Provided that all other factors affecting travel time, besides the CAVS policy, are continuous at the policy date, the RD design will yield a consistent estimate of the effect of the policy.[30]

[28] As a robustness check, estimations without the inclusion of the 210 are also performed, yielding results similar to the key findings presented below.

[29] Examples might include changes in demand for the goods and services provided by business along the I-10 or population growth (or decline) in the areas serviced by the I-10.

[30] Under reasonable assumptions, RD yields consistent estimates of β^i in the presence of time-varying omitted variables. Hahn, Todd, and Van der Klaauw (2001) show that nonparametric identification of a constant treatment effect with a sharp RD design requires that the conditional mean function is continuous at the threshold. If other discontinuous, unobserved changes occurred at the policy date, the effect of those unobservables would be

Equation (1) includes a flexible n^{th} order polynomial in the date, $f(Date_t)$, which controls for unobserved, time-varying factors that evolve smoothly and may influence travel times but are unrelated to the policy.[31] Following the approach of Davis (2008) and DiNardo and Lee (2004), an eighth-order polynomial was selected as the most parsimonious specification that adequately describes the underlying time trend with a reasonable degree of smoothness.[32]

While the global polynomial method better accounts for unobserved time-varying factors, misspecification remains a concern. Imbens and Lemieux (2008) note that although the properties of global polynomial methods are as attractive as those of kernel methods such as local linear regression, global RD estimates may be more sensitive to observations far from the discontinuity. Thus, in addition to the eighth-order specification, estimates for sixth through tenth-order polynomials are reported below.

RD: Local linear

As a robustness check of the global method results, local linear estimations of Equation (1) are also reported below. In a local linear regression, time varying factors are controlled for with a linear trend within some local bandwidth of the policy discontinuity. Separate linear trends are estimated on either side of the policy threshold, with the effect of the policy given by

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indistinguishable from the effect of the policy. For example lane closures due to construction would cause discontinuities in traffic flow. To reduce the likelihood that the effects observed below are caused by other such scenarios we perform several robustness checks including an examination of weekend travel time that would be affected by construction but not the CAVS policy.

[31] An alternative approach to the regression discontinuity design would be to use a difference-in-differences approach. However, it is difficult to construct an appropriate control group. As all freeways in California were subject to the policy no freeway in California could be considered untreated. Comparing against a freeway outside of California would strain the necessary assumptions of the difference-in-difference approach.

[32] The most common method of polynomial selection in the literature chooses the polynomial order that smoothly describes the underlying trend in the data, while presenting estimates for alternative polynomial orders (Lee and Lemieux, 2009). As this involves a substantial element of modeler discretion, misspecification is a concern. As DiNardo and Lee note, misspecification of the polynomial order (for example, using an eighth-order polynomial when the “correct” polynomial l is a sixth-order) can lead to biased estimates of the discontinuity and erroneous interpretations of statistical significance. An alternative method for polynomial selection is to use a more formal model fit criterion, such as generalized cross-validation (Van der Klaauw 2002, Black et. al. 2007,) or information criteria such as the Bayesian Information Criterion (BIC) (Matsudaira, 2008). The BIC method removes some of the modeler discretion by trading goodness-of-fit against a penalty for including additional regressors; however, the BIC may reward model fit in portions of the data set far from the policy date. Consequently, the polynomial order that minimizes the BIC statistic may do a poor job of fitting the data near the discontinuity. Acknowledging these tradeoffs, we determine the order of our preferred polynomial using both data inspection and the BIC. It was determined that an 8^{th} order polynomial best approximates the underlying time-varying trend in the data. The BIC chooses the 8^{th} order for the mainline during the peak morning supporting our choice of this specification as our preferred polynomial order. For completeness we also report results for other polynomial orders in the tables of results. Graphs of other polynomial orders are included in Figures B.1-11 in Appendix B.

the difference in the limits of the expectation functions approaching the policy start date from above and below. The critical assumption is that within the narrow bandwidth, unobserved time-varying factors can be approximated by a linear trend (Imbens and Lemiux, 2008). While local linear methods avoid modeler discretion in choosing the order of the polynomial, a choice of bandwidth and kernel must be made. We test our estimates across a variety of bandwidths and alternate kernels.[33]

The local linear specification is also used for the detector level analysis of the effect of the CAVS policy on traffic flows. As noted in the data section, the size of the detector level data prevents us from using the global polynomial specification. In detector level analysis, the dependent variable is logged-hourly traffic flow and covariates include weather covariates as well as hourly fixed effects.[34] The effect of the CAVS policy is estimated using local linear regression on each detector across the three month period. To determine the citywide effect of the policy on traffic flows in HOV and mainline lanes, the RD estimates for HOV lane detectors are averaged.[35]

5. The effect of the CAVS Policy on travel time: Evidence from the I-10

A. Results

Table 2 reports the OLS regression estimates of the effect of the CAVS policy on travel time on the I-10W. For each time window and lane, the table reports the point estimate and standard error for the coefficient of interest, the percentage effect of the CAVS policy on travel time, broken down by morning peak, afternoon peak and off-peak periods.[36] Columns I and V display the point estimates for the full data set (2004-2007). These point estimates are positive and significant in every lane at all times of day. Travel times increased 7.0% in the HOV lane during the morning peak, 6.7% in the afternoon and 5.3% during the mid-day off peak. Increases in travel time of 4.6% are also observed in the morning peak on the mainline, and during the afternoon peak (4.9%) as well as during the mid-day off peak, (5.9%).

[33] We adopt the Epanechnikov kernel in our preferred specification and perform robustness checks using the Triangle and Gaussian kernels in Table A.11 in Appendix A.

[34] Instead of using only weather covariates from Fullerton airport, weather variables are averaged across all stations in this specification.

[35] Standard errors are determined by 1,000 bootstrap simulations of the average.

[36] These regressions include gas price, lagged I-210 W travel time, weather covariates, indicator variables for hour of the day, and for month-day of week or day of week as noted. While standard tests suggest serial correlation is not a major concern, standard errors clustered at the week level are included in parenthesis for all regressions.

The remaining columns narrow the time window around the policy date. Columns II and VI present the policy coefficients for a window of one year on either side of the policy. The only estimates that remain statistically significant are those for the HOV lane. The morning peak point estimate (7.1%) remains roughly consistent across different time windows, with an increase in travel time of 7.3% during the afternoon peak and a 6.0% increase during the night off-peak. However, one should be suspicious of these results for at least two reasons. First, these estimates seem to contradict Figure 1 which indicates that the time differential between the HOV lane and the mainline is greater during the morning than the afternoon, suggesting the policy should have a greater impact during the morning peak.[37] Second, the mainline estimates are particularly sensitive to the choice of time window. This dependence on window length confirms concerns that OLS results could be biased by other time-varying factors, such as population growth or macroeconomic conditions, which are omitted from the estimation but could affect demand for travel.[38] This problem of dependence on window length was also encountered in Davis (2008), which examined the effect of driving restrictions on air pollution in Mexico City, where all factors affecting air pollution could not necessarily be controlled for. In the spirit of Davis (2008), we present global regression discontinuity estimates of the effect of the CAVS policy; further, we present local linear regression discontinuity estimates using a narrow window with a linear trend to control for unobserved time-varying factors.

Regression discontinuity estimates

Figure 2 illustrates the regression discontinuity strategy for estimating the effect of the CAVS policy on travel time.[39] Panel (a) depicts travel time residuals in the HOV lane during the morning peak and panel (b) for the mainline. Similarly, panel (c) depicts the HOV lane residuals during the afternoon peak and panel (d) displays the residuals for the mainline during the afternoon peak. Panels (e) – (h) present travel time residuals during off peak periods. The plotted points represent the averaged weekly residuals of log travel time regressed against the

[37] When the time differential between the HOV and mainline lanes is the largest, stickered hybrids will have the strongest incentive to move into the HOV lane - not just from the I-10 mainline but also alternate routes without an HOV lane option. Times of day with low levels of congestion will give hybrid drivers less incentive to drive in the HOV lane and reduce their travel time. During off-peak hours, traffic is free flowing and travel time will be invariant to the addition of hybrids. At these times the policy should have no effect. Congestion, as modeled by Vickery (1969), only occurs once total traffic exceeds a threshold level.

[38] Although further narrowing of the window may reduce this bias, these estimates would no longer control for seasonal variation.

[39] In these estimates we controlled for changes in travel time associated with weather and gasoline shocks as well as the weekly and monthly patterns of travel.

covariate vector X_t. These residuals should reveal any underlying trends of time-varying factors as well as any discontinuous changes in travel time at the policy date. The fitted lines are the predicted values of a regression of these residuals on our eighth-order polynomial and the CAVS policy variable. The eighth-order polynomial captures the underlying time trend while exhibiting a reasonable level of smoothness.

Consistent with the OLS estimates presented above, panels (a) and (c) reveal that travel time in the HOV lane increased during peak hours due to the CAVS policy, and that these effects are larger during the morning peak than in the afternoon. In sharp contrast to the OLS results, the panels appear to show no effect of the policy on travel time in the mainline. A closer examination of these panels reveals that congested lanes and times of day display noisier plots than less congested conditions. Indeed, as documented in Shrank and Lomax (2005) over half of congestion delays are the result of non-recurring events. During congested periods small accidents or shocks to demand can cause travel times to deviate substantially from predicted levels.[40]

Table 3 presents the regression discontinuity estimates of the effect of the CAVS policy on travel time.[41] The preferred specification of the eighth-order polynomial is presented in column III. Consistent with Figure 2, the results in column III confirm that the increase in travel time during the morning peak on the HOV lane is 9.0% (2.2 minutes) and is statistically significant at the 1% level. Columns I-VI of Table 3 also present results for sixth- through tenth-order polynomials, as well as the results for the polynomial order chosen under the BIC.[42] Across specifications, the estimate of the effect of the CAVS policy on travel time in the HOV lane is relatively stable, ranging between 8.4 and 11.6 percent, and is statistically significant at the 1% level. The point estimates in the afternoon peak, 5.7 to 6.7 percent, are smaller than those estimated during the morning peak, consistent with the fact that congestion is most severe in the morning peak.

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[40] Small and Chu (2003) further examine hypercongestion events. During hypercongestion, small events cause even larger delays than normal.

[41] Robustness checks of the global polynomial regression discontinuity estimates are presented in Tables A.6-A.8, and the results are in general consistent with those in Table 3. These robustness checks test the sensitivity of the results in our main specification by altering covariate specifications (fixed-effects, controls for competing routes, additional weather covariates, inclusion of holidays and gas prices), removal of days near the beginning of the policy, estimating separate polynomials on either side of the discontinuity, and altering weather aggregation methods

[42] The BIC selects the 8^{th} order polynomial as the preferred specification in the mainline during the morning peak. For the morning peak HOV lane, a 10^{th} order polynomial specification is chosen.

How plausible are the increased travel times in the HOV lane?

The introduction of the CAVS policy resulted in an initial distribution of nearly 15,000 stickers, with another 10,000 stickers distributed to Los Angeles area drivers slowly over time. To the extent this prolonged distribution may bias our estimation downward, we validate the plausibility of our results.[43] Caltrans occasionally performs car counts detailing the number, type and occupancy of cars passing a point on major freeways in California, including the I-10W. A two-hour car count conducted between 6:30 A.M. and 8:30 A.M. in 2006 found 167 single occupancy hybrids traveling the HOV lane. This represents 5.8% of total vehicles counted in the HOV lane by Caltrans during that time, implying the policy increased traffic flow by 5.8%.[44] Using a conventional speed-flow elasticity of 0.7, a 5.8% increase in traffic flow corresponds to an increase in travel time of 8.3%. Our estimate points to a 9% increase in travel time in the HOV lane during the morning peak, a value which is statistically indistinguishable from the 8.3% increase suggested by the car count data.[45]

Mainline effects

Table 3 reports the estimated effect of the CAVS policy on mainline travel times. Across specifications, there is no evidence that the CAVS policy affected mainline travel times, as none of the estimates are statistically different from zero at the 5% level. From the perspective of policymakers, one possible benefit of the CAVS policy is congestion relief for mainline drivers as hybrid cars move to the HOV lane. Economic theory (Vickery 1969) however, would suggest

[43] This downward bias may arise because the regression discontinuity method may not fully capture the effect of the stickers distributed significantly after the introduction of the policy, . However, much of as the effects from the portion of stickers distributed later in the program would be captured in the time-trend polynomial. Table A.7 in Appendix A presents estimates that allow the slope of the polynomial to interact with the policy. Table A.7 also presents results removing data from August 20 to September 5 to test the robustness of our estimates to a longer introductory phase. Removing substantially more data may bias the results as time varying factors cannot be distinguished from the effect of the policy.

[44] We can also check these effects by looking at proportions of traffic in California and Los Angeles and associating those with the sticker distributions. PeMS observes, on average, 1.3 million drivers during the morning peak of the 3.3 million commuters each day in L.A., which translates to 41% of all drivers in L.A. There are 132,279 HOV lane drivers tracked by PeMS, of which 7.5% or 9,971 drivers use the I-10 West. If the 14,843 hybrids that existed in L.A. prior to the policy all received stickers and were observed in similar proportion, approximately 6,000 would be observed by PeMS and 456 would be observed on the I-10 W during the morning peak. The daily total following a similar procedure for the afternoon peak would imply 682 hybrid drivers during the course of a day. See Table A.16 in Appendix A for a detailed explanation.

[45] Another possible crosscheck on these values is to use the total number of stickers ultimately delivered to each zip code. When the nearest freeway with an HOV lane is determined, it was found that 6,880 stickers were ultimately delivered to zip codes where the I-10 was the closest freeway with an HOV lane. Although many of these would be unlikely to use the route segment analyzed here, it suggests that the areas surrounding the I-10 received many stickers. See Table A.16 for further detail. Appendix D further details the translation of the travel time changes to car counts.

that induced demand, either from other routes or from new trips, would reduce some or perhaps all of these travel time savings. While the estimated discontinuities of travel time in the mainline lanes are not statistically different from zero, these estimates do not have sufficient statistical power to determine whether induced demand occurred.[46]

Taken at face value, a zero effect of the CAVS policy on travel time in the mainline is consistent with the fundamental law of highway congestion first presented by Downs (1962).[47] This law states that in response to an increase in highway capacity, travel time will return to previous levels of congestion by inducing traffic from other routes, and by individuals driving further and increasing their number of trips.[48] By removing vehicles from the mainline, the CAVS policy is effectively equivalent to an increase in highway capacity, potentially allowing new trips to arise and various agents to re-optimize their travel decisions. Drivers who had used other routes may start using the I-10W, and demand may increase during the peak (Arnott et al., 1993) on the I-10W in response to this new capacity.

