WHEN IS INCREASING CONSUMPTION OF COMMON PROPERTY SECOND BEST? SORTING, CONGESTION AND ENTRY IN THE COMMONS

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Abstract

It is well known that rival and non-excludable goods are prone to inefficient over-consumption. While economists prefer pricing or assignment of property rights to address these market failures, in many cases, these instruments are unavailable. In the absence of instruments to limit total use, this paper asks how to best allocate consumption across a set of substitute common-property resources. In this second-best setting, we show that some common property resources can be under-consumed. This depends on whether the external benefits of reallocating users to less congested resources outweigh the additional costs imposed by new entrants via induced demand. We apply our model to a specific example, highway travel and carpooling in high-occupancy vehicle (HOV) lanes in Los Angeles. We find that HOV lanes are under-consumed in the short run and over-consumed in the longer run. Surprisingly, increasing HOV lane use decreases welfare in expected net present value on every route we study. *JEL* Codes: D23, R41, Q20

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1 Introduction

Achieving first-best consumption of common property resources is challenging in many settings. Open access management of common property resources is generally expected to lead to inefficient over-consumption, *i.e.* the "tragedy of the commons" (Gordon, 1954; Hardin, 1968; Smith, 1968; Brown, 1974; Stavins, 2011). While in some cases users have constructed formal or informal institutions to more efficiently manage the commons (Acheson, 1988; Ostrom, 1990; Kaffine, 2009; Anderson and Parker, 2013), economists have generally advocated pricing or assignment of property rights as a remedy to over-consumption. Unfortunately, in many or perhaps even most contexts, these solutions are infeasible due to coordination costs, opposition to pricing mechanisms, or the public trust doctrine. The problem is further complicated when users sort amongst substitute common property resources, altering consumption levels across the commons.

In this paper, we consider the second best allocation of consumption across substitute common-property resources. Importantly, we focus on cases where economists' preferred price and quantity instruments are unavailable and policy makers must rely on reallocating users across resources as a means of improving welfare. These policies are important in a number of contexts ranging from transportation to healthcare to fisheries.[1] We use the term "linked common-property resources" to describe substitute resources that are rival and non-excludable with heterogenous access costs and congestion externalities. Congestion externalities are broadly defined to include any external costs arising from the intensity of use that affect the production or consumption costs of other users. Surprisingly, we find common property resources may be *over* or *under*-consumed in the decentralized equilibrium. In other words, the social planner may want to *increase* consumption of some common-property resources.

To illustrate the type of problem we study here, consider the important example of highway travel in mainline and high occupancy vehicle (HOV) lanes. Congestion costs in the US exceed $120 billion per year (Schrank, Lomax, and Eisele, 2012). Because of public opposition to congestion pricing, promoting HOV lane use has been a popular strategy to reduce congestion in many cities.[2]

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[1]For example, policies to promote carpooling, incentives for the purchase of private heath insurance or fishermen relocation programs.

[2]HOV, "high-occupancy vehicle" or "carpool" lanes are highway lanes where access is limited to vehicles carrying a minimum number of riders. The Federal Highway administration estimates there are over 150 highways with HOV lanes and over 1,000 HOV lane miles in US metropolitan areas (http://ops.fhwa.dot.gov/freewaymgmt/faq.htm).

But does increasing HOV lane use actually reduce congestion? In other words, are HOV lanes over or under-consumed? On one hand, HOV lanes are open access common-property resources, and as such users fail to internalize congestion costs they impose on others implying over-consumption.[3] However, on the other hand, HOV lanes are less congested than neighboring mainline lanes, which suggests reallocating mainline users to the HOV lane could reduce overall congestion costs.[4] This is perhaps what policy makers have in mind when promoting carpooling with subsidized parking, "guaranteed ride home" programs, and informational campaigns.

Given that these competing viewpoints can lead to very different policy recommendations, we seek to understand the properties of linked common-property resources more broadly. We begin by developing a general analytical model consisting of two rival and non-excludable goods, a low access cost (LAC) resource and a high access cost (HAC) resource. Users also have uncongestible outside alternatives, and thus can elect to not consume either resource if congestion costs are too large. Reductions in congestion levels may therefore lead to entry via induced demand. We compare outcomes under competition, where users weigh access and congestion costs and independently choose which resource to consume, against the second best allocations of a cost-minimizing social planner.[5]

Under these assumptions we derive the following results. First, because higher access costs imply the HAC resource is less congested in the decentralized equilibrium, in the case of no induced demand the HAC resource is *under*-consumed. This is because there is a net "congestion relief" benefit if some users are shifted from the LAC to the less congested HAC resource. Second, in the case of full induced demand, the HAC resource is *over*-consumed as new entrants erode any congestion relief benefits for the LAC resource. Third, for intermediate levels of induced demand, the decentralized equilibrium may be identical to the second-best outcome. Finally, we derive a

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[3]This is the view taken by much of literature in natural resource economics. For an excellent review see Stavins (2011). As we show below, this perspective is appropriate when induced demand effects are large.

[4]The intuition is that equating marginal external congestion costs implies shifting users from the more congested mainline to the less congested HOV lane. Equating marginal costs minimizes total costs, and is analogous to the cost-effectiveness of pollution taxes and emissions permits in environmental economics (Baumol and Oates, 1988). As we show below, this perspective is appropriate when induced demand effects are small.

[5]Our analysis is similar in spirit to the recent work by Fischer and Laxminarayan (2010) who study congestion across common-property resources in the case where some resources are privately managed and some are open-access. Costello, Quérou, and Tomini (2013) similarly examine a partial enclosure of the commons, with an emphasis on spatial externalities and resource heterogeneity. However, we focus on differences in access costs which could arise from differences in management or from a combination of other factors. We also incorporate induced demand effects, which we show to be crucial for calculating the social costs from changes in consumption.

simple expression that can be used to test whether HAC resources are over or under-consumed for a given level of induced demand depending on the equilibrium number of users and the marginal congestion cost of each resource. The greater the difference in equilibrium usage levels, the more likely it is the HAC resource is under-consumed, providing a rationale for policy makers to increase HAC use.[6]

Returning to the issue of highway congestion, we wish to test these analytical predictions and quantify the welfare effects of shifting commuters from mainline to HOV lanes. Estimating the full social costs of reallocating commuters across lane types is a challenging task. One approach would be to look for exogenous variation in access costs, estimate the relationships between costs and flows, and predict the effects of different policies that alter costs. Unfortunately, there are few natural experiments that provide exogenous variation in access costs.[7] Observable proxies for access costs such as geography may be correlated with unobserved preferences for commuting mode. Furthermore, even if it were possible to estimate these relationships, we generally know little about the costs incurred by those who choose not to drive.

We adopt a different strategy based on our analytical model and observed equilibrium traffic flows that does not require information about access costs or users of the outside option. Our model describes welfare effects from marginal changes in highway use and congestion. Using 10 years of traffic data from Los Angeles, we calculate how an increase in HOV lane use would change congestion in the mainline and HOV lanes. To do this, we first estimate congestion cost functions that describe the relationships between highway use and travel times. Since highway capacity is essentially fixed in the short-run, these relationships are identified from plausibly exogenous variation in travel demand. The effect of a change in HOV lane use on mainline congestion depends on the level of induced demand. Because induced demand is unknown, we adopt two different numerical approaches to capture the overall welfare effects.

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[6]In the specific case of HOV lane use, we also show including additional vehicle use-externalities (local or global air pollution, energy security, etc) does not necessarily imply that HOV lane use should be increased. It is true that when less than one driver enters the mainline for every two drivers that exit to form a carpool (an induced demand level less than 0.5), use-externalities provide greater justification for increasing HOV lane use. However for induced demand levels greater than 0.5, use-externalities provide greater justification for *not* increasing HOV lane use.

[7]While there is some empirical evidence of commuter responses to changes in access costs, these natural experiments typically involve only a single unobserved change in access costs. HOV lane access stickers for solo hybrid drivers (Bento et al., 2012) and higher tolls (Foreman, 2012) change the relative costs of accessing the mainline and HOV lanes, but because the transaction costs of carpool formation are unobserved, the total effect of these policies on access costs is unknown.

In the first approach, we calculate the critical level of induced demand whereby the observed traffic levels are second best.[8] Our median values suggest the decentralized equilibrium is second best for induced demand between 0.4 and 0.6 on most routes. Comparing these values with literature estimates for induced demand suggests HOV lanes are likely *under*-consumed in the short run but *over*-consumed in the long-run.[9]

In the second approach, we calculate the present value of changes in social costs due to an increase in HOV lane use by simulating future changes in traffic flows and congestion. We parametrically model the evolution of induced demand over time and simulate over 2.8 million future traffic scenarios. Under our preferred assumptions, a marginal increase in HOV lane use would decrease welfare in more than 90 percent of our estimates. Across a variety of social discount rates and induced demand levels, we find that increasing HOV lane use is unlikely to improve welfare in the long-run. This suggests existing policies to promote carpooling may actually make commuters worse off. Furthermore, while policies to promote carpooling are often viewed as a remedy for vehicle use-externalities such as air pollution, the effects of induced demand may actually *increase* use-externalities over time.

Our analysis of HOV lanes contributes to a large literature on traffic congestion. Early papers by Downs (1962) and Vickrey (1969) recognize that the common-property nature of roadways can lead to over consumption and that alleviating congestion may lead to substitution across alternate routes and induced demand effects. In addition, several authors have focused on second-best approaches to alleviating congestion. For example, Verhoef, Nijkamp, and Rietveld (1996) and Small and Yan (2001) investigate optimal tolls in the presence of an unpriced alternative and Arnott, de Palma, and Lindsey (1991) study the relationship between parking policy and congestion. Our work formalizes the concepts proposed in the early literature and defines the second-best for policies which change the allocation of drivers across alternatives.[10] More recently, Parry and Small (2009) consider the welfare implications of allocating commuters across transportation modes. However, similar to Anderson (2013), our numerical work focuses on peak periods when the reallocation of drivers has the largest effect on congestion costs.

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[8] Our assumption that solo drivers and carpoolers respond to changes in travel costs is well supported in the literature (Small, Winston, and Yan, 2005; Burger and Kaffine, 2009; Bento, Hughes, and Kaffine, 2013).

[9] The level of induced demand for freeway travel varies from 0.1 to 0.6 in the short-run (Hymel, Small, and Van Dender, 2010) to 1.0 in the long-run (Duranton and Turner, 2011). See Section 4.1 for further discussion.

[10] In the transportation literature, our numerical approach is most closely related to Yang and Huang (1999) who study optimal and second-best congestion pricing for highways with and without HOV lanes.

Apart from highway congestion and carpooling, the linked common-property problem appears to have implications in a broad and diverse set of markets. For example, grazing on public lands where both low-elevation (LAC) and high-elevation (HAC) pastures exists, or in fisheries, where the proximity to shore or the harvest technology used create differences in access costs and congestion. Countries with both public (LAC) and private (HAC) health clinics may provide patients with a trade-off between fees and wait times. In recreational demand, users may weigh congestion and travel costs when choosing between near (LAC) and distant (HAC) locations. In each of these examples, policy makers may pursue policies to shift some consumers from the LAC good to the HAC good as a means of reducing congestion costs for consumers of the LAC good. However if induced demand effects are large, the reduction in congestion may be eroded by new entrants.