B. Robustness checks

Local linear RD estimates

Table 4 presents the local linear RD estimates of the effect of the CAVS policy on travel time with observations weighted using an Epanechnikov kernel.[49] The central case of a 60-day bandwidth is presented in columns II and VII. The estimated effect of the CAVS policy on travel time is 7.2% in the morning peak HOV lane and is the only statistically significant result, at the 1% level. Across the different specifications, varying bandwidths between 50 and 90 days, the results are generally consistent with those found under the global RD method, albeit of slightly smaller magnitude. Under the local linear specification, the increase in travel time in the HOV lane during the morning peak is slightly smaller in magnitude (5.8 to 7.2%). It should be

[46] Without induced demand, simulation calculations suggest that the point estimate of the CAVS policy for the mainline lanes would be -0.018. The 95-percent confidence interval for the morning peak mainline point estimate of 0.069 and a standard error of 0.051 only rejects point estimates smaller than -0.031.

[47] The detector level analysis below estimates changes in traffic flow with more precision and provides evidence that at least some non-hybrid drivers adjusted their commutes in response to the CAVS policy.

[48] More recent studies, such as Duranton and Turner (2009), examine the effects of changes in capacity of the road network on vehicle-miles-traveled (VMT) and conclude that the long-run VMT elasticity with respect to capacity is unity. Cervero (2002) presents an overview of induced demand estimates and finds large disagreement on the magnitude of these effects in both the long and short term.

[49] All specifications include gas price, lagged I-210 W travel time, weather covariates, indicators for hour of the day, and day of week and a linear time trend in date. Standard errors, in parentheses, are clustered weekly. In Table A.11 in Appendix A, robustness checks using Triangular and Gaussian kernels are performed and yield similar results.

noted that the local linear method corrects for seasonal trends to some degree, but in a different fashion (through kernel weights and linear time trend) than the global polynomial approach. This may explain the differences in point estimates in the HOV lane during the morning peak and the absence of increases in travel time in the HOV lane during the afternoon peak.[50] As in the global polynomial specification, we do not find an effect of the CAVS policy on travel time in the mainline.

Effects of the policy by time of day

Thus far, we have examined the effects of the CAVS policy at peak and off-peak periods and calculated the average treatment effect. However, it is likely that these effects will vary even within peak periods, especially during the morning peak. Small (1982) finds that individuals will adjust work-trip departure times in response to changes in congestion and that such behavior can result in heterogeneous effects across the peak. Hybrid drivers previously commuting in the mainline may depart closer to their preferred time, given access to the lower congestion HOV lane. Therefore, we now estimate the hourly effects of the policy.

Table 5 presents the effect of the policy, broken down by hour under the preferred specification of an eighth-order global polynomial. The distribution of magnitudes does not seem to be randomly distributed but rather mimics the congestion levels noted in Figure 1. Congested times of day are most affected by the CAVS policy. As expected, the point estimate is insignificant at 5 A.M. and is largest during the most congested hours from 8 to 9 A.M. These magnitudes grow as rush hour progresses from 8.8 percent at 6 A.M. to 12.5 percent at 9 A.M. Arnott, de Palma and Lindsey (1993) note that congestion is often dependent upon the previous period, an effect that can be noted by the 7.2 percent increase at 10 A.M., an hour after the morning peak.[51] Also note that the effect of the policy on travel time is again most pronounced during the congested evening peak hours of 5 and 6 P.M. with effects of 6.0 and 8.2 percent respectively.

Further analysis

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[50] Tables A.9-11 in Appendix A present various robustness checks for the local linear specification, demonstrating that the estimates in Table 4 are valid across a wide variety of covariate and kernel specifications. However, as the data used is already limited by the bandwidth, some robustness checks performed in the global specification involving small subsets of data cannot be performed with the local linear specification.

[51] It can also be noted in Figure 1 that the peak as defined by the HOV regulations may not fully cover the true peak and that 10 A.M. has high demand. The asymmetric nature of travel times is also noted by other authors such as Small, Winston and Yan (2005) who document that travel times grow until late in the peak due to persistence of events earlier in the day.

The estimates presented above provide strong evidence that the CAVS policy increased travel times during peak hours on the HOV lane while mainline travel times remained unchanged. It is plausible that the pattern of effects found are the result of standard seasonal changes or that the patterns found are not unique. Furthermore, one may be concerned that the estimates are the result of demand changes unrelated to the policy. Two key tests are performed below: varying the policy date and estimating the effect of the policy on weekend travel times only.

Alternative policy dates

First, one may be concerned that the effects found in the HOV lane are the result of seasonal variation or that the technique would frequently find such discontinuities in travel time.[52] Estimating the effect of a false policy starting one year earlier or one year later would be a simple way to test the validity of the identification strategy. If the increases in travel time in the HOV lane during congested peak periods disappear when tested a year before or after the actual policy date, then the findings described above are strengthened.

Table 6, columns I, III, V, and VII, present the regression estimates of these false policy dates using the global polynomial approach under the preferred specification and an eighth-order polynomial time trend. In columns, I and V, the policy variable becomes active on August 20, 2004, and for columns III and VII, becomes active on August 20, 2006. None of the point estimates are significant at the 5% level in the HOV lane.[53] Together, these results establish that the pattern of effects on August 2005 (columns II and VI) are unique and re-enforce our finding that the changes to travel time that occur are the result of an actual change in travel time induced by the CAVS policy.

Weekend tests

Travel time on weekends is rather different than on weekdays, as weekend travel is relatively free flowing.[54] On the I-10W, for example, mean travel times on Saturday and Sundays

[52] In general, freeways can experience shocks from events such as highway construction or seasonal shifts in demand, which may introduce discontinuities that lead to prolonged changes in travel time. Such changes would affect all lanes and not just HOV lanes. These tests illustrate that the estimated discontinuities found above are infrequent and are not seasonal. To the extent that other shocks throughout the year may be approximated with a reasonable degree of smoothness, our flexible functional form should allow us to account for the effects of such events.

[53] In the mainline the only point estimate that is statistically significant at the 5% level is a decrease of 4.1% for the afternoon peak drivers using a false policy starting on August 20, 2004. This decline may represent a statistical anomaly or a one-time change in travel times, such as the reopening of a mainline lane after a period of construction.

[54] It is for this reason that weekends are removed from the analysis above.

at 9AM are around 15 minutes for mainline drivers, which is nearly 20 minutes lower than during the week. Because the road is free from congestion, the CAVS policy provides less incentive for hybrid drivers to use the HOV lane. Therefore, we estimate discontinuities for weekend travel times, which should be small and insignificant. On the other hand, if the weekday travel time results presented above are driven by some broader demand change unrelated to the CAVS policy, or perhaps due to a change in measurement methods by PeMS, one might expect to see increased weekend travel times as well.

Table 6 columns IV and VIII present global polynomial RD estimates using only observations from Saturdays and Sundays. None of the coefficients are significant at the 10% level, and there is no evidence that the CAVS policy affected weekend travel times. This is consistent with the policy primarily affecting congested travel times when the incentive for hybrids to use the HOV lane exists.[55]

6. The effect of the CAVS policy on traffic flow: evidence from the detector level analysis

Thus far, we have established convincing evidence of the effect of the CAVS policy on travel time on the I-10W, particularly the increased travel time in the HOV lane. It is unclear, however, if these changes are unique to the I-10W, and therefore an analysis from a larger set of roads can help generalize these results. <setical may be concerned with lack of statistically difference with the mainlane>Furthermore, the larger data set will allow for more precise estimates of the effect of the policy on mainline lanes. If the route level travel time estimates are correct, the policy should lead to increased traffic flow on HOV lanes citywide, and if agents adjusted to fill the capacity created by hybrids moving out of the mainline lanes, no change in traffic flow in mainline lanes would be observed.

Can the effects of the CAVS policy in the I-10W be generalized?

Figure 3 plots the kernel density smoothed distribution of the effects of the CAVS policy on traffic flow for both mainline and HOV lanes. While the mainline detectors indicate little evidence of an effect of the policy on traffic flow, there is a positive shift of 5.7% in the HOV lane, statistically significant at the 1% level, indicating that citywide traffic flows in HOV lanes

[55] Table A.9 in Appendix A repeats this estimation using local linear RD. This specification suggests there was a 2.5% increase in travel time during the morning peak. Although this is much smaller than the weekday morning peak values, it is possible that modest congestion on weekend mornings contributes to this effect.

increased after the policy. Applying a speed-flow conversion factor of 0.7, [56] a 5.7% increase in traffic flow in the HOV lanes is equivalent to 4% increase in travel time for HOV lane drivers.[57]

Figure 4 highlights the heterogeneity across detectors. To compare the I-10W to other roads, we compare the results for detectors along the I-10W with the route level analysis above and with detectors located at a similar distance from the central business district (CBD).[58] Estimates of the policy effect on traffic flow for the I-10W are presented in Table 7 column IV.[59] For detectors on the I-10W HOV lane, the mean estimate of the effect of the CAVS policy is that it increased traffic flow by 9.6%. This implies that travel time in the HOV lane would have increased 6.7% on I-10W detectors, which is statistically indistinguishable from the estimate of 7.2% found in the route level analysis using local linear regression (Table 4 column II). The I-10W mainline estimates find a statistically insignificant increase in traffic flow of 0.4%, similar to the route level travel time analysis.

In addition to confirming the route level travel time results presented above, these magnitudes also illustrate that the increased traffic flow in the I-10W HOV lane was similar to the increase in traffic flow found on freeways at the same distance from the CBD. The segment of the I-10W analyzed in the route level analysis runs from 3 to 20 miles of the CBD. Column I presents the average point estimate of detectors within 10 miles of the CBD is 9.1%, which is statistically indistinguishable from the 9.6% estimate for I-10W detectors. This similarity can also be seen in Figure 4, which demonstrates that despite the different HOV lane passenger restriction, the distribution of effects found on the I-10W is similar to those for detectors located on other freeways in downtown Los Angeles.[60]

How does the effect of the CAVS policy vary across the city?

[56] See the welfare analysis and Appendix D below for more on this relationship and how it is estimated.

[57] The citywide estimates of a 5.6% increase in HOV lane flow are larger than the central estimates of 2% reported by Brownstone et al. (2006). Alternative specifications based on car counts conducted in Virginia yielded estimates of a 7% increase in flow, similar to our estimates for detectors within 20 miles of the CBD. Note that the Virginia policy, begun in 1999, required applying for a special license plate, however there were no restrictions on the number of license plates distributed before July 1, 2006. New hybrid owners can continue to apply for a license plate allowing them to drive in the HOV lanes on the I-66 and Dulles Toll Road.

[58] As noted by Giuliano and Small (1993) and Anas et al. (1998), L.A. has multiple CBD's. Here the CBD was chosen to be intersection of the I-10 and I-5 freeways. This corresponds to the area near Union Station in LA.

[59] The detectors considered for this analysis were only those that fall along the portion of the I-10 route analyzed in the sections above.

[60] This suggests the 3+ occupancy restriction for the I-10 versus the 2+ restriction for other freeways is not a significant source of the heterogeneity of the policy effect.

To further explore the heterogeneity of the effect, Table 7 reports the average estimated impact of the policy on traffic flow by distance from the CBD. As noted above, for detectors within 10 miles of the CBD, column I reports a mean effect in the HOV lanes of 9.1 percent, while the mean estimated effect in the mainline lanes is a statistically insignificant 1.5%. Columns II and III increase the distance from the CBD to 20 and 30 miles respectively. As the distance increases, the effect of the CAVS policy on traffic flow in the mainline remains small and insignificant, while the effect in the HOV lane attenuates with distance (though remains statistically significant). For detectors located within 30 miles of the CBD, the mean estimated effect of the policy on traffic flow is 5.7%, statistically significant at the 1% level. Furthermore, as can be noted from the densities in Figure 4, the distributions become less concentrated and are centered closer to zero as the distance from the CBD increases.[61]

Further evidence of a negligible impact of the CAVS policy in the mainline

The effect of the CAVS policy on mainline traffic flow is estimated with more precision in the detector model than the route level analysis, due to the substantially larger dataset. In the most precisely estimated case, for detectors within 10 miles of the CBD, the point estimates and standard errors can provide deeper insight into the behavior of mainline drivers. Based on the estimated increase in traffic flow in the HOV lanes, a hypothetical decrease in mainline traffic flow of 1.7% would be observed in the absence of induced demand.[62] The estimated effect in the mainline in Table 7 is statistically different from this hypothetical scenario, implying that at least some agents adjusted their commuting patterns and began using mainline lanes. The 95-percent confidence interval not only rejects a hypothetical decrease in traffic flow of 1.7% but it also rejects any decrease in traffic flow greater than 0.5%. Thus the elasticity of induced demand in the mainline was at least 0.7, as elasticities below that level can be statistically rejected.[63]

This elasticity of 0.7 does not, however, reveal the source of this induced demand. Although at least 70% of the hybrids moving into the HOV lane were replaced by other vehicles, it is unknown if these are vehicles from other routes or from new trips. In the best-case scenario

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[61] The smaller HOV lane effect on more distant freeways may be explained by the fact that congestion is less severe on more distant freeways, providing less of an incentive for hybrid drivers to use the HOV lane. By contrast, freeways near the CBD are nearly always congested, providing a strong incentive for stickered hybrid drivers to move into the HOV lane.

[62] Simulation calculations suggest that for the average HOV lane detector to increase flow by 9.1%, 87 hybrids must be added to the HOV lane. Removing 87 hybrids from the average mainline detector would decrease flow by 1.7%.

[63] This implies that if all hybrid drivers had been using the mainline lanes adjacent to the HOV lanes, at least 70% of that capacity would be filled by diverted trips or by new VMT.

for greenhouse gas emissions, this induced demand is only a result of demand diverted from other routes. Alternately, it is possible the source of this induced demand is new VMT generated by individuals commuting more frequently or switching from other modes of travel,[64] resulting in increases in greenhouse gas emission. The consequences of each scenario will be further examined in the welfare section.

7. The effect of the CAVS policy on new hybrid registrations

A key factor in determining the welfare effects of the CAVS policy requires estimating the intended effect of the policy: increased hybrid sales. In this section, we examine the effect of the CAVS policy on new registrations of Toyota Prius and Honda Civic hybrids.[65] Two recent papers have found conflicting results on the effect of single occupancy HOV lane privileges on the rates of hybrid vehicle adoption.[66] In light of these mixed results of we reexamine the case of California using more detailed and higher frequency data than previous studies, and we highlight a key aspect of the hybrid market, a capacity constraint facing producers.

Related studies

Examining a similar program in Virginia, Diamond (2008) uses annual county-level registration data for 2000 – 2006 provided by the Virginia DMV to estimate the effect of HOV lane privileges on hybrid market share in Virginia. Diamond found the policy was associated with increases in annual market share of hybrids of between 30% and 50% in Northern Virginia; however, he found no evidence that the policy had an effect in other areas of the state. Using quarterly state-level sales data for 2000-2006 from JD Power and Associates, Gallagher and Muehlegger (2008) study the effect of single occupancy HOV lane privileges on per capita sales rates of hybrid vehicles. Gallagher and Muehlegger confirm the results of Diamond (2008), finding that in Virginia the policy was associated with a 65% increase in per capita hybrid sales.

[64] New VMT substituting from public transportation is likely to be small as only 4.1% of commuters in Los Angeles use bus and 0.7% use rail. Demand may come from workers altering work schedules. 18% of workers are allowed to work four 10-hour days per week, 9% are allowed to work nine 9-hour days per two weeks. Of all commuters, 5% use one of these options. In addition 8.6% are allowed to telecommute with 82% of those allowed, using that option on occasion. New VMT arising from any of these options will increase greenhouse gas emissions. (State of the Commute Report, 1999)

[65] Due to weak sales, the Honda Insight was discontinued in 2006. As a result, we omit the vehicle model from our analysis of the effect of the policy on hybrid vehicle adoptions.

[66] State and federal policy are not the only factors affecting adoption rates: rates may be high in areas where preferences for environmentalism are high (Kahn, 2007). These individuals may have a low adoption threshold and policies that provide benefits to other groups of individuals may increase or diversify the initial block of users, speeding up the adoption timeline (Young, 2009).

However, they find that in California, Florida, New Jersey and Utah the policy was associated with negative or imprecisely estimated changes in the rate of hybrid vehicle adoptions.

Registration data

To measure the effect of the CAVS policy on the rate of eligible hybrid registrations we obtained confidential registration data from the California Department of Motor Vehicles (DMV). This data consists of the population count of all newly registered hybrid vehicles by make, model and week of registration, from the first quarter of 2003 through the second quarter of 2008 (figure 5). In contrast to Gallagher and Muehlegger (2008) who rely on quarterly data constructed from a subset of total vehicle sales, we use the population of weekly new hybrid vehicle registrations to estimate the effect of the policy. While there may have been some delays between the date of purchase and the date of registration, registration data properly account for the net flow of vehicles into the state.[67]

Registration model

To identify the effect of the CAVS policy on registrations of each eligible hybrid model, we inspect the data for discontinuous jumps around the date the policy was implemented and changes in trend during the window when stickers were being distributed. If the policy induced people to purchase eligible hybrids, then we would expect to see a sharp and sustained increase in the rate of eligible hybrid registration in the weeks following the start of the policy and continuing until all stickers were distributed. To capture the effect of the policy, we separately regress new registrations Y_{it} by week *t* and by model *i* against an indicator for the policy, a linear time trend, and weekly average gas price p_t for Los Angeles County:

$$Y_{it} = \alpha_i + \beta_i \cdot policy_t + \phi_i \cdot t + \delta_i \cdot p_t + \varepsilon_{it} \qquad (2)$$

The indicator variable, $policy_t$, which takes a value of one during the duration of the policy and zero otherwise, is meant to capture the effect of the policy on new hybrid registrations. It is consistent with our model to interpret β_i as the change in the weekly average number of hybrid model type *i* vehicles that were registered as a result of the policy. In our

[67] The difference between the date of purchase and the date of registration is likely to be insignificant. California law requires that all newly purchased vehicles be registered within 10 days of the date of sale. In the case of dealership sales, the vehicle registration form is usually transmitted to the Department of Motor Vehicles within one business day of the date of sale. Furthermore, hybrid vehicle owners were required to register their vehicle in California before they could obtain a sticker.

preferred policy specification, the policy variable becomes active the day the DMV began issuing stickers (August 20th, 2005) and inactive the day after the last sticker was issued (February 21st, 2007). Acknowledging that anticipation of the policy may have caused the true increase in demand to occur much earlier, we estimate alternative specifications, including one in which the policy variable becomes active on the date Governor Arnold Schwarzenegger signed the bill, September 24, 2004.[68]

Figure 5 plots weekly new vehicle registrations for the Prius and Civic hybrids. A visual inspection of the data reveals an approximately linear trend in new weekly registrations of the Honda Civic and Toyota Prius. The linear time trend, ϕ_i, is included in (2) to capture this steadily increasing rate of hybrid registration apparent even before the introduction of the policy.[69] It can also be noted from figure 5 that for all models, hybrid registrations spike immediately following the release of the new vehicle model year, with larger effects in redesign years.[70] The dashed gray lines on each figure indicate the window during which the DMV was distributing stickers. Finally, average weekly gasoline prices for Los Angeles County are included to control for the impact of fuel prices on hybrid sales. It has been shown that the cost of gasoline has a significant effect on vehicle purchasing decisions (Bento et al. 2009), and these effects have been shown by Gallagher and Muehlegger (2008) and Beresteanu and Li (2009) to be especially strong for hybrid purchasers.

Results

Table 8 presents estimates of the effect of the CAVS policy for each model of hybrid and specified policy date. In Column I, total weekly hybrid registrations (both Prius and Civic), are regressed against our preferred policy specification starting on the day the DMV began issuing stickers. We estimate that during the policy window, 49 fewer hybrid vehicles were registered

[68] In addition to the August 20th, 2005 and September 24th, 2004 start dates, we estimate specifications where the policy variable becomes active thirteen weeks before or after the true policy start date. These specifications are included in Table A.20 in Appendix A.

[69] Alternative specifications include monthly or quarterly fixed effects to control for regular periodic or seasonal variation, such as consumer response to new vehicle model releases, a post-policy indicator to test for changes in adoption rates after the end of the policy, and a variable interacting time and the policy dummy to capture changes in the vehicle adoption trend induced by the policy. An additional specification includes the value of the federal tax credit awarded as part of the Energy Policy Act of 2005 to each of the hybrid vehicle models *i*. Using the same JD Power data set as in Gallagher and Muehlegger (2008), Sallee (2009) finds the federal tax credit for hybrid vehicles increased the rate of Prius adoptions by18%.

[70] New models years are generally released in the third or fourth quarter of the prior year. Because many consumers time their vehicle purchases to align with the release of new vehicle models, most vehicles experience a discontinuous jump in sales immediately following the new model release date.

each week than what would have been expected otherwise. Columns II and VIII break this estimate into Prius and Civic sales showing that the drop in total registrations was due to a decrease in the rate of weekly Prius sales while Civic sales remain constant. Taken at face value, our estimates suggest that during the policy window, overall hybrid vehicle registrations were approximately 4,500 vehicles fewer than what would have been expected in the absence of the policy. Columns IV, VII, X and XIII report estimates for alternative specifications in which the policy variable becomes active on the bill signing date. With the exception of column VII these estimates are statistically insignificant and near zero.[71] Across all specifications the effect of gas price on weekly registration rates is estimated to be positive and statistically significant. In column I, we estimate that a 10% increase in gasoline price leads to a 7.9% increase in hybrid registrations, similar to the 0.86 price elasticity estimated by Gallagher and Muehlegger (2008).

The existence of a capacity constraint

Through conversations with auto-industry executives[72] and anecdotal evidence from popular press,[73] we hypothesize that the lack of a stimulative effect of the policy on hybrid adoption may be due to the fact that hybrid vehicles were in excess demand prior to and during the bulk of the treatment window. This anecdotal evidence is consistent with Sallee (2009), who reports that between the first quarter of 2003 and the last quarter of 2006, average hybrid turnover times (the number of days a vehicle spent at the dealership before sale) ranged between two and five days, as compared to an industry average of over sixty.

If a supply constraint was binding during the policy window, we would expect no effect of the policy on the rate of new hybrid registrations, despite the clear incentives for reduced

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[71] Column VII reports the effect of the policy as positive and statistically significant, likely driven by the coincidental introduction of the very popular 2005 Prius hybrid on September 10th, 2004. In addition to a number of new features the 2005 Prius was more widely available than previous model years. The 2005 Prius experienced stronger sales in the quarter following its introduction than any other previous or subsequent Prius model year. The lack of increased sales for the Civic and Insight suggest that this uptick in sales was not due to a wide increase in demand for hybrids.

[72] In discussions with auto-industry executives from Honda, Toyota and Ford, each was quick to cite capacity constraints as a significant barrier to hybrid technology adoption. Executives at Toyota corroborate that in California, Prius hybrids were in excess demand for all of 2005 and most of 2006, resulting in dealers maintaining waiting lists from 2003 through the last quarter of 2006.

[73] For example, "Lack of supply reduces hybrid sales" by Chris Woodyard, USA Today, 5/9/2006. http://www.usatoday.com/money/autos/2006-05-09-hybrid-shortage-usat_x.htm.

commute time.[74] That is, while the policy may have expanded demand for hybrid vehicles, no growth in sales is observed because the market had a vertical supply curve.[75]

Purchasing patterns under a capacity constraint

As further evidence of the existence of a capacity constraint, we consider how patterns of hybrid vehicle adoption might vary under the presence of a capacity constraint. Data on the distribution of clean air stickers were collected from the California Department of Motor Vehicles, consisting of a complete list that includes the make, model, year and county of registration for each vehicle that received a Clean Air Vehicle Sticker. Figure 6 plots the original registration date of hybrid vehicles partitioned by those that did and did not receive a sticker and reveals that a significant share of the vehicles which received stickers were originally registered well in advance of the program start date, implying that a large mass of hybrids likely entered the HOV lanes at the beginning of the program. In Los Angeles County, a total of 27,228 stickers were distributed over the course of the program. Of those more than half, nearly 13,822, were distributed to vehicles registered before the implementation of the program. In the presence of a capacity constraint and large numbers of pre-existing hybrids, it is unlikely that significant room existed for the policy to increase hybrid sales.

We also see that the relationship between stickered hybrids and unstickered hybrids (eligible hybrid vehicles that did not receive a sticker) changes with time. Prior to the start of the policy the correlation between stickered and unstickered hybrids is 0.97 and statistically significant at the 1% level. By constrast, during the policy window, the rate of stickered registrations grows and the rate of unstickered registrations declines. During the policy window the correlation between stickered and unstickered hybrids is -0.53 and statistically significant at the 1% level. This suggests that consumers who valued the use of the HOV lane may have out-competed those who valued other qualities of hybrid vehicles while supply for the vehicles was

[74] Griliches (1957) distinguishes two types of lag in adoption: acceptance and availability. Although the policy may have effectively altered the acceptance rate by making the hybrid vehicle of higher value to some consumers, it would have been ineffective in altering the availability constraint. The rate of acceptance will depend on the benefits that HOV lane access provides. Thus Diamond (2008) finds that regions of Virginia where the policy provides travel time benefits see increased sales; however, regions with similar HOV and mainline travel times do not experience increased adoption rates. Similarly, many regions where Gallagher and Muehlegger (2008) find zero effects have less extensive HOV networks, or as in the case of Utah, allow access to the HOV lane for a $50 fee.

[75] The presence of a capacity constraint in California may explain the results of Gallagher and Muehlegger (2008), who find that the use of non-market incentives in Virginia had a positive effect on hybrid adoption while the effect was negative and insignificant in California. Because the Virginia policy was implemented at a time when the supply of hybrid vehicles was unconstrained, increases in the quantity of hybrid sales were possible.

fixed. However if access to HOV lanes induced commuters to purchase hybrids, the population exposed to hybrid technology may have expanded or become more heterogeneous.[76]

In this section we find no evidence that the CAVS policy stimulated adoption of new hybrids. Our results suggest that the policy was associated with a small negative change in hybrid sales; although, this can likely be attributed to supply constraints. Such constraints may explain why previous studies in California do not find an effect of HOV lane access on adoption while policies adopted earlier by other states have been found to increase sales.

8. Implications of the CAVS policy for the distribution of costs and benefits, greenhouse gas emissions, and overall cost-benefit ratio

As discussed in the preceding sections, allowing single occupant hybrid vehicles into the HOV lane under the CAVS policy will have several effects. Travel times will be altered in the HOV lane, as well as in the lanes or roads where these hybrids originate. Such changes will have welfare consequences for three classes of agents: hybrid owners, carpoolers, and other drivers who stand to benefit from reduced congestion as hybrids move to the HOV lane.[77] Furthermore, greenhouse gas emissions may also change in response to the policy. We explore these implications below.

Assumptions

Our calculations rely on values drawn from our estimates in the preceding analysis, additional PeMS and Caltrans data, as well as from the literature. The additional parameters used to supplement our estimates in the preceding sections are presented in Table 9. A key input into our calculations is the hourly regression discontinuity estimates of the CAVS policy effect

[76] While the energy and environmental benefits of hybrids are well understood, the impact of incentives on the pace of hybrid technology adoption is less studied. In many models of information diffusion in social networks, the rate of early adoption contributes to the pace of social learning and the eventual success of an emergent technology (Blume 1993, Chatterjee and Xu 2004, and Jackson and Rogers 2007). Thus, in addition to the direct energy and environmental benefits that hybrid subsidies may provide, there may be an indirect benefit from the effect of early incentive programs on the rate and profile of hybrid vehicle adoption.