2 Analytical model of linked common-property resources

We define a "linked common-property resource" as a good with the following characteristics. Consumption is rival and non-excludable, congestion arising from the intensity of use raises a user's cost of consumption and serves to ration demand. There exists one or more substitute goods with similar characteristics but different access costs. Changes in the level of consumption of one of these substitute goods affects congestion, and in turn consumption and congestion levels of the other goods in equilibrium, forming a *link* between the costs of consuming each good. A reduction in the level of congestion may entice users who had previously consumed none of these goods to enter the market via an "induced demand" effect. Finally, we assume optimal pricing of congestion is unavailable in these markets. In this case, our analysis pertains to policy in a second-best setting, where the policy maker can only influence the allocation of users across the substitute resources. This assumption reflects the political realities in many common-property markets where there may be public resistance to "closing the commons."

To illustrate the properties of these goods, we begin by building a simple analytical model.[11] We consider $\bar{N}$ total cost-minimizing users who each consume at most one unit of the good. Users

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[11]Because the numerical exercise examines a transportation example, the analytical model developed below will be more similar to urban and transportation models than to resource models. Nonetheless, Appendix A.2 recasts our model in a production framework similar to Gordon (1954). Furthermore with appropriate modification, the model below could be extended to capture features, such as dynamics, that are more salient in the resource economics literature.

who consume a unit of the good can select between the High Access Cost (HAC) good, or the Low Access Cost (LAC) good, where n_h is the number of HAC users and n_l is the number of LAC users. Because both goods are congestible common-property goods, users may also choose to not consume either good, and instead pursue some uncongestible alternative outside option, where n_a is the number of outside option users. Everyone must be allocated, such that $\bar{N} - n_h - n_l - n_a = 0$. Users of the common-property resources and alternative option receive the same benefit from consumption such that cost minimization implies utility maximization.

Users who choose the LAC good only face the congestion cost of use, given by $T_l(n_l)$. Users who choose the HAC good face both a congestion cost of use $T_h(n_h)$ as well as an access cost $\tau(n_h)$.[12] Finally, those who choose the outside option face a cost given by $A(n_a)$. All functions are assumed to be increasing and strictly convex.

Before discussing the decentralized equilibrium and the solution to the social planners problem, a few points of clarification are useful. First, we reiterate that the alternative outside option is uncongestible. The increasing function $A(n_a)$ captures the heterogeneity of individual costs faced by users. Similarly, access costs $\tau(n_h)$ are also uncongestible and may vary by user. Thus, the HAC user with the lowest access cost pays $\tau(0)$ and the lowest cost user of the outside option faces a cost $A(0)$. Ordering subsequent users based on their costs generates the functions $\tau(n_h)$ and $A(n_a)$, whereby each user pays their individual cost.[13] As a result, no surplus is generated for users of the alternative option.[14]

The analytical model developed in the sections below highlights the main economic forces at work in this setting and simplifies exposition. However, the appendices to the paper present several useful extensions. Appendix A.1 presents a graphical illustration of our model. Appendix A.2 illustrates the intuition behind our main results in a production framework following a graphical analysis similar to Gordon (1954). Finally, appendix A.3 presents analogous results from a model with many substitute common-property resources.

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[12]If both goods are costly to access, this can represent the difference in access costs between the HAC and LAC goods. In our numerical application below, access cost τ captures both the transaction cost of carpool formation and any fuel savings from carpooling.

[13]For example in our numerical application, $A(n_a)$ captures the difference between a user who could telecommute or has access to good public transit, and one who does not. Similarly, $\tau(n_h)$ captures the difference between those who can easily form a carpool and those who cannot.

[14]Because the HAC resource is congestible, HAC users with low access costs do receive some rents, which are accounted for in our analysis below.

2.1 Decentralized equilibrium

We begin by analyzing a decentralized equilibrium, where users minimize costs by sorting across their three options (LAC, HAC, alternative option). In the decentralized equilibrium, we require no user be able to lower their costs by choosing another option, *i.e.* users achieve a Nash Equilibrium, such that:

$$T_l(n_l) - T_h(n_h) = \tau(n_h) \tag{1}$$

$$T_l(n_l) = A(n_a)$$

$$\bar{N} - n_h - n_l - n_a = 0.$$

The first condition says that users equate the marginal private benefit of using the HAC good (congestion savings) with the marginal private cost of the HAC good (the access cost). The second condition requires the marginal user of the LAC good be indifferent between the congestion cost in the LAC and the cost of the outside option. In other words, users will consume the LAC good until the congestion cost equals the cost of the next best alternative.

2.2 Social Planner

Next, we consider the allocation of users by a social planner. The social planner chooses n_h, n_l, n_a to minimize total costs, subject to the constraints that all users have to be allocated, and the fact that congestion relief for the LAC good will induce users from the outside option until congestion costs in the LAC are equal to the cost of the outside option:

$$\min_{n_h, n_l, n_a} \quad T_h(n_h)n_h + \int_0^{n_h} \tau(n)dn + T_l(n_l)n_l + \int_0^{n_a} A(n)dn \tag{2}$$

$$s.t. \quad \bar{N} - n_h - n_l - n_a = 0$$

$$T_l(n_l) = A(n_a)$$

with the corresponding Lagrangian:

$$T_h(n_h)n_h + \int_0^{n_h} \tau(n)dn + T_l(n_l)n_l + \int_0^{n_a} A(n)dn \tag{3}$$
$$+\lambda_1(\bar{N} - n_h - n_l - n_a) + \lambda_2(T_l(n_l) - A(n_a))$$

and first-order conditions:

$$T_h + n_h T_h' + \tau - \lambda_1 = 0 \tag{4}$$

$$T_l + n_l T_l' - \lambda_1 + \lambda_2 T_l' = 0 \tag{5}$$

$$A - \lambda_1 - \lambda_2 A' = 0. \tag{6}$$

which define the cost-minimizing, second-best allocation of users n_h, n_l, and n_a across the three options.[15]

With some iterative substitution, the first FOC can be written as:

$$T_l - T_h = \tau + n_h T_h' - n_l T_l' \frac{A'}{A' + T_l'} \tag{7}$$

which states the marginal private benefit of an additional HAC user equals the marginal private cost plus the marginal net external cost.[16] Alternatively, Equation 7 can be written as:

$$T_l + n_l T_l' \frac{A'}{A' + T_l'} = T_h + \tau + n_h T_h' \tag{8}$$

which makes it clear that the social planner's second-best allocation equilibrates marginal social costs across the resources.

The term $\frac{A'}{A' + T_l'}$ represents the effect of induced demand on the marginal external cost for the LAC good. If $A' = \infty$, this represents a case of no induced demand (vertical supply curve for users of the outside option), and in the limit $\frac{A'}{A' + T_l'} = 1$. Similarly, if $A' = 0$, this represents a case of full induced demand (horizontal supply curve for users of the outside option), and $\frac{A'}{A' + T_l'} = 0$. To

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[15]This allocation satisfies the second-order sufficient conditions for a local constrained minimization.

[16]The final term in the analogous expression in Appendix A.3 captures the complex sorting across multiple (K) substitute common-property resources plus the outside option.

simplify exposition, let $\alpha = 1 - \frac{A'}{A'+T_l'}$ where $\alpha = 0$ represents no induced demand and $\alpha = 1$ represents full induced demand. The above social planner FOC can then be written as:

$$T_l - T_h = \tau + n_h T_h' - n_l T_l'(1 - \alpha) \tag{9}$$

Ultimately we are interested in comparing the distribution of users under the decentralized equilibrium with that under the social planner. Comparing the decentralized equilibrium equation $T_h(n_h) - T_l(n_l) = \tau(n_h)$ with the social planner condition in Equation 9, we see that the marginal net external costs, or $n_h T_h' - n_l T_l'(1 - \alpha)$, drives a wedge between the decentralized equilibrium and the social planner solution. The first term reflects the costs an additional HAC user imposes on all other HAC users by increasing congestion. The second term reflects the benefits an additional HAC user creates for the LAC users by relieving congestion, taking into account induced demand. Because users do not internalize either the external congestion costs or benefits, then intuitively the question of whether or not a social planner would want to increase or decrease HAC good use hinges on whether the external costs to HAC users are larger or smaller than the external benefits to LAC users (see Appendix Figure A2).

3   Analytical results

We now formally compare the allocation of users in the decentralized equilibrium with the allocation selected by the social planner. We focus on the role of access costs and entry of new users via induced demand in determining the efficiency of the decentralized allocation.

3.1   Comparison of decentralized equilibrium with social planner

We begin by considering a simple model where the congestion cost functions for each good are identical functions of the number of *users*, access costs are equal, and the total number of users of the two goods is fixed. Formally,

Assumption 1. *Congestion cost functions are symmetric, such that if $n_h = n_l$, then $T_h(n_h) = T_l(n_l)$.*[17]

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[17] If the resources are different in scale (such as in the numerical example where there are more mainline lanes than

Assumption 2. *Access costs are equal, such that $\tau(n_h) = 0 \quad \forall n_h$.*

Assumption 3. *The number of users of the two common-property resources is fixed, such that $\alpha = 0$.*

This leads to our first proposition comparing the decentralized equilibrium with the social planner's problem in this simple case.

Proposition 1. *Under Assumptions 1-3, the decentralized equilibrium for HAC use is second best.*

Proof. By Assumption 2, the decentralized equilibrium requires $T_h(n_h) = T_l(n_l)$, which by Assumption 1 requires that $n_h = n_l$, and therefore $T'_h = T'_l$. By Assumption 3, the marginal net external costs are given by $n_h T'_h - n_l T'_l$, which equals zero. Finally, comparing Equation 1 against Equation 9, the allocation of users in the decentralized equilibrium and under the social planner will be equal when the marginal net external costs are equal to zero. $\qquad\square$

The intuition is that, if access costs are the same, congestion costs and thus the numbers of users are equilibrated, and the congestion costs of an additional user of the HAC good exactly balances the congestion relief benefit for the LAC good. As such, there is no need for a social planner to increase or decrease HAC use relative to the decentralized equilibrium allocation.[18] While this is a useful starting point for analysis, it assumes away any difference in access costs. Including differences in access costs will drive a wedge between congestion costs for the two goods (see Appendix Figure A1), which leads to our second proposition.

Proposition 2. *Under Assumptions 1 and 3, the HAC good is under-consumed in the decentralized equilibrium.*

Proof. The decentralized equilibrium requires $T_h(n_h) + \tau(n_h) = T_l(n_l)$, which by Assumption 1 requires that $n_h < n_l$, and therefore $T'_h < T'_l$. By Assumption 3, the marginal net external costs

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HOV lanes), this assumption can be simply adjusted to require that congestion cost functions are identical in terms of *density*. The results below follow with only minor modification.