[77] All calculations in this section are for a one-way commute on the I-10W. As noted in section 2, data availability limits our ability to estimate the travel time effects of the policy along the I-10E. As the detector level flow estimates found similar effects of the policy across core freeways, return trips on the I-10E would likely generate similar travel time and greenhouse gas effects. It should also be noted that while we focus on the I-10W, the results in section 5 suggest that the policy would have a similar effect on travel time and greenhouse gas on other core freeways throughout Los Angeles. At the conclusion of this section, we present back-of-the-envelope calculations of the state-wide effect of the CAVS policy.

on peak period travel time from Table 5.[78] 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. The value of time is assumed to be constant for all drivers and equal to $21.45 (Small et al. 2005).[79] Based on Caltrans observations, we assume carpools in the HOV lane have an occupancy of 3.1 people, while mainline vehicles have 1.1 people.[80] The number of hybrid vehicles purchased because of the CAVS policy is taken to be zero, per section 7. The elasticity of new VMT with respect to an increase in capacity is assumed to be 0.15, which Hymel et al. (2009) consider the short-run elasticity best supported by the existing literature.[81] We assume hybrid vehicles achieve 45 miles-per-gallon (the lower bound required to receive an HOV lane sticker), while the vehicles they replace are assumed to receive 20 miles-per-gallon.[82] Finally, the marginal social damage of greenhouse gas emissions is assumed to be $25 per ton.[83] The technical details of the calculations used to generate the results below are discussed in further detail in Appendix D.

Distributional impacts and changes in greenhouse gas emissions

Hybrid owners receiving clean air vehicle stickers benefit from avoiding the transaction cost of carpool formation and being allowed to use the HOV lane. The value of time saved in

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[78] The effect of the policy on travel time is translated into changes in traffic flow using the elasticity of flow with respect to travel time, which is estimated for the I-10 HOV lane following Burger and Kaffine (2009).

[79] The value of time in Small et al (2005) was estimated for commuters in Los Angeles County, rendering it especially appropriate. While we have assumed that all agents have a similar value of time, consumer surveys such as J.D. Power's 2004 automobile survey, have found that hybrid drivers tend to be older, whiter, more affiliated with the Democratic Party, and wealthier than the average driver (average incomes of $100,000 compared to $85,000 for non-hybrid buyers). This would slightly increase the benefits of the policy to hybrid drivers.

[80] 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.

[81] While our traffic flow estimates in section 6 allow us to bound the elasticity of induced demand, it does not allow us to distinguish between new VMT and other sources of induced demand, requiring us to use estimates from the literature. It should be noted that there is substantial debate in the literature regarding this elasticity (see Hymel et al (2009) for a thorough discussion of the literature on induced demand and capacity expansions). While this elasticity will influence the magnitude and direction of change in greenhouse gas emissions, in the final cost-benefit analysis performed below, changes in greenhouse gas emissions are ultimately second order in the costs-benefit analysis under all scenarios.

[82] 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.

[83] Under current predictions of carbon prices, $25 per ton is on the larger end of values used in Parry and Small (2005). However, the ultimate benefits and costs of the policy (and qualitative conclusions) are relatively invariant to emissions. Assuming a smaller price of carbon would only make the benefits and costs even more invariant. Larger values, such as $85 per ton as suggested by Stern (2006) would only lead to slight changes in the final benefit-cost calculations (see Nordhaus (2007) for discussion on social discounting and why Stern's estimates are inconsistent with real interest and savings rates).

aggregate for hybrid drivers on the I-10W was $438,743 per year.[84] The number of hybrids induced into the HOV lane was 904 per day, or an average of 100 hybrids per peak hour. Aggregate benefits divided by the number of hybrid drivers gives an average benefit per hybrid driver of around $500 dollars per year.[85] For carpoolers using the HOV lane before the CAVS policy, the increased demand for the HOV lane from hybrid owners reduces carpooler welfare. The aggregate value of time lost by existing carpoolers on the I-10W is approximately $4.5 million dollars affecting nearly 22,000 carpoolers.[86] The average cost per carpooler is $187 dollars per year. Finally, congestion relief benefits may also accrue to other drivers not traveling in the HOV lane, as hybrids that leave other roads for the HOV lane may improve travel times on their route of origin. The hypothetical congestion relief benefits for other drivers are roughly $1.9 million dollars; however, this is likely to be a substantial overestimate. The number of hybrids to be replaced in the mainline is very small compared with total traffic in the area, and it is likely that there exists the requisite number of drivers who utilize uncongested outside options of free-flowing routes, public transportation and side streets. Furthermore, estimates in section 6 imply that an elasticity of induced demand on the I-10 of less than 0.7 can be statistically rejected.[87] As a consequence, in the final benefit-cost analysis below we present benefit-cost analysis of the policy including and excluding these potential congestion relief benefits.

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[84] Small et al. (2005) find that drivers may be willing to pay for increased reliability and predictability of travel times. Following their procedure, we constructed hourly reliability measures in the HOV and mainline lanes (defined as the difference between the 50th percentile and 80th percentile of the travel time distribution). Using their estimated value of reliability, hybrid drivers would gain an additional aggregate welfare benefit of $100,000-$150,000 per year. However, Small et al. consider drivers choosing between an uncongested route with a certain travel time and a congested route with uncertain travel time, and it is unclear if drivers would value the choice between two congested routes with uncertain travel times in a similar manner.

[85] To validate our calculation of the benefit per hybrid owner, we investigated what this value would imply for the premium a household is willing to pay for a hybrid with a sticker. Doubling the $500 dollars a year benefits (for a two-way commute) and discounting it (5%) over the likely life of the program (6 years) gives a net present value of the sticker of $5,314. Our implied estimate is similar to that presented in recent work by Shewmake (2010), who estimates a premium of $5,000-$6,000 for a stickered hybrid in 2007 relative to the identical hybrid without a sticker, as well as suggestions of a $3,000-$5,000 premium for a stickered hybrid from some in the auto industry (http://hffo.cuna.org/12433/article/2599/html).

[86] These values are an upper bound on costs if some marginal carpoolers broke their carpools. However, it is unlikely that this represents a significant effect, for two reasons. First, our estimates of the number of hybrids entering the HOV lane based on increased travel time are consistent with physical hybrid counts conducted by Caltrans. Second, many carpools are characterized as "fampools" (family carpools), and few state that travel time is the primary reason for carpooling (Southern California Association *of* Governments, *"State of the Commute Report 1999,"* Los Angeles, July 2000. http://www.scag.ca.gov/publications/pdf/SOC_1999.pdf).

[87] This suggests that either hybrids entering the HOV lane originated from other, less congested transportation options, or that drivers re-optimized their travel decisions leaving less congested transportation options and "filling" the I-10 mainline. In either case, the congestion relief benefits would be less than the $1.9 million reported above.

We highlight several key findings related to the distributional impacts: First, the total cost for carpoolers substantially outweighs the benefits to hybrid drivers. A similar result has been found when comparing HOV lanes with High Occupancy Toll (HOT) lanes. An HOT lane is a lane reserved for either high occupancy vehicles or toll paying individuals. Small, Winston and Yan (2006) simulating several HOV and HOT lane policies find that consumer welfare is lower using an HOT lane than an HOV lane when the toll revenue is not returned to carpoolers. The CAVS policy functions similar to an HOT policy where drivers gain access to a lane either by carpooling or paying a toll; however, in the case of the CAVS policy no toll revenue is generated. Second, the cost per individual carpooler is relatively small, and is smaller in magnitude than the benefit per hybrid owner. Third, to the extent that hybrid drivers are wealthier than the average carpooler, this policy is likely to be regressive.[88] Finally, the diffuse costs across a large number of carpoolers and concentrated benefits to a small number of hybrid drivers may have enabled the approval of the policy.

Changes in greenhouse gas emissions occur through two possible channels. First, reductions in greenhouse gas emissions will occur if the policy stimulated hybrid purchases. Second, increased emissions will occur if the increased vacancy in the mainline, caused by hybrids entering the HOV, induced new trips in the mainline.[89] We calculate that greenhouse gas emissions due to hybrids entering the I-10W HOV lane would in fact rise by 200 tons, a small increase equivalent to the yearly emissions of 35 average fuel-economy vehicles.[90]

Cost-benefit analysis of the CAVS policy

In the cost-benefit calculation we include the costs of congestion and greenhouse gas emissions, and abstract from other transportation related externalities, such as accidents and local

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See Appendix D for calculation details, as well as an extended discussion of the potential welfare benefits to this class of agents.

[88] This would require that the benefits of the CAVS policy accrued to consumers, which is consistent with findings by Shewmake (2010) and auto industry reports that the benefits of the policy were capitalized into the value of stickered hybrids. Recent work by Sallee (2010) also finds that other polices designed to encourage the adoption of hybrids, such as federal and state tax incentives, were fully captured by consumers.

[89] All agents who switch routes are assumed to produce no changes in greenhouse gas emissions, and only new trips produce additional greenhouse gas emissions.

[90] Figure 7 displays the direction of change in greenhouse gas emissions under alternative parameter assumptions regarding the elasticity of new VMT and the fraction of stickered hybrids purchased because of the CAVS policy, and we note that calculations of the change in greenhouse gas emissions under these alternative assumptions are presented in Appendix D.

air pollution.[91] Table 10 displays our best estimates of the net benefits of the clean CAVS policy, broken down by welfare source. The net benefits are negative, and equal to -$1.9 million dollars (excluding congestion relief benefits for mainline drivers leads to even more negative net benefits of -$3.7 million dollars).[92] Table 10 also reports the transfer ratio, equivalent to the cost of transferring 1 dollar to hybrid drivers. The transfer ratio is 5.28 (9.37 excluding benefits for mainline drivers), implying a cost of roughly 5 dollars to transfer 1 dollar of benefit to hybrid drivers.

The key finding from this table is that regardless of the effect of the policy on greenhouse gas emissions, congestion costs dominate the benefit-cost comparison. Given the large effects of the CAVS policy on congestion, varying nearly all parameters relevant to greenhouse emissions within reasonable ranges has minimal impact on the key finding that the overall welfare impacts are negative.[93] This result is consistent with studies that have found congestion costs to be the single largest externality associated with driving, with congestion externalities per-mile roughly an order of magnitude larger than greenhouse gas externalities (Parry et al. 2007). Because congestion is not priced, policies that promote clean technologies by lowering the total cost of driving may exacerbate the costs of congestion.

Comparison of overall costs with other greenhouse gas policies

One final point of consideration is how the overall costs of this policy compare to other greenhouse gas reducing policies. California Assembly Bill 32 Scoping Plan is a comprehensive study of the cost of reducing greenhouse gases prepared by the California Air Resources Board. The Scoping Report considered a wide-range of policies, spanning transportation, electricity and natural gas sectors, industry, agriculture and forestry, with estimated costs per ton of emissions ranging from -$300 for greenhouse gas standards for vehicles, to $300 for additional solar water heaters.

Calculating the marginal cost per ton of greenhouse gas emissions under the most optimistic scenario for the CAVS policy (that is, elasticities of induced demand and new VMT

[91] Parry et al (2007) survey the literature on automobile externalities and provide the following summary of the external costs of automobile usage: greenhouse warming, 0.4 cents per mile; oil dependency, 0.6 cents per mile; local pollution, 2.3 cents per mile; congestion, 3.5 cents per mile; accidents, 3 cents per mile. All values assume on-road fuel economy of 20 miles per gallon.

[92] Net benefits of the policy were negative across all alternative parameter specifications.

[93] Offsetting the net congestion costs on the I-10W would require that each hybrid using the I-10 HOV lane reduces net greenhouse gas emissions by 83 tons annually. The Toyota Prius reduces annual greenhouse gas emissions by roughly 4 tons relative to an average fuel-economy vehicle.

equal to 0, 100% of hybrids purchased because of the policy) yields a cost of roughly $2000 per ton. Thus, even under the best-case scenario, the CAVS policy reduces greenhouse gases at a cost roughly an order of magnitude higher than even the most expensive polices considered in the Scoping Plan.

State-wide welfare effects of the CAVS policy

The analysis above presents the estimated welfare effect of the CAVS policy for a one-way commute on the I-10W. In order to generalize this welfare effect over the state of California, we make two strong assumptions. First, the estimated distribution of traffic flow effects in Los Angeles displayed in Figure 3 is assumed to be identical for the entire state. Second, the welfare effect scales linearly with the traffic flow effect. From above, the net welfare effect for the I-10W is -$4150 per hybrid for a two-way commute, including hypothetical congestion relief benefits. As this represents the net welfare effect of a hybrid on the 3+ HOV lane of the I-10W, this number is adjusted to -$2100 per hybrid to represent average mainline congestion and the 2+ occupancy requirement on most of the HOV lanes in California.[94] Linearly scaling this value to the traffic flow effect for the I-10W (9.6%), and integrating over the distribution in Figure 3 yields a state-wide net cost of the policy of $95 million dollars annually.

As a final point of comparison with the maximum potential greenhouse gas benefits of the policy, 75,000 hybrids would reduce emissions by roughly 300,000 tons per year under average driving conditions. Although we found no evidence that the CAVS policy induced any hybrid purchases, we present this as the upper-bound on potential benefit of the program. At $25/ton of emissions, this gives an annual statewide benefit of the policy of $7.5 million dollars.

Long-run impacts on hybrid adoption

Finally, we note that the above analysis only considers the short-run impact of the CAVS policy on hybrid registration. While we find no evidence of a short-run increase in hybrid adoption, this policy (as well as similar policies across the US) may have contributed to the normalization and legitimization of a nascent technology, thereby increasing hybrid adoption in the long-run. At the time the policy was implemented, there was concern about the reliability of hybrid technology, as evidenced by popular press articles such as “Some hybrids not as reliable

[94] Caltrans observations suggest an average HOV lane 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 hypothetical congestion relief benefits for mainline drivers.

as gas-powered models" (by James R. Healey, *USA Today*, 7/25/2004). To the extent that consumers may have viewed the CAVS policy as an implicit endorsement of hybrid vehicles, concerns about reliability may have been assuaged by the policy. Nonetheless, nearly 25 hybrid purchases per sticker would have to be stimulated state-wide in the long-run before the benefits of greenhouse gas savings would offset the congestion costs.