[18]If Assumption 1 is stated in terms of densities, then if the LAC good is L times larger than the HAC good, there will be L times as many users of the LAC good as of the HAC good. On the other hand, because the LAC good is L times larger, the congestion effect of an additional user of the LAC good is $\frac{1}{L}$ of the effect in the HAC good. Thus, while more users benefit from congestion relief for the LAC good, the magnitude of the smaller congestion relief exactly balances against the larger marginal congestion effect and fewer users of the HAC good.

are thus $n_h T'_h - n_l T'_l < 0$. Thus the marginal external benefits to LAC users exceed the marginal external costs to HAC good users. Finally, comparing Equation 1 against Equation 9, the social planner would increase the number of HAC users relative to the decentralized equilibrium. □

In this case, potential users of the HAC good do not internalize the fact that the congestion relief they will provide to the LAC users is larger than the congestion cost they would impose on existing HAC users, leading to too few HAC users in the decentralized equilibrium. Policies that move users from the more congested LAC good to the less congested HAC good (e.g. increasing carpooling) would increase welfare, assuming per Assumption 3, the number of users is fixed (no induced demand from the outside option).[19]

However, the assumption that the number of users is fixed is likely only valid in the very short-run. In the long-run, induced demand may be near 1; that is, for every user leaving the LAC good, another user will ultimately replace her.[20]

Assumption 4. *There is full induced demand such that $\alpha = 1$.*

This leads to our third proposition, considering the efficiency of HAC use under full induced demand.

Proposition 3. *Under Assumption 4, the HAC good is over-consumed in the decentralized equilibrium.*

Proof. By Assumption 4, the marginal net external costs are simply $n_h T'_h > 0$. Comparing 1 against 9, the social planner would decrease the number of HAC users relative to the decentralized equilibrium. □

The intuition for this proof is that, with full induced demand, additional HAC users provide no congestion relief for the LAC good. Furthermore, HAC users do not internalize the congestion cost

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[19]They are a variety of ways of increasing HAC use. Here, we focus on the effects that come from moving the marginal LAC user to the HAC resource. Of course, some real world policies to promote HAC use could affect all users. For example in our numerical application, subsidized parking for carpoolers would lower access costs τ for all HOV lane users. Such policies would create new rents for inframarginal users that would need to be weighed against policy cost and the net change in congestion costs we identify. Our approach abstracts from these issues and instead highlights the impacts of marginal changes in resource use and congestion.

[20]This is empirically the case for freeway use in the long-run per Duranton and Turner (2011), who find expansions in freeway capacity are met one-for-one by increases in vehicle use, consistent with The Fundamental Law of Congestion. This is also a common assumption in resource models that consider open access issues (e.g. Kaffine (2009) and Costello, Quérou, and Tomini (2013)).

they impose on other HAC users, leading to too many HAC users in the decentralized equilibrium. In this case, policies to increase HAC use would reduce welfare, as the HAC good is over-consumed, despite the lower level of congestion relative to the LAC good. Note that this is true even when Assumption 1 does not hold and congestion cost functions differ.

However, the time scale at which full induced demand is realized may be long. In the short- to medium-run, induced demand likely falls somewhere between the extremes of no induced demand ($\alpha = 0$) and full induced demand ($\alpha = 1$).[21]

Proposition 4. *Under Assumption 1, there exists a critical level of induced demand $0 < \alpha^\star < 1$ such that the decentralized equilibrium is second-best.*

Proof. From Equation 9, marginal net external costs will be zero when $\frac{n_h T_h'}{n_l T_l'} = (1 - \alpha^\star)$ for some $\alpha^\star$. By Assumption 1 and the decentralized equilibrium condition in Equation 1, $n_h T_h' < n_l T_l'$, and thus $(1 - \alpha^\star)$ and therefore $\alpha^\star$ is bound between zero and one. □

In this case, at the critical level of induced demand $\alpha^\star$, the marginal external costs imposed on HAC users in the decentralized equilibrium are exactly equal to the marginal external benefits provided to LAC users. Thus, at this critical level of induced demand, the decentralized equilibrium is in fact second best despite the fact that users fail to internalize their congestion externalities in the decentralized equilibrium.[22] Two corollaries follow from Proposition 4.

Corollary 1. *Under Assumption 1, for levels of induced demand below the critical level $\alpha < \alpha^\star$, the HAC good is under-consumed. For levels of induced demand above the critical level $\alpha > \alpha^\star$, the HAC good is over-consumed.*

Proof. The proof follows intuitively from Proposition 4. If $\alpha < \alpha^\star$, then marginal external costs are less than net marginal external benefits $(n_h T_h' - n_l T_l'(1 - \alpha) < 0)$ and the HAC good is under-

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[21]Appendix Figure A3 provides intuition for the relationship between the alternative option cost function and induced demand. Section 4.1 reviews recent estimates of induced demand for travel.

[22]Recall that we have assumed that changes in the number of outside users do not generate any rents in the outside option. In the context of our numerical example (HOV lane use), this is a reasonable assumption as one fewer telecommuter or transit user will not change the cost of telecommuting or public transit for other outside option users. However, one may wonder how our results might change in other contexts if rents are generated in the outside option. For the extreme cases of induced demand, Propositions 2 and 3 hold exactly. However, for intermediate levels of induced demand, as in Proposition 4, the additional rents in the outside option will increase the likelihood that the HAC good is underconsumed for a given α, effectively increasing $\alpha^\star$.

consumed. If $\alpha > \alpha^\star$, then net marginal external costs are $n_h T'_h - n_l T'_l (1 - \alpha) > 0$ and the HAC good is over-consumed. $\qquad\square$

Corollary 1 provides a useful criterion for determining whether the HAC resource is over or under-consumed for intermediate values of induced demand $0 < \alpha < 1$. If the equilibrium usage levels (n_h and n_l) and marginal congestion costs (T'_h and T'_l) can be determined, one can simply compare the critical level of induced demand $\alpha^\star$ with the actual level of induced demand α. Note that because τ influences the equilibrium usage levels (n_h and n_l), determining $\alpha^\star$ does not require knowledge of τ, which may be difficult to measure in practice. However, this is not to say τ has no impact on the critical level of induced demand, as the following corollary demonstrates.

Corollary 2. *Under Assumption 1, the critical level of induced demand is increasing in access cost* τ, $\frac{\partial \alpha^\star}{\partial \tau} > 0$.

Proof. From the decentralized equilibrium condition 1, $\frac{\partial n_l}{\partial \tau} > 0$ and $\frac{\partial n_h}{\partial \tau} < 0$. From Proposition 4, the critical level $\alpha^\star$ satisfies $n_h T'_h - (1 - \alpha^\star) n_l T'_l = 0$. By the implicit function theorem, $\frac{\partial \alpha^\star}{\partial \tau} = -\frac{\frac{\partial n_h}{\partial \tau}(T'_h + n_h T''_h) - (1-\alpha)\frac{\partial n_l}{\partial \tau}(T'_l + n_l T''_l)}{n_l T'_l} > 0$ $\qquad\square$

The implication of Corollary 2 is that the greater the difference in access costs between the different resources, the more likely it is the HAC good is under-consumed for a given level of induced demand. In other words, more induced demand is required before the costs of entry outweigh the benefits of reallocating users from the high congestion LAC good to the low congestion HAC good. By contrast, if the difference in access costs is small, then even a small amount of induced demand may outweigh the benefits of reallocating users.

Taken together, the above results show that in a linked common-property resource setting, the HAC good may be under or over-consumed, depending on access costs, congestion costs, and the level of induced demand. In the numerical analysis beginning in Section 4, we examine HOV and mainline freeways in Los Angeles, using observed traffic data to determine the parameters of the model outlined above.

3.2 Second best including other use-externalities

In the previous results, the only externality created by decentralized consumption decisions arose from changes in congestion levels. In many contexts however, users may generate additional use-externalities (for example, loss of existence value from overconsumption of fisheries or forests, positive spillover benefits from vaccinations, or pollution from HOV or mainline drivers). If E represents an external cost-per-user, then $E(n_h + n_l)$ represents the total external costs not internalized by users. In the case of fishing, grazing or public healthcare, the impact on the above result is clear, as the total number of users is (weakly) increasing in HAC use. As such, the critical level of induced demand identified in Proposition 4 will decrease (increase) as external user costs (benefits) increase.

However, in the case of HOV lane use, external costs are associated with the number of *vehicles*. This adds an additional wrinkle to the consideration of external costs in this system. As most HOV lanes require at least two commuters, if induced demand is less than 0.5, then total vehicles and thus external costs are decreasing as HOV lane use is increased. If induced demand is greater than 0.5, then external costs are increasing with HOV lane use. We define n_l and n_h as the number of *vehicles* and assume each carpool contains two users. Since the social planner is concerned with welfare effects across *users*, each term containing n_h and τ in (2) is multiplied by two to reflect the number of users per vehicle. Re-deriving the first-order condition with vehicle use externalities yields:

$$2T_l - 2T_h = 2\tau + 2n_h T_h' - 2n_l T_l'(1 - \alpha) + E(2\alpha - 1) \tag{10}$$

On one hand, forming a carpool from two mainline drivers replaces two vehicles with one vehicle. This lowers congestion in the mainline and reduces use-externalities. On the other hand, every HOV lane vehicle carries two users who are each affected by increased congestion. Dividing Equation 10 by two, the final term becomes $E(\alpha - \frac{1}{2})$, with the remaining terms identical to those in Equation 9.[23] Including these external costs results in the following proposition and corollaries for the case of HOV lane use:

Proposition 5. *Under Assumption 1, if induced demand is small ($\alpha < 0.5$), the HAC good is more*

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[23]In some sense, it is rather surprising that the non use-externality terms are identical to those in Equation 9. However, this reflects the fact that while congestion relief doubles in the mainline, this benefit is offset by a doubling of the number of users affected by congestion in the HOV lane.

under-consumed when $E > 0$ relative to the case when $E = 0$. If induced demand is large ($\alpha > 0.5$), the HOV lane (HAC) is more over-consumed when $E > 0$ relative to the case when $E = 0$.

Proof. The net marginal external costs are given by the term $n_h T_h' - n_l T_l'(1-\alpha) + E(\alpha - \frac{1}{2})$. When $\alpha < 0.5$, the last term represents an additional benefit associated with an additional HOV user, and the social planner would further increase HOV use relative to the case where $E = 0$. By contrast, when $\alpha > 0.5$, then additional HOV users create additional external costs and the social planner would decrease HOV use. $\square$

Thus, at low levels of induced demand, including use-externalities provides a stronger case for increasing HOV use. By contrast, at higher levels of induced demand, including use-externalities provides a stronger case for decreasing HOV use. The following corollaries consider the impact of external costs on the critical level of induced demand where the decentralized equilibrium is second best.

Corollary 3. *An increase in use-externalities will increase the critical level of induced demand when $\alpha^\star < 0.5$, but will decrease the critical level of induced demand when $\alpha^\star > 0.5$*

Proof. From the proof of Proposition 5, the critical level of induced demand where the decentralized equilibrium is second best is $\alpha^\star = \frac{E - 2n_h T_h' + 2n_l T_l'}{2(E + n_l T_l')}$. Differentiating gives $\frac{d\alpha^\star}{dE} = \frac{1}{2(E + n_l T_l')} - \frac{E - 2n_h T_h' + 2n_l T_l'}{2(E + n_l T_l')^2} = \frac{1}{2(E + n_l T_l')} - \frac{\alpha^\star}{(E + n_l T_l')}$. If $\alpha^\star < 0.5$ then $\frac{d\alpha^\star}{dE} > 0$, and if $\alpha^\star > 0.5$ then $\frac{d\alpha^\star}{dE} < 0$. $\square$

Corollary 4. *As the use-externality increases relative to congestion costs, the critical level of induced demand converges in the limit to $\alpha^\star = 0.5$*

Proof. From the proof of Corollary 3, the critical level of induced demand where the decentralized equilibrium is second best can be written as $\alpha^\star = 1 - \frac{E + 2n_h T_h'}{2(E + n_l T_l')}$. In the limit as $E \to \infty, \alpha^\star \to \frac{1}{2}$. $\square$

The corollaries show that as use-externalities grow in importance, the critical level of induced demand converges towards the "magic number" of 0.5. The intuition is that if use-externalities are sufficiently large relative to congestion concerns, then the key question is whether or not increasing HOV use leads to an overall increase or decrease in the number of vehicles, with 0.5 as the cutoff between those two outcomes. Because automobile use is associated with a variety of externalities

in addition to congestion, we include these costs when considering whether or not increasing HOV lane use improves welfare.

4   Are carpool lanes under-consumed?

We apply the framework developed in Sections 2 and 3 to investigate the question of whether carpool (HOV) lanes are over or under-consumed. This setting is nearly ideal for several reasons. First, freeway lanes satisfy the criteria for the linked common-property resource problem outlined above. Freeway consumption is rationed by congestion, and mainline and HOV lanes are differentiated by the transaction costs of carpool formation. We assume the difference in access costs captures all the (non-travel time) costs and benefits that differ across lane types. Second, the marginal costs of congestion are easily calculated. We exploit detailed data on traffic flows in Los Angeles to estimate the marginal external costs of congestion in mainline and HOV lanes in realtime for twelve representative commuter routes in Los Angeles, CA.[24] Third, congestion pricing is unpopular and policy makers have instead advocated a variety of measures aimed at increasing the use of HOV lanes (HAC) as a means of congestion relief in mainline lanes (LAC) on high-traffic routes. Therefore, understanding whether HOV lanes are over or under-consumed has important policy implications.

4.1   Induced travel demand

As the analytical section identified induced demand as a key determinant of whether or not HAC goods are over-consumed, we begin by reviewing estimates of induced travel demand for US highways. Beginning with Downs (1962) and Vickrey (1969), economists have recognized traffic levels may respond to changes in congestion. Recent empirical studies estimate the relationship between increases in highway capacity and traffic flows. Capacity expansions shift out the travel cost function by lowering congestion costs resulting in a greater number of commuters choosing to drive in equilibrium.[25] The movement of commuters from the mainline to the HOV lane is analogous to an expansion of mainline highway capacity since the net result is a reduction in mainline congestion.

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[24]As noted in the introduction, this approach provides a number of advantages over alternative methods that require credible instruments or experiments that would be difficult or impossible to construct.

[25]The mechanisms by which commuters respond to increased highway capacity are numerous. For example, switching between driving routes, reduced use of public transit or telecommuting, or an increase in the overall level of travel.

Examples of work in this area include Noland (2001) who study 50 US states and the District of Columbia and Cervero and Hansen (2002) who study 34 urban counties in California. Hymel, Small, and Van Dender (2010) provide a thorough review of this literature. In the short-run, estimates of induced demand range from 0.10 to 0.6. In the longer run, estimates range from 0.7 to 1.0 (Noland, 2001; Cervero and Hansen, 2002; Hymel, Small, and Van Dender, 2010). Duranton and Turner (2011), provide the most recent estimates of induced demand in US metropolitan areas from 1983 to 2003. They estimate a long-run elasticity of vehicle kilometers traveled with respect to highway capacity of approximately 1.0. Because estimates vary broadly, our analysis does not rely on a particular assumption about the level of induced demand.

4.2 Data

Our analysis focuses on the peak commuting hours of 8 am and 5 pm for 12 highway routes in Los Angeles, California from 2002 through 2011.[26] Los Angeles is well-known for high levels of traffic congestion and for having one of the most extensive networks of HOV lanes in the nation.[27] We exploit detailed data on traffic flows from the Freeway Performance Measurement Systems (PeMS). From PeMS we observe average vehicle speed and hourly flow rates at nearly 600 locations on the city's major highways. Summary statistics are shown in Table 1. Following the traffic engineering literature we use vehicle density, defined as the number of vehicles per mile, as our measure of consumption. The day-to-day variation in observed density and travel time define the travel time density curves from which we calculate the marginal external cost of congestion for each route and each time period in our sample.

4.3 Numerical strategy

Our goal is to determine whether consumption of the HOV lane in the decentralized equilibrium achieves the second best or whether increasing consumption would raise or lower social costs. To do this, we make the following assumptions: $n_{ht} = n_{ht}^{DE} + \epsilon_{ht}$ and $n_{lt} = n_{lt}^{DE} + \epsilon_{lt}$, where n_{ht} and n_{lt} are the observed vehicle densities in the HOV and mainline lanes, n_{ht}^{DE} and n_{lt}^{DE} are the decentralized

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[26]The data Appendix A.5 discusses our procedure for selecting peak hours. Appendix A.7 explores implications of our focus on peak hours.

[27]Los Angeles county alone has 36% of the HOV lanes miles in the state of California. See data Appendix A.5 for the procedure used to define the routes used in our analysis.

equilibrium densities and ϵ_{ht} and ϵ_{lt} are well-behaved optimization errors such that the observed densities are unbiased estimates of the decentralized equilibrium densities. Because we assume commuters weigh their own costs across alternatives taking into account the expected choices of other commuters, our focus on observed densities has the advantage of implicitly accounting for unobserved individual heterogeneity that could complicate a reduced form policy analysis.

We use the observed travel times and vehicle densities to estimate congestion cost functions for each route that describe the relationships between highway use and travel times. Specifically for each route, lane-type and year in our sample we estimate:

$$T_{it} = \beta_{iy} n_{it}^2 + \epsilon_{iy} + \epsilon_{it} \tag{11}$$

where T_{it} is travel time and n_{it} is vehicle density on route lane-type i at time t. We use a quadratic model both because it fits the observed data well, for example see Figure 1, and because it enables us to easily recover the marginal congestion costs $n_i T_i'$. In estimating Equation 11 we assume the variation in observed traffic densities comes from exogenous travel demand shocks.[28] This assumption seems quite reasonable for highway travel. Highway capacity and the relationships between vehicle density and travel times are largely determined by fixed physical characteristics of the roadway including number of lanes, lane width, grade, and curvature. Shifts in travel demand trace out the travel time density curve. That said, factors such as weather and changes in the types of vehicles and drivers on the roadway may affect the relationships between vehicle density and travel time (Kockelman, 1998). To hold constant these factors, our main results focus on peak weekday commuting hours. In addition, we allow the estimated travel time functions to vary by year in order to minimize effects from changes in drivers or vehicle types.[29]

Even with the estimated congestion relationships, we note that because both the number of potential commuters $\bar{N}$ and the alternative option cost function $A(n_a)$ are unobserved, it is impossible to calculate the total social cost of commuting in either the decentralized equilibrium or the social planner's problem directly. Instead, we examine the marginal congestion costs at the decentralized

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[28]There is a fair amount of variation in aggregate travel demand even within weekday peak hours. For example, hourly mean vehicle miles traveled (VMT) in 2011 for all PeMS locations in Los Angeles and Ventura counties at 8 am excluding holidays and weekends is approximately 5.81 million miles. The 10th and 90th percentiles of aggregate VMT in 2011 are 5.68 and 5.94 million miles with minimum and maximum values of 4.97 and 6.07 million miles.

[29]While weather could in principle shift both the congestion relationships and travel demand, we are fortunate that our study area has a relatively consistent climate.

equilibrium taking the realized level of induced demand α, as an unknown parameter.

In the analysis that follows we adopt two different approaches. In the first approach, we solve for the critical level of induced demand that would make the observed traffic flows second best. Then we compare these levels to estimates of induced demand from the literature to see under what circumstance the decentralized equilibrium would be second-best. In the second approach, we use estimates from the literature to parameterize the evolution of induced demand over time. We then simulate the present value of changes in social cost from marginally increasing HOV lane use given our congestion cost relationships and observed traffic densities.

Driving is associated with a variety of use-externalities, for example air pollution, carbon emissions and accidents. In this case, the marginal social cost of a change in HOV lane use is given by the terms on the RHS of Equation 10, excluding the private transaction cost of carpool formation (τ).[30] We convert congestion costs, measured in minutes, to dollars using the mean value of time of $21.46 per hour as estimated by Small, Winston, and Yan (2005) for Southern California drivers. For non-congestion use-externalities we use $0.06 per vehicle-mile (Parry, Walls, and Harrington, 2007) times route length.

4.3.1 Critical levels of induced demand

Beginning with the first approach, we determine the critical level of induced demand for which the observed traffic flows are second best. Comparing the first-order conditions (1) and (9), we see that the decentralized equilibrium is equivalent to the social planner's solution when the right-hand side of Equation 9, $n_h T_h' - n_l T_l'(1-\alpha)$, is zero. Formally, Proposition 4 shows there exists some level of induced demand $\alpha^\star$ such that the decentralized equilibrium achieves the second best consumption of the HOV lane. This is true when:

$$\alpha = \alpha^\star = 1 - \frac{n_h T_h'}{n_l T_l'} \tag{12}$$

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[30]Specifically, we assume each carpool contains two riders and model marginal social costs as $2\omega n_h T_h' - 2\omega n_l T_l'(1-\alpha) + 2E(\alpha - \frac{1}{2})$, where ω is the commuter's value of time. We assume the same average value of time for HOV and mainline commuters. Analysis of the 2009 National Household Travel Survey data for California suggests carpoolers have incomes similar to other drivers.

and equivalently, when non-congestion use-externalities are included:

$$\alpha = \alpha^\star = \frac{E - 2n_h T'_h + 2n_l T'_l}{2(E + n_l T'_l)}.$$ (13)

Corollary 1 tells us that for induced demand less than this critical level, $\alpha < \alpha^\star$, HOV lanes are under-consumed. Similarly for induced demand greater than the critical level, $\alpha > \alpha^\star$, HOV lanes are over-consumed. Given use externalities E and the observed highway densities, n_h and n_l, the only quantities that must be estimated in Equation 12 or 13 are the slopes of the travel time density curves T'_h and T'_l. Travel times are constructed from the raw data using Appendix Equation 9 and the travel time density relationships are estimated per Equation 11. We then calculate $\alpha^\star$ by evaluating the derivatives of the fitted functions, T'_h and T'_l, at the observed densities and substitute these values into Equation 12 or 13. To allow for changes in highway characteristics over time, for example due to lane construction, we repeat this procedure separately for each year in our sample.