9. Conclusions

This paper examines the effects of the Clean Air Vehicle Sticker policy on travel time in the HOV and mainline lanes of the I-10 in California. Travel time is compared before and after the policy was implemented. Our central estimates confirm an increase in travel time during the morning peak on the HOV lane of 9.0% and a 5.7% increase during the afternoon peak. The estimated effects in the mainline are small and insignificant, suggesting that there was no decrease in travel time for mainline drivers. The lack of an effect stems from the fact that, as hybrids move from the mainline to the HOV lane, it creates an incentive for other agents to re-optimize their travel decisions.

We have also examined the effects of the policy using detector level data on flow for a larger set of freeways in LA and concluded that the average flow in the HOV lanes is 5.7 percent higher due to the policy, while the effect in the mainline lanes was once again statistically insignificant.

Our results also suggest there was no perceptible increase in hybrids due to the policy, nor is any substitution from other hybrids toward ULEV hybrids detected. In fact, it seems unlikely that the policy would have increased the penetration of hybrids, given the large number of hybrids present before the start of the policy.

When evaluating the distribution of costs and benefits to hybrid owners and carpoolers, three key findings emerged: First, comparing against the total benefits to hybrid owners with stickers, the total cost for carpoolers substantially outweigh the benefits to hybrid drivers. Second, the cost per individual carpooler is relatively small, and is smaller in magnitude than the benefit to the average hybrid owner. Finally, to the extent that hybrid drivers may be wealthier than the average carpooler, this policy may be regressive.

Finally, we found that the net benefits of the program, including GHG emissions, were negative across all scenarios regardless of specification, and range from -$2 to -$5 million dollars. The key take-away of the analysis was that regardless of the effects of the policy on new hybrid registration, congestion costs dominate the benefit-cost comparison.

Although beyond the scope of this paper, one may wonder how politicians managed to get this legislation approved, since the total benefits are substantially lower than the total cost. A potential explanation is that the spread of the total costs across a large number of carpoolers may have made it possible for the policy to be approved, especially if carpoolers perceived that such a policy would be likely to generate environmental benefits.

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Table 1: Yearly Travel Time at Peak/ Off-peak by Lane and Road

Time	Lane	2004		2005		2006		2007	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Morning peak	I-10 HOV	22.58 (1.29)	4.20	22.72 (1.30)	4.13	23.68 (1.35)	4.64	24.17 (1.38)	5.36
	I-10 M.L.	27.11 (1.55)	7.39	28.20 (1.61)	8.04	30.02 (1.72)	9.15	29.75 (1.70)	9.76
	I-210	31.56 (1.48)	10.54	33.59 (1.58)	10.90	33.30 (1.56)	10.05	34.40 (1.61)	10.36
Afternoon peak	I-10 HOV	17.84 (1.02)	1.89	18.11 (1.03)	2.18	18.22 (1.04)	1.84	17.63 (1.01)	1.89
	I-10 M.L.	18.30 (1.05)	2.27	18.94 (1.08)	2.87	19.05 (1.09)	2.82	17.79 (1.02)	2.18
	I-210	21.36 (1.00)	3.89	21.86 (1.03)	3.74	22.40 (1.05)	3.48	21.94 (1.03)	2.80
Mid-day off-peak	I-10 HOV	17.94 (1.02)	1.99	18.29 (1.05)	2.49	18.31 (1.05)	1.89	17.73 (1.01)	1.84
	I-10 M.L.	19.22 (1.10)	2.75	20.25 (1.16)	4.18	20.82 (1.19)	3.43	18.76 (1.07)	2.72
	I-210	20.96 (0.98)	2.55	22.16 (1.04)	3.48	22.37 (1.05)	2.42	22.33 (1.05)	2.94
Night off-peak	I-10 HOV	15.72 (0.90)	0.43	15.66 (0.89)	0.53	16.01 (0.91)	0.59	15.68 (0.90)	0.49
	I-10 M.L.	16.29 (0.93)	0.92	16.45 (0.94)	0.98	16.46 (0.94)	1.09	15.97 (0.91)	1.02
	I-210	19.37 (0.91)	1.20	20.13 (0.95)	1.18	20.33 (0.95)	1.31	21.08 (0.99)	1.48

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

Table 2: OLS Regression Estimates with Various Time Windows

Time window	I	II	III	IV
	01/01/2004 - 12/31/2007	08/20/2004 - 08/20/2006	01/01/2004 - 12/31/2007	08/20/2004 - 08/20/2006
Regressand/lane				
	Morning peak		Mid-day off-peak	
CAVS policy/ HOV	0.070	0.071	0.053	0.060
	(0.013)***	(0.020)***	(0.010)***	(0.014)***
Observations	4944	2485	5928	2977
R-squared	0.69	0.71	0.33	0.34
CAVS policy/ Mainline	0.046	-0.017	0.059	0.002
	(0.019)**	(0.029)	(0.021)***	(0.022)
Observations	4944	2485	5927	2976
R-squared	0.75	0.75	0.34	0.39
	Afternoon peak		Night off-peak	
CAVS policy/ HOV	0.067	0.073	0.044	0.047
	(0.009)***	(0.013)***	(0.004)***	(0.006)***
Observations	3952	1984	8894	4469
R-squared	0.51	0.54	0.30	0.46
CAVS policy/ Mainline	0.049	0.001	0.012	-0.010
	(0.015)***	(0.013)	(0.007)*	(0.007)
Observations	3952	1984	8894	4469
R-squared	0.43	0.42	0.46	0.50
Day of Week-Month FEs	Y	Y	Y	Y
Day of Week Fes	N	N	N	N

Notes: Values shown are the coefficients from 16 separate OLS regressions of log(travel time) in lane *i* 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. Weekends and holidays as well as the day before and after a holiday are dropped. * significant at 10%, ** significant at 5%, *** significant at 1%.

Table 3: Regression Discontinuity Estimates: Global Polynomial Results

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Polynomial order	6	7	8	9	10	BIC	6	7	8	9	10	BIC
Regressand/lane												
	Morning peak						Mid-day off-peak					
CAVS policy/ HOV	0.088	0.084	0.090	0.090	0.116	0.116	0.048	0.050	0.027	0.027	0.041	0.041
	(0.026)***	(0.028)***	(0.028)***	(0.027)***	(0.026)***	(0.026)***	(0.021)**	(0.021)**	(0.021)	(0.021)	(0.021)	(0.021)**
Observations	4944	4944	4944	4944	4944	4944	5928	5928	5928	5928	5928	5928
R-squared	0.70	0.70	0.70	0.70	0.71	0.71	0.34	0.34	0.34	0.34	0.35	0.35
CAVS policy/ Mainline	-0.011	-0.022	0.060	0.060	0.070	0.060	-0.064	-0.063	-0.008	-0.009	-0.007	-0.009
	(0.049)	(0.053)	(0.051)	(0.051)	(0.049)*	(0.051)	(0.042)	(0.042)	(0.049)	(0.051)	(0.051)	(0.050)
Observations	4944	4944	4944	4944	4944	4944	5927	5927	5927	5927	5927	5927
R-squared	0.75	0.75	0.76	0.76	0.76	0.76	0.41	0.41	0.41	0.41	0.41	0.41
	Afternoon peak						Night off-peak					
CAVS policy/ HOV	0.063	0.066	0.057	0.057	0.067	0.062	0.033	0.033	0.016	0.016	0.022	0.022
	(0.021)***	(0.021)***	(0.021)***	(0.022)***	(0.024)***	(0.015)***	(0.008)***	(0.008)***	(0.007)**	(0.007)**	(0.008)***	(0.008)***
Observations	3952	3952	3952	3952	3952	3952	8894	8894	8894	8894	8894	8894
R-squared	0.52	0.52	0.52	0.52	0.53	0.52	0.40	0.40	0.41	0.41	0.42	0.42
CAVS policy/ Mainline	-0.001	0.004	0.059	0.059	0.055	0.059	-0.008	-0.005	0.016	0.017	0.023	0.023
	(0.031)	(0.028)	(0.036)*	(0.036)*	(0.037)	(0.036)*	(0.019)	(0.017)	(0.022)	(0.021)	(0.021)	(0.021)
Observations	3952	3952	3952	3952	3952	3952	8894	8894	8894	8894	8894	8894
R-squared	0.47	0.47	0.47	0.47	0.48	0.47	0.53	0.54	0.54	0.54	0.54	0.54

Notes: Values shown are the coefficients from 48 separate regressions of log(travel time) in lane *i* 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. Weekends and holidays as well as the day before and after a holiday are dropped. * significant at 10%, ** significant at 5%, *** significant at 1%.

Table 4: Local Linear Regression Discontinuity Estimates

	I	II	III	IV	V	VI	VII	VIII	IX	X
Kernel bandwidth: days	50	60	70	80	90	50	60	70	80	90
Regressand/lane										
	Morning peak					Mid-day off-peak				
CAVS policy/ HOV	0.071	0.072	0.065	0.060	0.058	0.000	0.001	-0.002	-0.005	-0.006
	(0.017)***	(0.016)***	(0.021)**	(0.024)**	(0.028)**	(0.023)	(0.019)	(0.016)	(0.015)	(0.016)
Observations	330	405	480	545	615	396	486	576	654	738
R-squared	0.78	0.76	0.75	0.75	0.74	0.34	0.34	0.36	0.31	0.28
CAVS policy/ mainline	0.054	0.055	0.046	0.042	0.043	-0.021	-0.020	-0.021	-0.023	-0.024
	(0.030)*	(0.037)	(0.043)	(0.045)	(0.049)	(0.036)	(0.032)	(0.029)	(0.028)	(0.028)
Observations	330	405	480	545	615	396	486	576	654	738
R-squared	0.80	0.78	0.77	0.77	0.76	0.39	0.40	0.42	0.38	0.35
	Afternoon peak					Night off-peak				
CAVS policy/ HOV	0.001	-0.002	-0.004	-0.001	0.002	0.011	0.012	0.010	0.009	0.010
	(0.016)	(0.012)	(0.011)	(0.011)	(0.012)	(0.008)	(0.007)*	(0.006)*	(0.006)	(0.006)*
Observations	280	340	400	452	516	630	765	900	1017	1161
R-squared	0.48	0.50	0.53	0.51	0.50	0.48	0.48	0.49	0.49	0.50
CAVS policy/ mainline	0.000	-0.005	-0.008	-0.002	0.000	0.012	0.015	0.017	0.018	0.018
	(0.014)	(0.013)	(0.013)	(0.014)	(0.017)	(0.010)	(0.010)	(0.009)*	(0.009)*	(0.010)*
Observations	264	324	384	436	492	594	729	864	981	1107
R-squared	0.31	0.33	0.36	0.32	0.29	0.49	0.49	0.50	0.51	0.51

Notes: Values shown are the coefficients from 40 separate regressions of log(travel time) in lane *i* on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include logged gas price, lagged 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. Weekends and holidays as well as the day before and after a holiday are dropped. Epanechnikov kernels are used in all regressions. * significant at 10%, ** significant at 5%, *** significant at 1%

Table 5: Hourly Global Polynomial Regression Discontinuity Estimates

Regressand/ Lane	I	II	III	IV	V	VI
	Morning peak					
	5 A.M.	6 A.M.	7 A.M.	8 A.M.	9 A.M.	10 A.M.‡
CAVS policy/ HOV	0.027	0.088	0.096	0.125	0.122	0.072
	(0.025)	(0.040)**	(0.042)**	(0.037)***	(0.038)***	(0.038)*
Observations	989	989	989	988	989	988
R-squared	0.52	0.56	0.59	0.58	0.54	0.37
	Afternoon peak					
	4 P.M.	5 P.M.	6 P.M.	7 P.M.	8 P.M.‡	
CAVS policy/ HOV	0.045	0.060	0.082	0.038	0.007	
	(0.027)	(0.024)**	(0.028)***	(0.025)	(0.017)	
Observations	988	988	988	988	988	
R-squared	0.28	0.39	0.49	0.51	0.39	

Notes: Values shown are the coefficients from 11 separate regressions of log(travel time) in lane *i* on the regressands. Standard errors, clustered by week, are in parentheses. Covariates include an 8th order polynomial trend in time, 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. Weekends and holidays as well as the day before and after a holiday are dropped. ‡ Not part of official peak. * significant at 10%, ** significant at 5%, *** significant at 1%.

Table 6: Global Polynomial Regression Discontinuity Estimates: Robustness

Regressand/ lane	I	II	III	IV	V	VI	VII	VIII
	Date change			Weekend	Date change			Weekend
	Morning peak				Mid-day off-peak			
CAVS policy/ HOV	-0.006	0.090	-0.073	0.002	-0.017	0.027	-0.002	-0.020
	(0.034)	(0.028)***	(0.039)*	(0.014)	(0.027)	(0.021)	(0.030)	(0.031)
Observations	4944	4944	4944	1980	5928	5928	5928	2376
R-squared	0.70	0.70	0.70	0.31	0.34	0.34	0.34	0.42
CAVS policy/ Mainline	-0.008	0.060	-0.024	0.011	-0.028	-0.008	0.048	-0.020
	(0.032)	(0.045)	(0.060)	(0.020)	(0.026)	(0.049)	(0.058)	(0.038)
Observations	4944	4944	4944	1980	5927	5927	5927	2376
R-squared	0.75	0.76	0.75	0.41	0.41	0.41	0.41	0.50
	Afternoon peak				Night off-peak			
CAVS policy/ HOV	-0.032	0.057	-0.006	0.023	-0.003	0.016	-0.008	0.008
	(0.025)	(0.022)***	(0.029)	(0.043)	(0.010)	(0.007)**	(0.012)	(0.019)
Observations	3952	3952	3952	1584	8894	8894	8894	3554
R-squared	0.52	0.52	0.52	0.50	0.41	0.41	0.41	0.36
CAVS policy/ Mainline	-0.042	0.059	0.040	0.023	-0.005	0.016	-0.014	0.002
	(0.021)**	(0.035)*	(0.048)	(0.046)	(0.006)	(0.022)	(0.022)	(0.021)
Observations	3952	3952	3952	1584	8894	8894	8894	3554
R-squared	0.47	0.47	0.47	0.56	0.54	0.54	0.54	0.47
Date of policy	8/20/2004	8/20/2005	8/20/2006	8/20/2005	8/20/2004	8/20/2005	8/20/2006	8/20/2005

Notes: Values shown are the coefficients from 32 separate regressions of log(travel time) in lane *i* 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. Holidays as well as the day before and after a holiday are dropped. Weekend specifications include only observations from weekends. Date change specifications use only weekday observations with policies starting one year before the true policy date, the date of the true policy, and one year after the true policy date. * significant at 10%, ** significant at 5%, *** significant at 1%.