4.3.2 Present value of policy interventions in the HOV lane

In the second approach we ask whether an increase in HOV lane use, for example due to policies which incentivize carpooling, lowers or raises the social costs of driving on the margin.[31] Social costs depend on increased congestion in the HOV lane, reduced congestion in the mainline lanes and changes in other driving-related externalities, per Equation 10. The levels of each cost change over time due to an increase in HOV lane use and the evolution of induced demand. We must first take a stand on the unobserved induced demand function $\alpha(t)$. We assume induced demand is initially zero ($\alpha(0) = 0$) while in the long run (10 years in our preferred estimates), induced demand reaches a maximum ($\alpha(t \geq T) = 1.0$) in year T. We adopt the following model for the level of α in year $0 < t < T$:

$$\alpha(t) = (\frac{t}{T})^\gamma$$ (14)

where γ is a shape parameter that determines how α increases over time. Notice this relationship allows for α to vary smoothly from zero to one as time increases from $t = 0$ to $t = T$. If $\gamma > 1$, $\alpha(t)$ approaches full induced demand convexly and if $\gamma < 1$, $\alpha(t)$ approaches full induced demand

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[31]We assume marginally increasing HOV lane use from the decentralized equilibrium level is costless, and abstract from the specific mechanism to achieve this increase. Our assumption is conservative in the sense that costly policies make it less likely that increasing HOV lane use will increase welfare.

concavely. Because the potential behavioral channels of adjustment to changes in congestion are likely more numerous in the short run, we focus on $\gamma < 1$ such that $\alpha(t)$ is concave.

Restricting γ to the range between zero and one still allows for a great deal of flexibility in the shape of $\alpha(t)$ which may not be representative of actual behavior. Therefore, we further restrict γ in the following way. First, we note that estimates of induced travel demand in the short-run range between approximately 0.1 and 0.6. Therefore, we assume the level of induced demand at one year, $\alpha(1)$, falls in this range. Second, using Equation 14 we calculate the values of γ which bound these levels of α. In the simulations that follow, we assume γ is uniformly distributed between these bounds in order to randomly vary $\alpha(t)$. While varying the short-run range of α directly may be more intuitive, drawing gamma is conservative in the sense that it will bias us towards a higher proportion of $\alpha(t)$ functions that rise more slowly over time, increasing the odds that the marginal social costs of driving fall with increased HOV lane use.

Once $\alpha(t)$ is determined, then the change in social cost from a marginal increase in HOV lane use in each year can be calculated from Equation 10. We then calculate the present value of the marginal social cost arising from a change in HOV lane use by discounting costs in each year t at the social discount rate r and summing over all years. Our preferred estimates assume a social discount rate of $r = 0.03$, time to full induced demand of $T = 10$ years, and a 100-year planning horizon.

We use separate travel time density relationships for each route and each year in the sample. Mechanically, our simulation iterates through the 239 hourly mean densities in the mainline and HOV lanes observed each year on each of our 12 routes. For each density realization we conduct 100 draws of γ to define alternate $\alpha(t)$ functions as described above. For each draw, we calculate the present value of the marginal social cost of an increase in HOV lane use along each route. Repeating this procedure for all 10 years in our sample generates 239,000 estimates for each route (over 2.8 million in total) from which we derive the summary statistics presented below.

5   Numerical results

We begin by illustrating the technical relationships that govern traffic flows. Next, we summarize the critical levels of induced demand ($\alpha^\star$) that would make the decentralized equilibrium second

best and compare these values of $\alpha^\star$ with estimates of induced demand from the literature. Then, we simulate marginal social costs from changes in HOV lane use for our preferred parameters and investigate the timing of social cost changes. Finally, we explore how the present value of marginal social cost varies with the social discount rate (r) and the time at which full induced demand is realized (T).

Figure 1 shows travel time density plots for the am and pm peak directions on a representative freeway, I-605 in 2011.[32] Several features are worth noting. First, for both the mainline and HOV lanes, travel times increase with density from approximately 6 minutes at 15 - 20 cars per mile to approximately 15 - 16 minutes at 50 cars per mile. The slopes of the mainline and HOV curves are quite similar, though the mainline curves are shifted out somewhat relative to the HOV lane curves. This feature, common to nearly all of our travel time curves, suggests vehicles in the HOV lane travel at slower speeds, all else equal. Overall, the similarity of the travel time curves supports Assumption 1, though the curves are not identical.

When access costs differ across goods we expect to observe different levels of consumption for the HAC and LAC goods in equilibrium, resulting in speed and travel time differences across lane types.[33] We see from Table 1 that HOV lanes exhibit travel times that are on average between one and eight minutes less, between 9% and 101% of the free-flow traffic speed, compared with the corresponding mainline lanes. The largest differences occur on I-10 where access costs are higher due to the requirement that carpools consist of 3+ rather than 2+ persons. Given similar travel time density curves, the relatively shorter travel times in HOV lanes imply lower vehicle densities. We see evidence of this in the righthand columns of Table 1 where vehicle densities are on average 10 to 22 cars per mile lower in HOV lanes relative to mainline lanes. The results above are consistent with the general setup of our analytical framework and lend credibility to the numerical results that follow.

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[32]Results for the other routes in our sample are available from the authors upon request.

[33]In addition, Appendix A.4 provides evidence of a positive relationship between transaction costs and $\alpha^\star$ as predicted in Corollary 2 of Proposition 4.

5.1 Critical levels of induced demand

Table 2 summarizes points on the distributions of the critical level of induced demand $\alpha^\star$ for each of the routes in our sample.[34] Panel a.) presents results ignoring non-congestion related use-externalities, while panel b.) includes other use-externalities. Beginning with panel a.) we see the mean $\alpha^\star$ ranges from 0.27 for I-210 E to 0.78 for I-10 W. The median values are slightly larger ranging from 0.31 to 0.79. When use-externalities are added in panel b.) we see that the distributions of $\alpha^\star$ move toward the central value of 0.50 per Corollary 3. Median values range from 0.32 to 0.76. The critical $\alpha^\star$ decreases on routes with median values greater than 0.50 when use-externalities are considered, and the critical $\alpha^\star$ increases on routes with median values less than 0.50. The relatively small movement in $\alpha^\star$ when non-congestion use-externalities are included is consistent with previous literature that finds congestion costs tend to dominate calculations of external costs (Parry and Small, 2005; Parry, Walls, and Harrington, 2007; Bento et al., 2012).

Recall that induced demand less than $\alpha^\star$ implies the HOV lane is under-consumed and induced demand greater than $\alpha^\star$ implies the HOV lane is over-consumed. Comparing the median values in Table 2 to the estimates reported in Hymel, Small, and Van Dender (2010) we see that most routes are under-consumed in the short-run. Looking at the maximum for each route we note that $\alpha^\star$ is never equal to 1.0. This implies that in the long-run as the level of induced demand approaches 1.0 (Duranton and Turner, 2011), HOV lanes are *always* over-consumed. Figure 2 illustrates this intuition graphically. HOV lanes are under-consumed for $\alpha^\star$ to the right of α_{SR} and HOV lanes are over-consumed for $\alpha^\star$ to the left of α_{LR}. While we have shown theoretically that the HAC good is always under-consumed with zero induced demand (Proposition 2), note Figure 2 shows that HOV lanes are also under-consumed for a range of *positive* values of induced demand (Proposition 4). Note that there also exists some intermediate level of induced demand where HOV lane consumption is (on average) second-best. Finally, notice that when other use externalities are considered, the distribution contracts inward toward a critical value of 0.5 consistent with Corollary 3.

The above results suggest HOV lanes are under-consumed in the short-run but are likely over-consumed in the long run. In reality, induced demand evolves over time meaning increasing HOV lane use initially improves welfare but that these gains may be offset by higher congestion costs in

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[34]Appendix A.6 summarizes the marginal congesting costs that lead to these results. Values range from $0.60 to $1.12 per mile in the mainline and from $0.21 to $0.61 per mile in the HOV lane.

the future. We investigate these dynamic considerations in the following section.

5.2 Present value of policy interventions in the HOV lane

Table 3 summarizes the changes in the present value of social costs of driving due to an increase in HOV lane use during peak hours assuming a social discount rate of 3% and induced demand that is fully realized after 10 years.[35] The values listed have units of dollars per car/mile-day. Positive values indicate that adding a car to the HOV lane results in a net *increase* in social costs over the planning period. Median values range from $23.32 for I-10 W (am peak) to $859.99 for I-210 E (pm peak). This suggests that across the routes we study, increasing HOV lane use would likely reduce welfare over the long-run. Furthermore, only the three most congested routes, I-10 E, I-10 W and the northern portion of I-405 S have negative social costs at the 10th percentile. To put these numbers in perspective, an increase in density of one car per mile (3 to 5 percent) on each of the twelve routes implies the present value of social cost increases by $14.1 million at the mean and $11.4 million at the median values shown in Table 3.[36] These sums include approximately $650,000 in *additional* use-externalities due to an increase in total vehicle use.

Another way to evaluate social costs in light of increasing induced demand is to consider the timing of welfare changes. Table 4 summarizes the mean "switch" year, when marginal costs first become positive (*i.e* annual costs outweigh benefits), which occurs after 3 to 9 years. The mean "break-even" year, when accumulated costs first outweigh accumulated benefits, occurs after 6 to 25 years on most routes. Larger access costs, such as on I-10, lead to a longer period of congestion relief. However, on most routes induced demand effects quickly dominate.

We view our preferred levels of r and T as quite reasonable. Social discount rates in the literature typically fall in the range of 0.02 to 0.07 and Duranton and Turner (2011) estimate full induced demand on a time-scale of only 10 years. However, one may be concerned about the sensitivity of our results to these assumptions. If instead we assume a social discount rate of $r = 0.10$ and that it takes 20 years for induced demand effects to be fully realized, we still find that increasing HOV lane consumption is unlikely to reduce social costs. Using these assumptions, the median values of

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[35]Appendix A.7 replicates these calculations using all hours from 6 am to 8 pm. These results are qualitatively similar.

[36]Calculated by multiplying the values in Table 3 by the length of each route, assuming 239 commute days per year and summing across the twelve routes.

social costs range between -$155.83 and $144.09 and social costs are expected to increase on average for 8 of the 12 routes we study. Table 4 shows the benefits of higher HOV lane use persist longer relative to our preferred results. However even in this extreme case, the social costs of commuting begin to increase after 4 to 10 years on most routes.

Figure 3 further explores this issue for a range of values of r and T. We repeat our simulations for values of r ranging from 0 to 0.20 and T from 1 to 30 years. For each combination of r and T we estimate the probability that increasing HOV lane use will reduce social costs. For simplicity, we pool the routes in our sample so that changes in costs across routes are weighted equally. The proportion of negative estimates can be thought of as an estimate of the cumulative distribution function for social cost decreases due to an increase in HOV lane use. Figure 3 plots level curves of the cumulative distribution function over the ranges of r and T. Intuitively, the probability of a welfare increase grows as both r and T become larger. Comparing our preferred parameters ($r = 0.03$ and $T = 10$) with the even odds line ($p = 0.5$ where the chance of improving welfare is 50/50) shows that our results are quite robust. Discount rates would need to be substantially higher, or induced demand would need to grow much slower, before increasing HOV lane use in Los Angeles is likely to be welfare improving.

6   Discussion and conclusions

We show that in the linked common-property resource setting high access cost resources can be *over* or *under*-consumed from the point of view of a cost-minimizing social planner. Because differences in access costs lead to higher congestion costs for low access cost resources, a reallocation of users may reduce overall costs. Crucially, whether increasing consumption of the high access cost resource improves welfare depends on the amount of entry from induced demand. The finding that increasing consumption of some common-property resources may be desirable is novel in light of models which consider individual resources in isolation or assume full induced demand. On the other hand, because positive induced demand negates some or all of the congestion relief benefit from reallocating users from LAC to HAC resources, equating marginal congestion costs across resources may not always be optimal.

In the particular case of highway traffic on Los Angeles freeways, our numerical results suggest

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HAC resources (HOV lanes) are likely under-consumed in the short-run when induced demand effects are small. However in the longer-run, HOV lanes are likely over-consumed. We show that on most routes, increasing carpooling provides a net congestion benefit for moderate levels of induced demand up to 0.4 or 0.6. However, for full induced demand, where every commuter leaving the mainline is eventually replaced by a new driver, increasing HOV lane use is never second-best.

In present value terms, we find that increasing carpooling in Los Angeles likely increases social costs due to induced demand effects. That said, most highways would see lower total congestion costs for several years following an increase in HOV lane use. In particular I-10, with its 3+ HOV lanes, stands out from the other routes as being more likely to benefit from increased carpooling. By Corollary 2, higher access costs mean a higher level of induced demand is necessary to outweigh the congestion relief benefits of increasing HOV lane use. While our numerical results support this prediction, whether switching from a 3+ to 2+ restriction would be beneficial is an unresolved empirical question.[37] Finally, including vehicle related use-externalities such as air pollution or accidents further weakens the case for increasing HOV lane use.

Overall, the framework developed here could have broad implications for a number of markets. For example, public healthcare systems use waiting lists, *i.e.* congestion, to ration demand for some procedures (Lindsay and Feigenbaum, 1984; Martin and Smith, 1999). There is evidence that longer wait lists may contribute to the demand for private health insurance (Besley, Hall, and Preston, 1999). Whether policies to promote private insurance, such as those proposed for Australia and the UK (Duckett, 2005; Parry, 2001), lower total social costs depends on the extent to which shorter wait lists result in induced demand in the public sector.[38] While in general we expect demand for healthcare to be inelastic, we expect induced demand effects to be larger for some elective procedures or for healthcare systems in less-developed countries.

In commercial fisheries there is evidence of congestion costs (Boyce, 1993) and that more distant locations are less likely to be fished (Smith, 2002; Holland and Sutinen, 2000).[39] If fishermen do

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[37]Interestingly, Los Angeles experimented with a reducing the occupancy requirement on I-10 from 3+ to 2+ beginning on January 1, 2000. However, on July 24, 2000 the requirement was subsequently raised back to 3+ during peak periods due to increased HOV lane congestion and slower speeds (Turnbull, 2002).

[38]In healthcare there may also be positive externalities that depend on the total number of people receiving healthcare. For example, higher levels of vaccination may reduce the likelihood the unvaccinated contract disease, *i.e.* "herd" or "community" immunity in the health literature. In this case, the net effect of changes in overall consumption depends on both the positive and negative use-externalities.

[39]In this context, a higher level of fishing effort is thought to increase costs, though Holland and Sutinen (2000) provide evidence that some level of effort from other users may be desirable because of agglomeration effects.

sort across fishing grounds according to expected profits as suggested by Gordon (1954), then we expect trade-offs between differences in access costs and congestion of the type we model. Empirical studies of location choice and capital allocation do support the notion that fishing effort responds to expected profits, though in some cases habits or other sources of behavioral "inertia" may limit this response (Boyce, 1993; Holland and Sutinen, 2000; Abbott and Wilen, 2011). Therefore, our results suggest that under open access it may be desirable to incentivize consumption of some locations or species depending on the relative levels of congestion and induced demand effects.[40] For example, fishermen relocation programs in the developing world have been motivated, at least in part, by the desire to reduce overfishing.[41] Whether these policies achieve this goal depends on the extent to which subsistence fishermen transferred to other locations are replaced by new entrants.

Taken together, our results suggest policy makers need to carefully consider relative congestion levels and the potential for induced demand when designing policies in a linked common-property resource setting. Further empirical research into fisheries, healthcare, forestry, grazing, traffic and other similar markets would provide additional insight into the importance of the mechanisms outlined in this paper.

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[40]Interestingly, we note Smith (2002) shows that the intensity of fishing in the California sea urchin fishery depends in part on the state unemployment rate, which suggests substitution to alternative options consistent with our model for induced demand. There could of course be many other possible mechanisms of induced demand.

[41]The other explicit goal of these programs is to reduce poverty. For an example of one such program see http://www.fao.org/docrep/field/003/ac063e/AC063E02.htm

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7 Figures

Figure 1: Representative travel time density relationships for mainline and HOV lanes.

(a) Route I-605 South am Peak

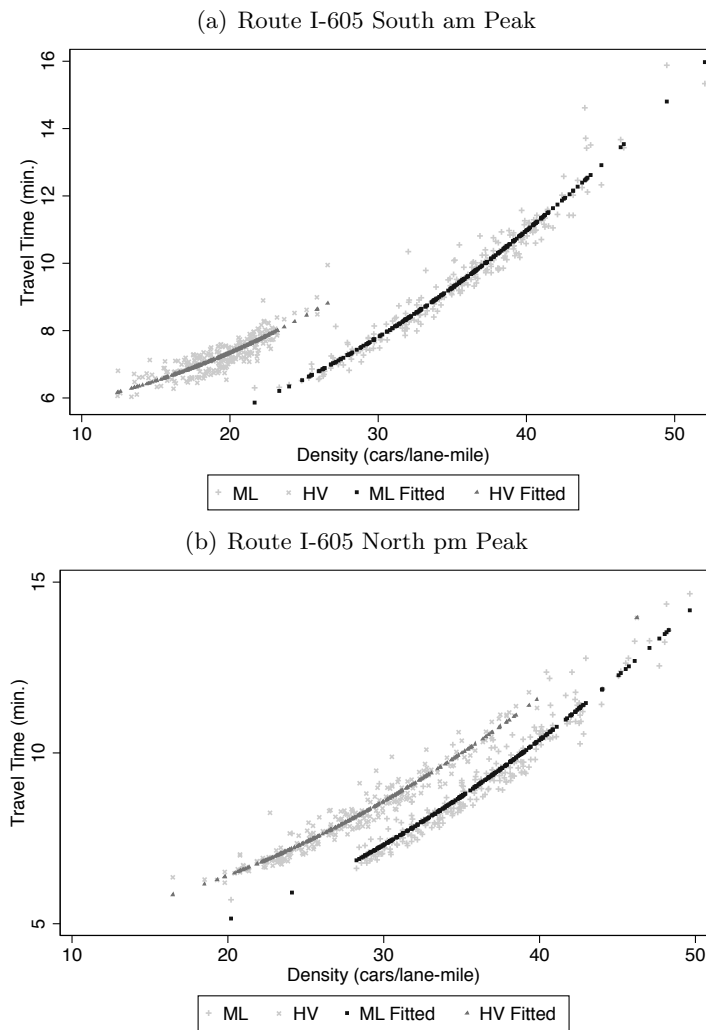

(b) Route I-605 North pm Peak

Figure 2: Distribution of critical alphas across twelve routes in Los Angeles with and without additional use-externalities. Dashed lines indicate possible realizations of the short-run and long-run induced demand levels.
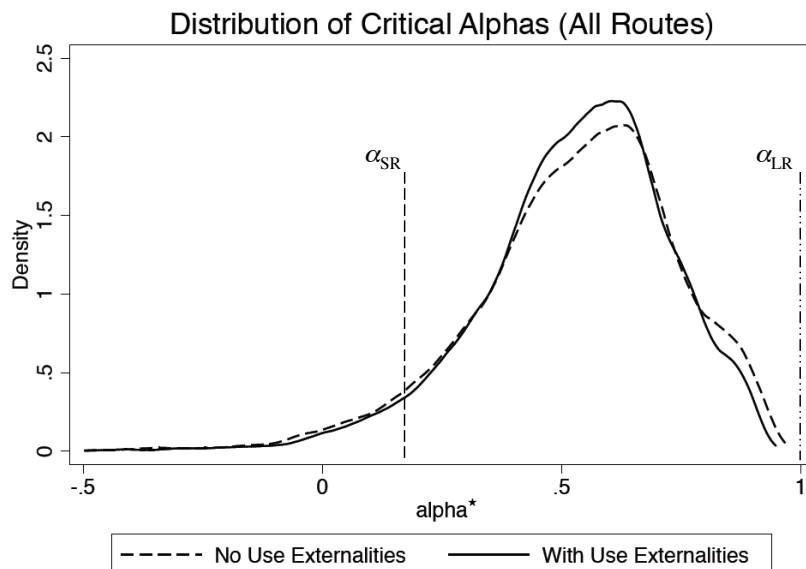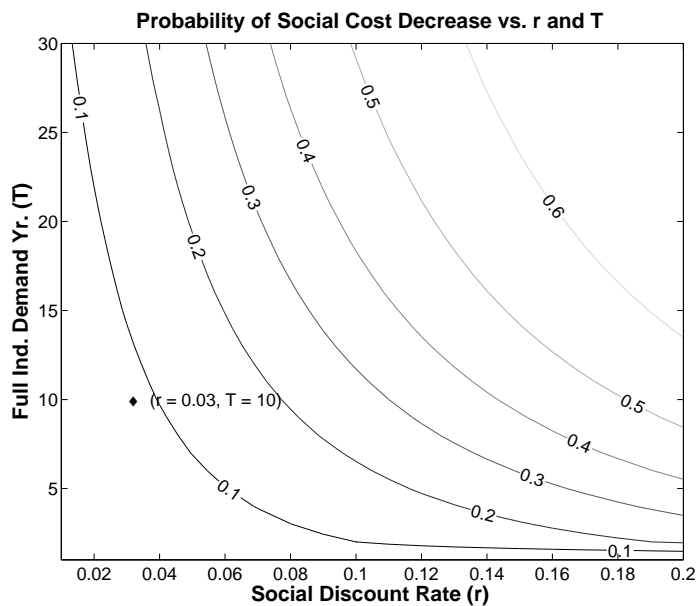

Figure 3: Parameter space for the social planner simulation and the probability of a decrease in the present value of social costs.