Table 7: Average Treatment Effect by Distance from CBD: Local Linear Detector Level Results for Flow

		I	II	III	IV
		All detectors			I-10W
	Distance from CBD	10	20	30	‡
Regressand/Lane					
		Average treatment effect			
CAVS policy/ HOV		0.091	0.067	0.057	0.096
		(0.015)***	(0.009)***	(0.010)***	(0.004)***
	Detectors[1]	50	174	200	14
	Observations[2]	8,297	28,959	33,069	2,799
	Flow	955	884	858	877.42
CAVS policy/ Mainline		0.015	0.011	0.012	0.004
		(0.010)	(0.014)	(0.012)	(0.038)
	Detectors[1]	152	406	477	27
	Observations[2]	24,461	65,324	76,006	4,671
	Flow	5189	5230	5141	4990
Increased traffic flow in HOV		87	59	49	84
Simulated flow change in mainline		-0.017	-0.011	-0.010	-0.017

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

2. The total number of observations entering the detector level regressions.

Notes: Values shown are the average of policy coefficients 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 Error of the Mean are in parentheses and are calculated using 1,000 bootstrap samples. Covariates 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. "Increased traffic flow in HOV" is the level increase in vehicles per detector. These numbers are used to calculate the "simulate the flow change in the mainline," assuming all hybrid drivers entering the HOV lane originated in the mainline lane. ‡ Route 10 is detectors between post miles 35.239 and 18.489. These range between 3.3 and 19.2 miles from the city center. * significant at 10%, ** significant at 5%, *** significant at 1%

Table 8: Registration Estimates

	All hybrids	Prius						Civic					
Regressand	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
CAVS policy [1]	-49.08	-48.89	-37.19		-74.36	-65.48		0.13	2.98		2.17	4.83	
	(17.32)**	(21.33)**	(20.79)*		(36.48)**	(34.67)*		(7.52)	(7.13)		(12.67)	(12.43)	
Signing of CAVS policy [2]				23.48			191.89			-1.59			-14.4
				(20.43)			(30.5)***			(5.78)			(9.71)
Post policy [3]					-46.22	-51.47	319.39				3.69	3.37	-24.31
					(64.78)	(63.51)	(59.51)***				(14.34	(14.87)	(14.67)*
Weekly gas price (LA)	503.29	396.77	309.15	254.41	404.34	314.01	185.59	109.62	71.31	75.77	109.02	70.99	80.73
	(63.26)***	(75.81)***	(80.47)***	(84.08)**	(76.03)***	(79.39)***	(78.09)**	(29.53)***	(35.24)**	(35.76)**	(29.51)***	(35.05)**	(35.82)**
Observations	560	280	280	280	280	280	280	280	280	280	280	280	280
R-squared	0.81	0.8	0.8	0.8	0.8	0.81	0.82	0.59	0.6	0.6	0.59	0.6	0.6
Quarterly FE	N	N	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y

Notes: Values shown are the coefficients of 13 separate regressions of weekly new, state-wide registrations in California on a the listed regressands and a linear time trend in date. Standard errors are in parentheses. Ultra Low Emission Vehicles (ULEV) qualified for the policy including Prius, Civic and Insight. The Insight, having low sales, was discontinued during the time period and is omitted from the analysis. *1)* 8/20/2005 through 2/20/2007. *2)* 9/24/2004 through 2/20/2007. *3)* 2/20/2007 through 6/30/2008. * significant at 10%, ** significant at 5%, *** significant at 1%.

Table 9: Additional Parameters

Parameter	Value	Source
Hourly flow in HOV and mainline	Varies	PeMS
Yearly trips	260	-
I-10W route length	17.5 miles	PeMS
Value of time	$21.45	Small et al. (2005)
I-10W HOV occupancy per vehicle	3.1	Caltrans
2+ HOV occupancy per vehicle	2.2	Caltrans
I-10W mainline occupancy per vehicle	1.1	Caltrans
Elasticity of new VMT	0.15	Hymel et al (2009)
Hybrid fuel efficiency	45 mpg	EPA
Fleet fuel efficiency	20 mpg	EPA
Marginal social damage of GHG emissions	$25/ton	Various

Notes: This table lists the additional parameter values used to supplement our estimates of the travel time, traffic flow and registration effects in order to determine the implications of the CAVS policy on distributional impacts and greenhouse gas emissions

Table 10: Benefit-Cost Comparison for the I-10 West

	Central estimates
Hybrid driver benefits from use of HOV lane	$438,743
Benefit per hybrid driver	$485
Carpooler costs from increased HOV lane congestion	$4,103,610
Cost per carpooler	$187
Congestion relief benefits for mainline drivers	$1,794,011
Benefit per mainline driver	$36
Net congestion costs	$1,870,856 ($3,664,867)
Greenhouse gas benefits	-$7,470
Net benefits of clean air vehicle sticker policy on the I-10	-$1,878,326 (-$3,672,337)
Transfer ratio	5.28 (9.37)

Notes: Annual values. Values in parenthesis exclude benefits of congestion relief for mainline drivers. Transfer ratio defined as the cost of transfering $1 dollar to hybrid drivers.

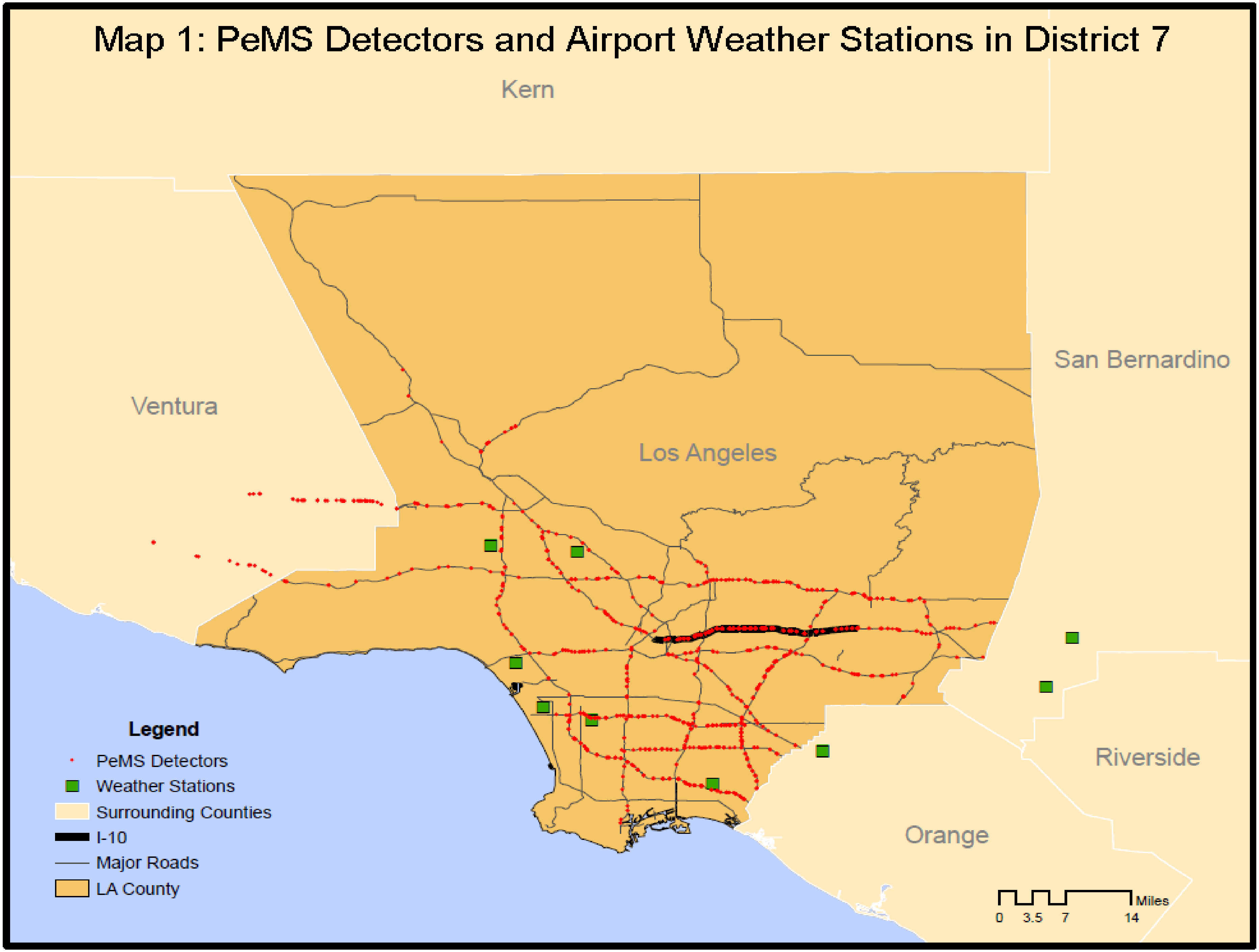
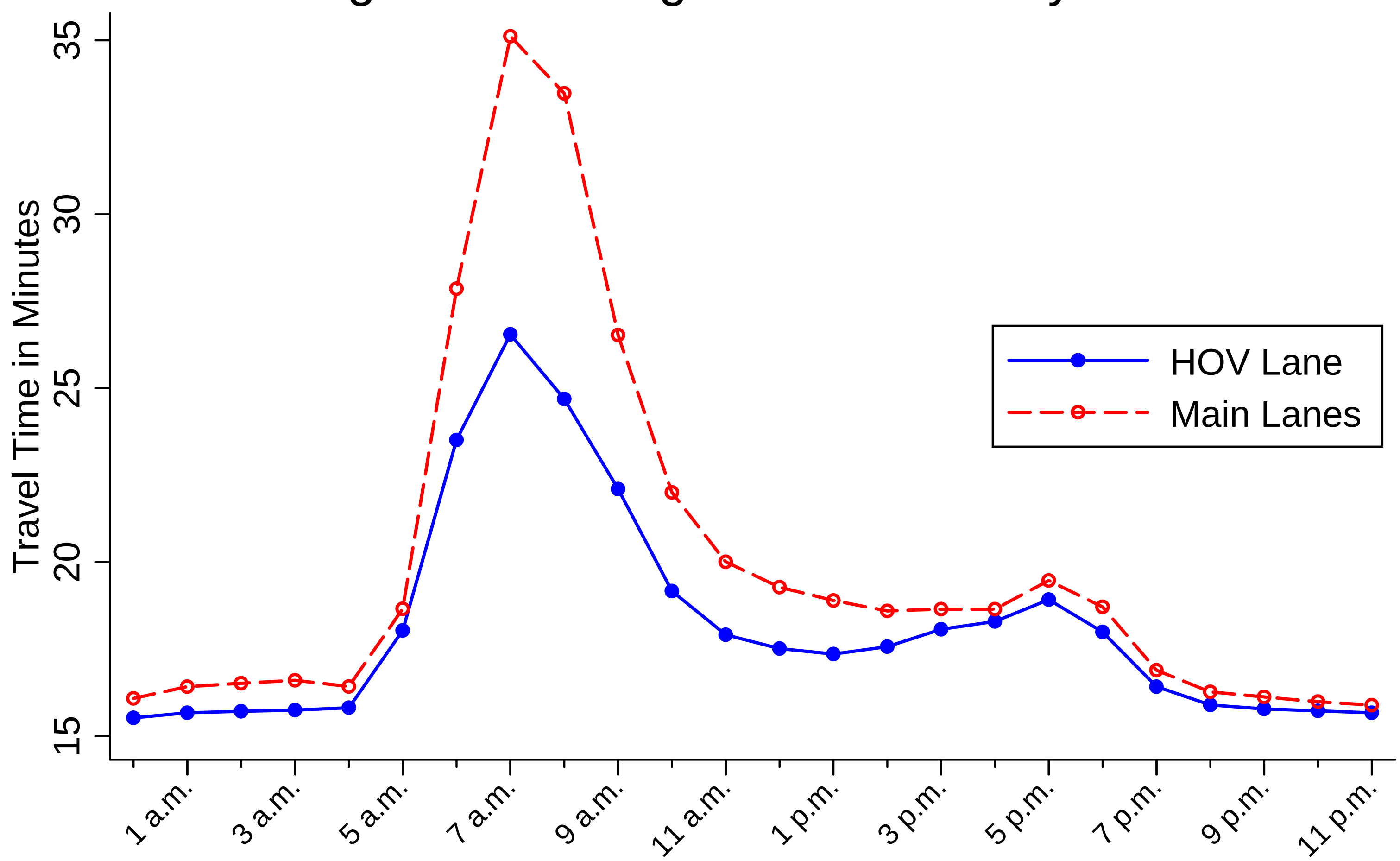
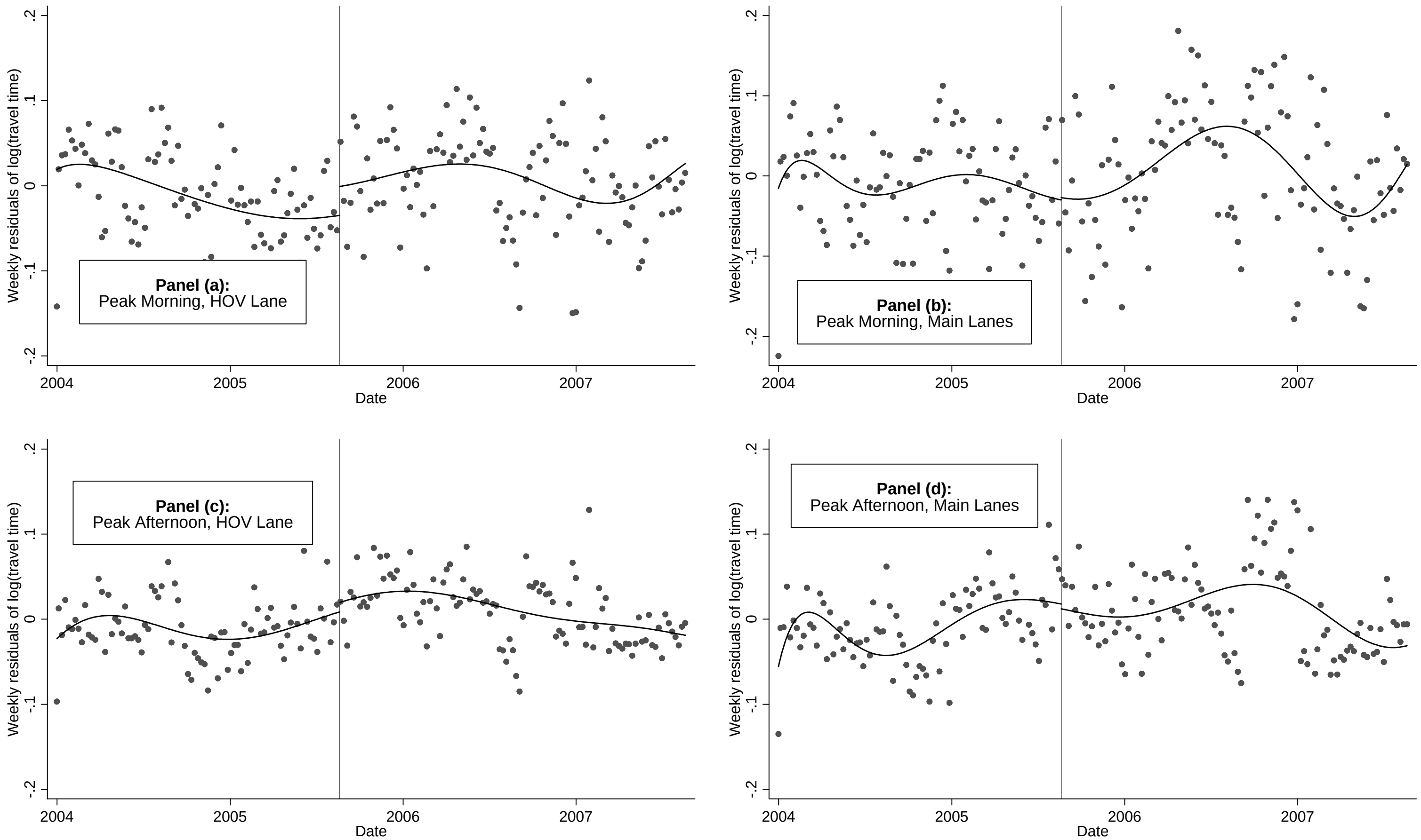