8 Tables

Table 1: Descriptive statistics for Los Angeles freeway routes.

Route	Postmile Range (Abs. PM)	Route Length (miles)	Travel Time (minutes)	Trav. Time Diff. (minutes)	Trav. Time Diff. (% of Free Flow)	ML Density (veh./lane-mile)	HOV Density (veh./lane-mile)
105 E (PM Peak)	7 to 13	5.0	7.0	2.1	44%	43.2	30.0
105 W (AM Peak)	7 to 13	5.5	7.1	0.9	19%	36.6	26.6
10 E (PM Peak)	20 to 31	8.7	11.4	8.1	101%	47.4	22.4
10 W (AM Peak)	20 to 31	9.0	10.0	7.0	85%	43.1	15.9
210 E (PM Peak)	26 to 45	18.2	33.3	1.5	9%	43.3	38.5
210 W (AM Peak)	26 to 45	18.3	25.1	7.6	45%	41.4	26.1
405 N North Rt. (PM Peak)	53 to 70	4.9	6.5	2.3	51%	42.9	27.3
405 N South Rt. (AM Peak)	25 to 45	19.3	23.0	5.0	28%	37.9	23.6
405 S North Rt. (AM Peak)	53 to 70	12.5	18.9	7.7	67%	42.5	23.7
405 S South Rt. (PM Peak)	25 to 45	19.5	30.8	5.8	32%	44.0	35.0
605 N (PM Peak)	12 to 20	6.7	9.9	1.4	23%	41.3	33.7
605 S (AM Peak)	12 to 20	6.7	7.7	3.2	52%	38.8	20.5

Table 2: Points on the distribution of critical alphas for Los Angeles freeway routes.

(a) Critical induced demand ($\alpha^\star$) ignoring use-externalities.

Route	n	mean	min.	p5	p10	p50	p90	p95	max.
105 E (PM Peak)	2,401	0.45	-0.67	0.09	0.22	0.49	0.64	0.67	0.81
105 W (AM Peak)	2,401	0.41	-1.36	0.08	0.18	0.43	0.61	0.65	0.80
10 E (PM Peak)	2,401	0.70	-0.52	0.35	0.46	0.72	0.88	0.90	0.94
10 W (AM Peak)	2,401	0.78	0.02	0.58	0.65	0.79	0.90	0.92	0.97
210 E (PM Peak)	2,401	0.27	-1.65	-0.15	0.00	0.31	0.51	0.57	0.75
210 W (AM Peak)	2,401	0.52	-0.32	0.30	0.36	0.52	0.66	0.70	0.81
405 N North Rt. (PM Peak)	2,401	0.59	-0.18	0.38	0.43	0.60	0.72	0.75	0.89
405 N South Rt. (AM Peak)	2,401	0.56	0.12	0.38	0.41	0.57	0.70	0.72	0.82
405 S North Rt. (AM Peak)	2,401	0.60	-1.33	0.26	0.36	0.61	0.87	0.90	0.95
405 S South Rt. (PM Peak)	2,401	0.41	-0.31	0.09	0.17	0.43	0.64	0.67	0.82
605 N (PM Peak)	2,401	0.37	-1.42	0.02	0.12	0.40	0.60	0.63	0.78
605 S (AM Peak)	2,401	0.68	0.14	0.52	0.57	0.69	0.77	0.79	0.87

(b) Critical induced demand ($\alpha^\star$) including use-externalities.

Route	n	mean	min.	p5	p10	p50	p90	p95	max.
105 E (PM Peak)	2,401	0.46	-0.51	0.12	0.24	0.49	0.63	0.66	0.79
105 W (AM Peak)	2,401	0.42	-1.27	0.12	0.21	0.44	0.60	0.64	0.79
10 E (PM Peak)	2,401	0.69	-0.28	0.37	0.46	0.71	0.86	0.88	0.93
10 W (AM Peak)	2,401	0.75	0.11	0.57	0.63	0.76	0.87	0.90	0.95
210 E (PM Peak)	2,401	0.29	-1.51	-0.10	0.03	0.32	0.51	0.57	0.74
210 W (AM Peak)	2,401	0.52	-0.16	0.32	0.38	0.52	0.65	0.68	0.80
405 N North Rt. (PM Peak)	2,401	0.58	0.02	0.39	0.44	0.60	0.71	0.74	0.86
405 N South Rt. (AM Peak)	2,401	0.56	0.16	0.39	0.42	0.56	0.68	0.71	0.79
405 S North Rt. (AM Peak)	2,401	0.59	-0.93	0.28	0.37	0.61	0.84	0.87	0.94
405 S South Rt. (PM Peak)	2,401	0.42	-0.22	0.13	0.19	0.44	0.63	0.66	0.81
605 N (PM Peak)	2,401	0.39	-1.22	0.06	0.15	0.41	0.59	0.62	0.77
605 S (AM Peak)	2,401	0.66	0.17	0.52	0.56	0.67	0.75	0.77	0.85

Table 3: Points on the distribution of the present value of social cost changes for increasing HOV use. Preferred estimates: r = 0.03 and T = 10.

Route	n	mean	min.	p5	p10	p50	p90	p95	max.
105 E (PM Peak)	239,000	135.57	3.44	63.76	72.25	112.04	209.85	240.15	9,953.80
105 W (AM Peak)	239,000	132.58	-7.14	54.12	62.87	109.40	228.08	281.66	1,302.50
10 E (PM Peak)	239,000	38.00	-1,408.90	-449.23	-338.61	37.06	366.88	521.80	3,087.70
10 W (AM Peak)	239,000	53.50	-585.28	-196.83	-145.99	23.32	239.81	363.80	2,781.10
210 E (PM Peak)	239,000	990.49	112.78	337.60	409.22	859.99	1,696.10	2,081.45	7,514.00
210 W (AM Peak)	239,000	405.50	51.21	156.23	184.19	355.63	691.19	811.87	1,822.20
405 N North Rt. (PM Peak)	239,000	94.06	-592.93	36.67	46.61	85.28	153.41	182.91	396.81
405 N South Rt. (AM Peak)	239,000	306.75	40.96	132.25	152.35	250.57	555.78	669.14	1,457.30
405 S North Rt. (AM Peak)	239,000	555.84	-691.27	-76.81	-25.10	282.02	1,442.55	2,401.40	8,236.50
405 S South Rt. (PM Peak)	239,000	831.58	55.96	253.99	302.18	687.50	1,556.30	1,861.55	4,706.70
605 N (PM Peak)	239,000	190.53	35.14	74.45	86.16	160.82	303.48	372.21	4,756.70
605 S (AM Peak)	239,000	65.51	-53.85	25.29	33.46	62.65	100.06	113.36	500.64

Table 4: Mean year when marginal social costs become positive (switch) and when the present value of social costs first becomes positive (break-even).

	Preferred Estimates (r = 0.03, T= 10)		Myopic Planner with Slow Ind. Dem. (r = 0.10, T= 20)	
Route	Mean Switch Year	Mean Break-Even Year	Mean Switch Year	Mean Break-Even Year
105 E (PM Peak)	4.6	9.8	6.3	40.0
105 W (AM Peak)	3.3	6.1	4.0	15.0
10 E (PM Peak)	8.8	60.3	14.9	94.8
10 W (AM Peak)	8.8	58.8	14.9	96.7
210 E (PM Peak)	3.1	5.6	3.8	13.9
210 W (AM Peak)	4.9	10.5	6.7	44.2
405 N North Rt. (PM Peak)	5.6	13.5	8.1	60.4
405 N South Rt. (AM Peak)	5.1	11.1	7.1	47.7
405 S North Rt. (AM Peak)	5.7	24.6	8.6	54.7
405 S South Rt. (PM Peak)	3.6	6.8	4.5	21.0
605 N (PM Peak)	3.8	7.2	4.8	22.5
605 S (AM Peak)	6.7	19.2	10.2	82.0

A For Online Publication - Appendices

A.1 Graphical illustration of the analytical model

Much of the intuition behind our analytical results can be obtained from a graphical illustration of our model. We begin by considering the congestion cost relationships. By Assumption 1, we set $T(n_h) = T(n_l)$ such that congestion costs are symmetric. Figure A1 illustrates this symmetric case. From Equation 1, differences in access costs between resources (τ) drives a wedge between congestion costs in equilibrium. Therefore, with symmetric congestion cost functions it must be the case that consumption of the LAC resource is relatively higher, *i.e.* $n_l > n_h$, as shown in Figure A1. While the symmetry assumption simplifies the proofs of Propositions 1, 2 and 4, our numerical results illustrate a case where the congestion functions are similar but not symmetric. The intuition developed both in Section 3 and in the present section, also applies for these cases.

Given that access costs and congestion costs differ across the LAC and HAC resources in equilibrium, we can now illustrate our main analytical results. Figure A2 presents the case of the HAC resource. The marginal private benefits (MPB) of consuming the HAC resource are defined by the difference in congestion costs across goods, $T(n_l) - T(n_h)$. Intuitively in the case of HOV lanes, the benefit of traveling in the HOV lane is the reduction in travel time relative to the more congested mainline lane. However, consumers of the HAC resource also face higher access costs. In equilibrium, the marginal consumer sets $T(n_l) - T(n_h) = \tau$ resulting in consumption level $n_{h,D.E.}$ as shown in Figure A2. Note that these consumers do not consider the costs or benefits they impose on other consumers of the LAC and HAC resources. Because the social planner does consider these costs in minimizing total social costs, the second-best level of consumption may be larger or smaller than $n_{h,D.E.}$. On one hand, an additional HAC consumer increases the congestion costs of other consumers of the HAC resource and therefore, marginal social costs are higher than marginal private costs.[1] This is shown as MSC_1 in Figure A2. Here, because $n_{h,1}^* < n_{h,D.E.}$, the HAC resource is *over-consumed* in equilibrium. However, an additional HAC consumer may also lower congestion costs of consumers of the LAC resource as shown by MSC_2.[2] In this case, the HAC

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[1]*i.e.* creates a marginal external *cost* for HAC consumers.

[2]*i.e.* creates a marginal external *benefit* for LAC consumers.

resource is *under-consumed* in equilibrium. As we have shown previously, which effect dominates depends on the level of induced demand α.

Finally, Figure A3 illustrates the relationships between the alternative option, the LAC good and induced demand. Congestion costs for the LAC good and costs for the alternative option are shown as $T(n_l)$ and $A(n_a)$, respectively. Since we assume users will consumer the LAC resource until congestion costs equal the cost of the alternative option, we represent the total resource supply as the horizontal sum of $T(n_l)$ and $A(n_a)$.[3] For any given level of consumption of the HAC resource (n_h), our assumption that all consumers must be allocated implies the total remaining consumption is $D_1 = \bar{N} - n_h$. Equating costs P_1, consumption across the two remaining resources is represented by $n_{l,1}$ and $n_{a,1}$. Now, imagine a shift of ϵ_h consumers to the HAC resource. This lowers costs for consumers of the LAC and alternative resources to P_2 and results in consumption levels $n_{l,2}$ and $n_{a,2}$. In the example drawn in Figure A3 we see that the change in consumption of the LAC resource is less than the shift in users to the HAC good, *i.e.* $n_{l,1} - n_{l,2} < \epsilon_h$. This is the induced demand effect. Intuitively, shifting some consumers to the HAC resource lowers congestion costs which reduces the number of consumers who choose the alternative outside option. More generally, if $A(n_a)$ is perfectly elastic, ϵ_h consumers shift out of the alternative option and there is full induced demand. If $A(n_a)$ is perfectly inelastic, the shift causes ϵ_h consumers to leave the LAC resource and induced demand is zero.