Map 1: PeMS Detectors and Airport Weather Stations in District 7
Kern
San Bernardino
Ventura
Los Angeles
Riverside
Orange
Legend
PeMS Detectors
Weather Stations
Surrounding Counties
I-10
Major Roads
LA County
Miles
0
3.5
7
14

Figure 1: Average Travel Time by Hour



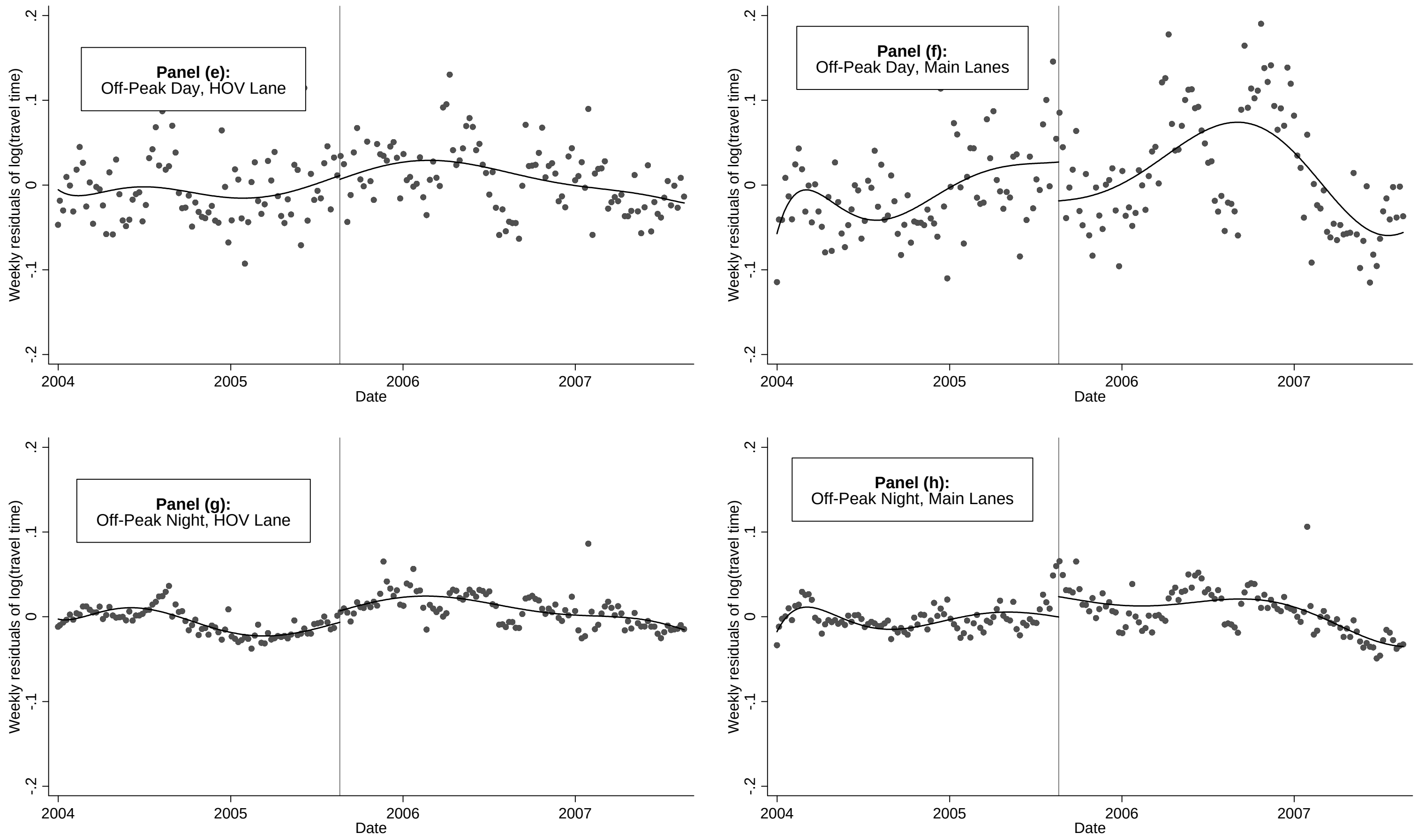
Notes: The figure displays the average hourly travel time in the indicated lane for each hour of the day on the I-10 W. Weekend values have been removed.

Figure 2: Interstate 10 W Travel Time

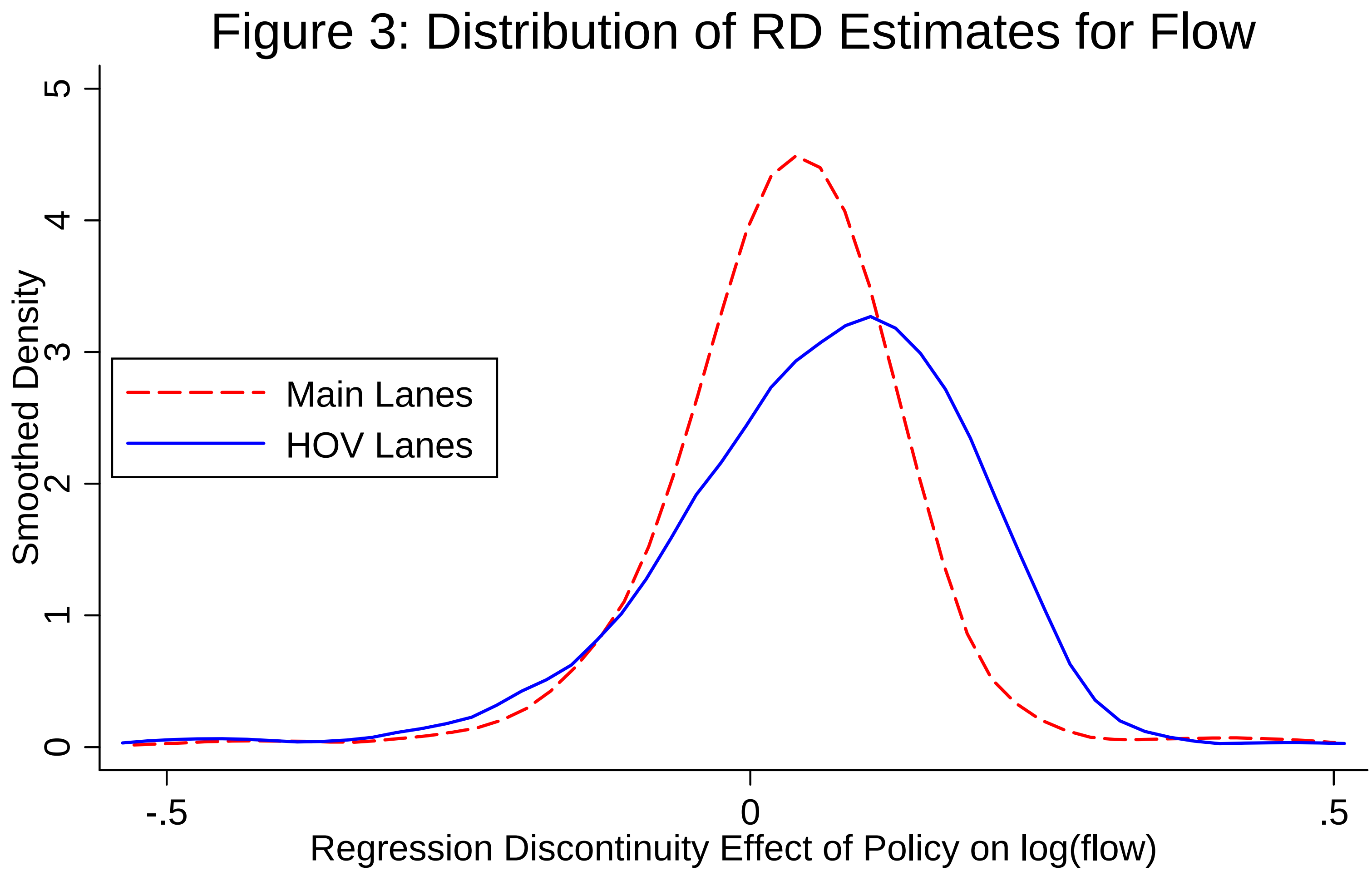


Notes: Values plotted are averaged residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies 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. Weekends and holidays as well as the day before and after a holiday are dropped.

Figure 2: Interstate 10 W Travel Time

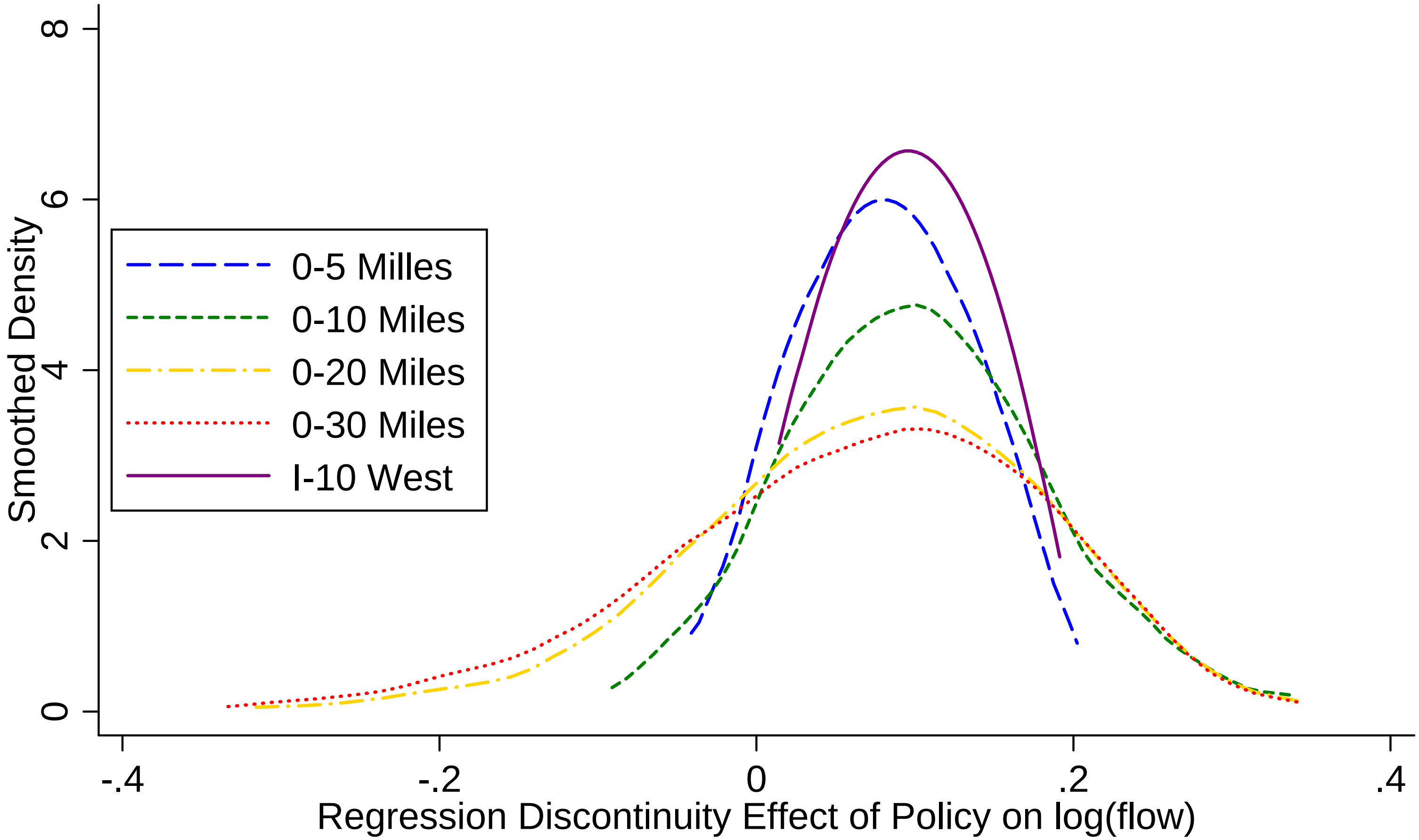


Notes: Values plotted are averaged residuals of a regression of log(travel time) for the stated lane during the stated time of day on logged gas price, travel time for the 210 W, dummies for day of the week-month, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies 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. Weekends and holidays as well as the day before and after a holiday are dropped.



Notes: The figure displays the smoothed cross-detector distribution of local linear regression discontinuity estimates. The smoother uses an Epanechnikov kernel with a bandwidth of 0.05. Detector level effects for the stated lane during the peak time of day from a regression of log(flow) on logged gas price, dummies for day of the week, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover using a 30 day bandwidth and an Epanechnikov kernel.

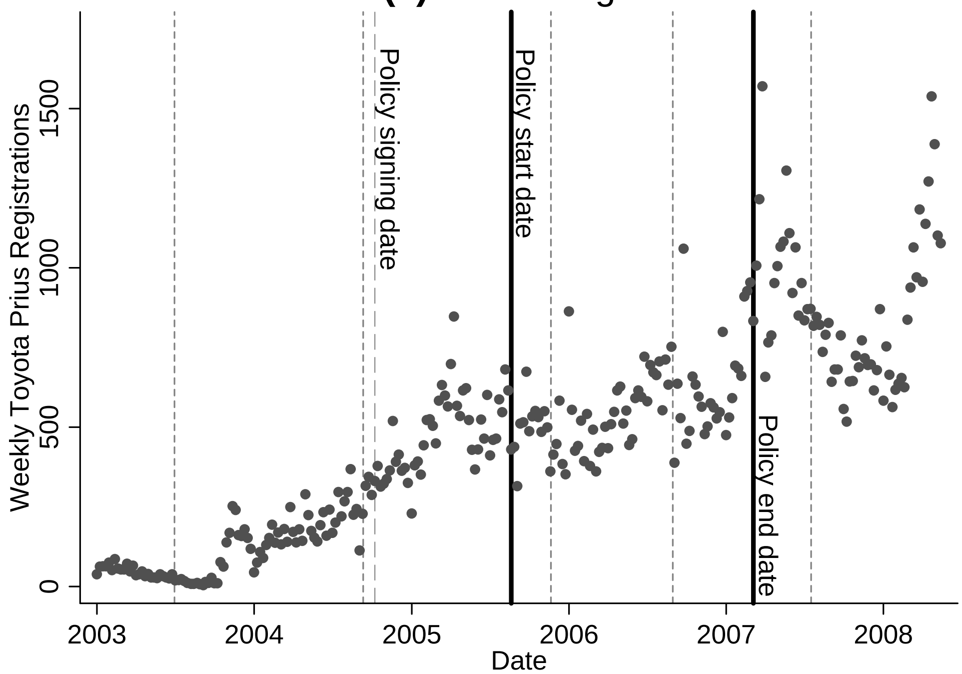
Figure 4: Distribution of HOV RD Effects by Distance



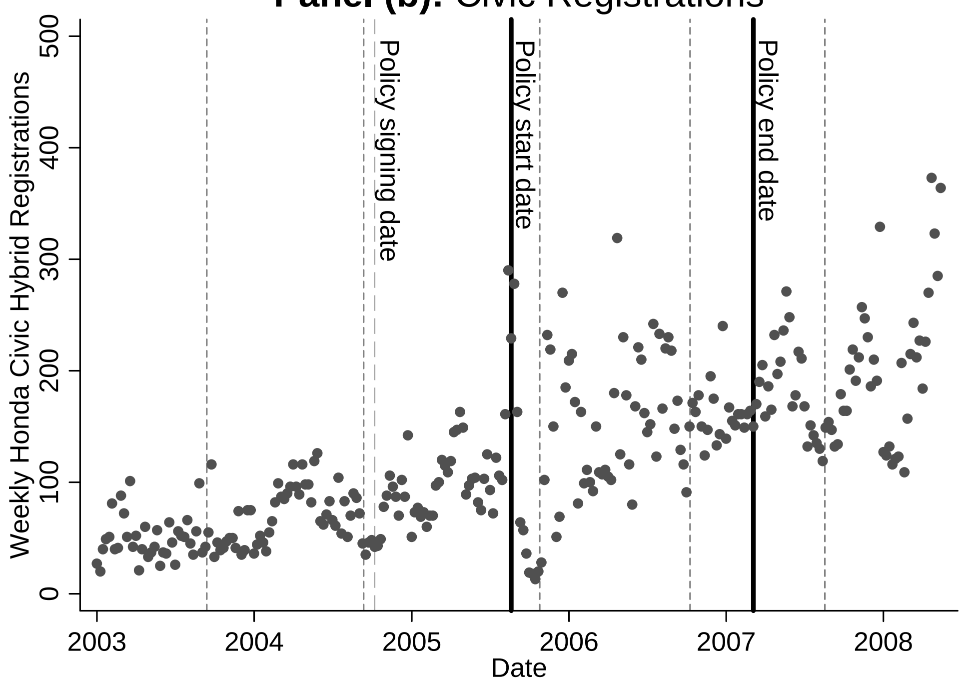
Notes: The figure displays the smoothed cross-detector distribution of local linear regression discontinuity estimates. The smoother uses an Epanechnikov kernel with a bandwidth of 0.05. Detector level effects for the stated lane during the peak time of day from a regression of log(flow) on logged gas price, dummies for day of the week, dummies for hour of the day, quadratic rainfall, quadratic visibility, and five dummies for sky cover using a 30 day bandwidth and an Epanechnikov kernel.

Figure 5: Weekly Hybrid Registrations

Panel (a): Prius Registrations

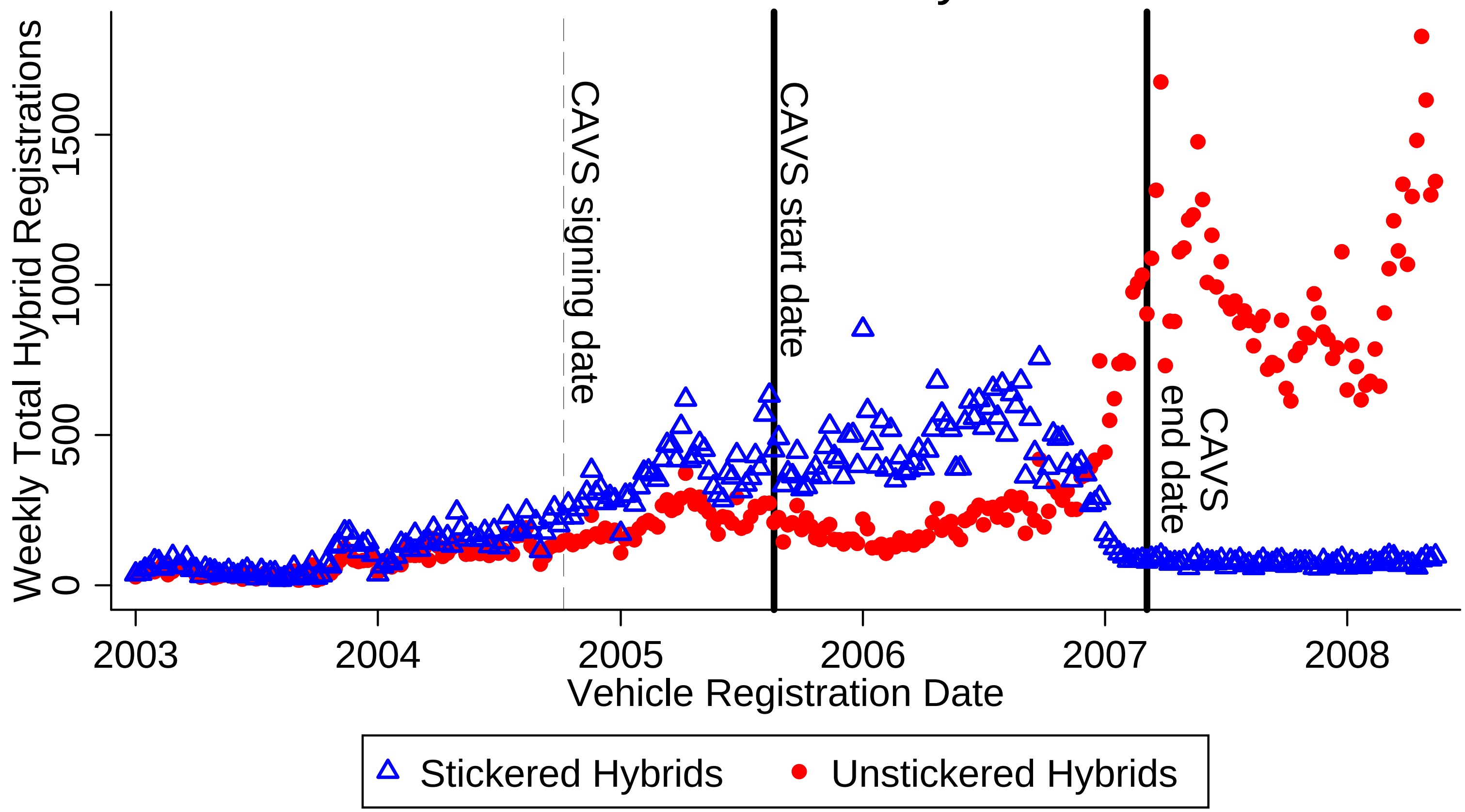


Panel (b): Civic Registrations



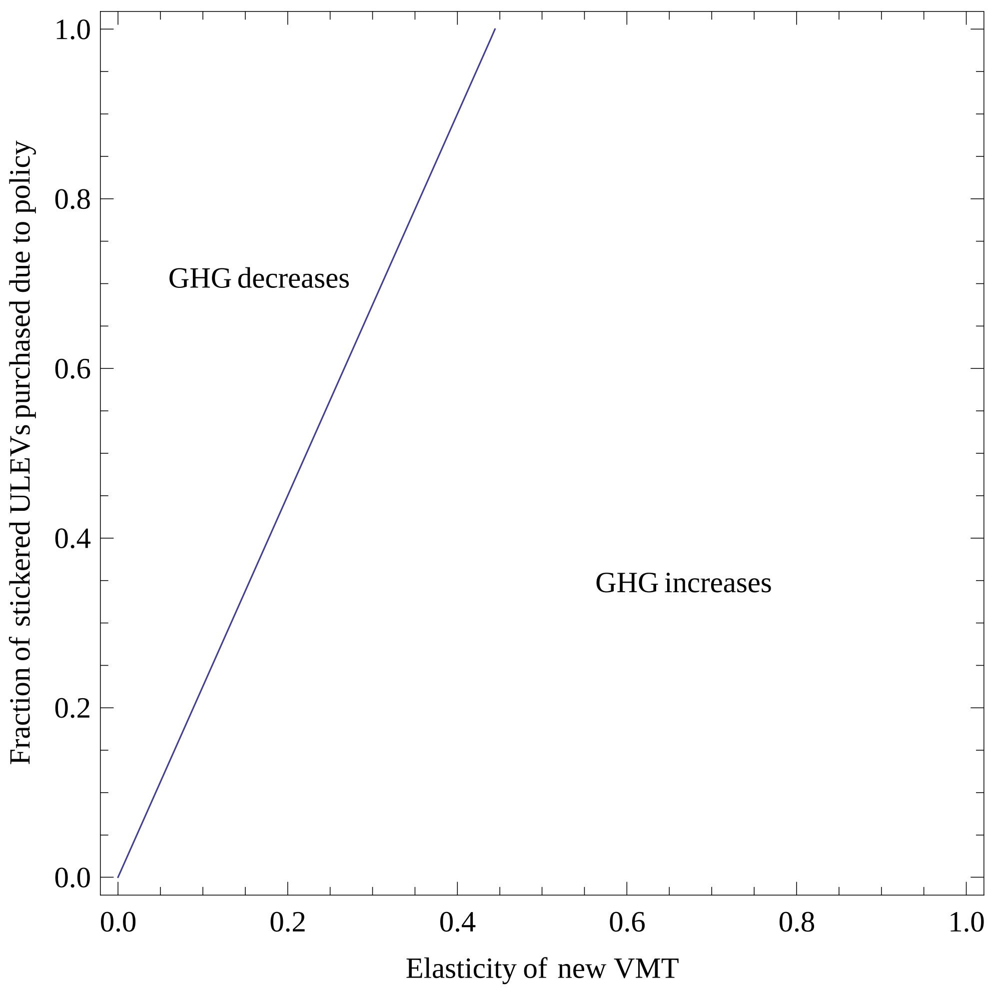
Notes: Values plotted are weekly registrations of new hybrids for the indicated model. Dashed gray lines indicate new model releases.
Source: Caltrans

Figure 6: Original Registration Date of Stickered and Unstickered Hybrids



Notes: Values plotted are weekly registrations of new hybrids for vehicles that ultimately received and did not receive stickers. Vehicles purchased before the policy date could apply for stickers once the policy began. The two groups track eachother closely before the policy and diverge after the policy starts.
Source: Caltrans

Figure 7: Parameter Space of Greenhouse Gas Changes



Notes: Parameter space showing direction of change in greenhouse gases (GHG) due to the policy.