A.2 Main analytical results in a production framework

Because we are primarily interested in congestion, our analytical results use the congestion function framework developed in Section 3. However, the intuition behind are main results is also readily illustrated using a production framework. To do this we follow the seminal example of Gordon (1954). For simplicity we use linear functional forms and assume constant marginal costs. The left panel of Appendix Figure 4 plots the average (AP) and marginal (MP) productivity of effort for the high access cost (HAC) resource. In the highway example, productivity can be thought of as the demand for travel minus congestion costs. The right panel plots AP and MP for the low access

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[3] Note that the slope of $T(n_l + n_a)$ defines the induced demand effect. For example, in the case where $T(c_l)$ and $A(c_a)$ are simple linear functions, it is straightforward to show that the slope of $T(n_l + n_a)$ is $T'_l \frac{A'}{A' + T'_l} = T'_l(1 - \alpha)$. The slope also has the intuitive interpretation that it represents the combined change in cost per user of the LAC and alternative option resources from a marginal change in HAC consumption.

cost (LAC) resource and productivity for the alternative option A. When zero effort is applied to either common property resource, $AP_h < AP_l$, which reflects the difference in access costs across these resources.

As is well known, the optimal allocation of effort sets marginal productivity equal to marginal cost (P_1), here shown as $n_{h,opt}$ and $n_{l,opt}$ for the high and low access cost resources. This allocation generates rents equal to the areas $abcd$ and $efgh$ for users of the high and low access cost resources. Consistent with the model in Section 2, no rents are generated in the uncongestible alternative option because each user of this good pays her individual consumption cost. Next, consider the decentralized equilibrium. Here users do not account for the effect of their consumption on productivity (congestion) and consider only their costs and the average productivity across resources.[4] This results in equilibrium consumption levels $n_{h,1}$ and $n_{l,1}$ and the familiar result that zero rents are generated for users of either common-property resource. Finally, note that returns to total effort allocated to the LAC resource and the alternative option are represented by the horizontal sum of average productivity shown as $AP_l + A$. In the decentralized equilibrium total effort for these goods equals $\bar{N} - n_h$ and equates aggregate average productivity with costs P_1.

Next, consider what would happen were a social planner to increase the number of users of the HAC resource by an amount ϵ_h, shown in Appendix Figure 5. Effort in the high access cost resource increases to $n_h + \epsilon_h$. Total effort allocated to the low access cost resource and alternative option decreases to $\bar{N} - (n_h + \epsilon_h)$. This raises productivity for users of the LAC resource and alternative option from P_1 to P_2. Effort in the LAC good decreases from $n_{l,1}$ to $n_{l,2}$ and from $n_{a,1}$ to $n_{a,2}$ in the alternative option. The changes in each good sum to ϵ_h. Shifting ϵ_h users to the high access cost good reduces welfare by lowering productivity and increasing effort. This effect is captured by area $ijkl$. However, the shift creates rents for users of the LAC good because productivity for the remaining users (P_2) exceeds costs (P_1). This effect is captured by area $mnop$.

As in our main model, the relative slopes of the alternative option and LAC resource curves determine the overall welfare effects and indicate whether the high access cost resource is over or under consumed. First, because we assume benefits to users of each good are equal and constant across goods, the slope of average productivity for resource i equals the negative of the slope of congestion costs, *i.e.* $AP_i' = -T_i'$. Therefore, the welfare effects from changes in effort and

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[4]As before we assume users can substitute across resources.

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productivity captured by areas $ijkl$ and $mnop$ equal the congestion externality terms in in the FOC's of the social planners problem, Equation 9. Specifically, area $ijkl = n_h T_h'$ and area $mnop = n_l T_l'(\frac{A'}{A_l'+T_l'})$. Second, whether increasing consumption of the HAC resource improves overall welfare depends on the relative size of areas $ijkl$ and $mnop$. Gains in the LAC resource are larger when there are relatively more users of the LAC resource and when average productivity (congestion cost function) for the LAC resource is relatively steep. Third, in Appendix Figure 5 we have drawn the alternative option with a negative slope. If the alternative option is perfectly inelastic (vertical), *i.e.* induced demand is zero ($\alpha = 0$), moving ϵ_h users to the HAC good decreases effort in the LAC resource by ϵ_h. Under the assumptions of Proposition 2, the HAC resource is under consumed. On the other hand, if the alternative option is perfectly elastic (horizontal), *i.e.* there is full induced demand ($\alpha = 1$), increasing effort in the high access cost resource does not change effort or productivity in the low access cost resource and creates no rents. Because increasing effort in the HAC resource decreases productivity for HAC users but generates no benefit in the LAC, the HAC is over consumed consistent with Proposition 3. Finally, the decentralized equilibrium is second-best if the decrease in welfare from the HAC resource exactly equals the rents created in the LAC resource. Specifically, this is true when $n_h T_h' = n_l T_l'(AP_l + A)'$ where $(AP_l + A)'$ is the slope of the aggregate productivity for the low access cost resource and alternative option. In our linear example it is easy to show that $n_h T_h' = n_l T_l' \frac{A'}{A'+T_l'}$ which replicates the result in Proposition 4. Overall, these results closely follow our main analytical results outlined above.

A.3   General model with $K+1$ resources

Suppose now that there are $K+1$ common-property resources. Let i represent a particular resource of interest and $\mathcal{K}$ the set of other common-property resources, with k indexing the $k = 1, ..., K$ other common-property resources. Every N user is allocated such that $\bar{N} = n_i + \sum_{k=1}^{K} n_k + n_a$. The cost of consuming each common-pool resource is given by $T_j(n_j) + \tau_j$ for $j = i, 1, ..., K$.[5]

We begin by analyzing a decentralized equilibrium, where users minimize costs in choosing across i, $k \in \mathcal{K}$ and the outside option. Nash Equilibrium requires that no user be able to lower their costs by choosing another option, such that:

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[5]Note that in contrast to the model in Section 2, here we simply assume τ_j is constant but different across resources.

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$$T_k(n_k) - T_i(n_i) = \tau_i - \tau_k \quad \forall k \tag{1}$$

$$T_j(n_j) + \tau_j = A(n_a) \quad j = i, 1, ..., K$$

$$\bar{N} - n_h - \sum_{k=1}^{K} n_k - n_a = 0.$$

The first condition says that for all $K + 1$ common-property resources, the congestion cost differential is equal to the access cost differential, such that total costs are equilibrated across all resources. The second condition requires that for any common-property resource, the marginal user is indifferent between the outside option and the common-property resource.

Next, we consider the allocation of users by a social planner. The social planner is considering the allocation of users to the resource of interest i, while accounting for the fact that outside option users may enter (or exit) the remaining K common-property resources:

$$\min_{n_i, n_k, n_a} \quad \sum_{j=i,1}^{K} [T_j(n_j)n_j + \tau_j n_j] + \int_0^{n_a} A(n)dn \tag{2}$$

$$s.t. \quad \bar{N} - n_i - \sum_{k=1}^{K} n_k - n_a = 0$$

$$T_k(n_k) + \tau_k = A(n_a) \quad \forall k$$

with the corresponding Lagrangian:

$$\sum_{j=i,1}^{K} [T_j(n_j)n_j + \tau_j n_j] + \int_0^{n_a} A(n)dn + \lambda(\bar{N} - n_i - \sum_{k=1}^{K} n_k - n_a) + \sum_{k=1}^{K} \mu_k(T_k(n_k) + \tau_k - A(n_a)) \tag{3}$$

and first-order conditions:

$$T_i + n_i T_i' + \tau_i - \lambda = 0 \tag{4}$$

$$T_k + n_k T_k \tau_k - \lambda + \mu_k(T_k') = 0 \tag{5}$$

$$A - \lambda - \sum_{k=1}^{K} \mu_k A' = 0. \tag{6}$$

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which define the cost-minimizing, second-best allocation of users n_i, n_k, and n_a across all options.[6]

With some iterative substitution, the first FOC can be written as:

$$T_i + n_i T_i' + \tau_i - T_k - \tau_k - \frac{A' \sum_{k=1}^{K} n_k \prod_{k=1}^{K} T_k'}{\prod_{k=1}^{K} T_k' + A' \sum_{k=1}^{K} (\prod_{m \in \mathcal{K} / k}^{K} T_m')} = 0, \tag{7}$$

or

$$T_k - T_i = \tau_i - \tau_k + n_i T_i' - \frac{A' \sum_{k=1}^{K} n_k \prod_{k=1}^{K} T_k'}{\prod_{k=1}^{K} T_k' + A' \sum_{k=1}^{K} (\prod_{m \in \mathcal{K} / k}^{K} T_m')}, \tag{8}$$

which states that the marginal private benefit of an additional user of resource i is equal to the marginal private cost of another user of resource i, plus the net marginal external costs. The complicated final term reflects the complex substitution pattern across resources. Specifically, an increase in the number of users of i leads all other users to resort across the K other common-property resources and the outside option. The intuition from Appendix Figure A3 is readily extended to the case with K common-property resources. Finally, setting $K = 1$, $i = h$, $k = l$, and $\tau_i - \tau_k = \tau$ recovers the expression 7 presented in the main text.[7]

A.3.1 Implications for empirical example

In the empirical exploration of HOV lane use, we use the analytical framework presented in Section 2 which considers two common-property resources, representing an HOV lane and the adjacent mainline lanes. As such, our calculations assume that increasing HOV lane use draws drivers from the adjacent mainline lane. However, two relevant empirical concerns emerge. First, new HOV lane users may come from not only the mainline lanes, but also from alternate congestible highways and surface streets. Second, congestion relief in the mainline may be offset not only by entry of new users from the uncongestible alternative option but also from congestible alternatives. These alternative congestible options can be thought of as belonging to the set of K congestible options in the analysis above. Here, we briefly argue that if some users are moving from other congested options, the congestion relief benefits calculated in the main text upper-bound the benefits of increasing

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[6]This allocation satisfies the second-order sufficient conditions for a local constrained minimization.

[7]This is more clear when recognizing that the outside option can be thought of as equivalent to another common-property resource such that $A' = T_{K+1}'$, $T_{K+1} \in \mathcal{K}$ and $|\mathcal{K}| = K + 1$. In which case, the denominator of the final term in 8 can be expressed as $\sum_{k=1}^{K+1} (\prod_{m \in \mathcal{K} / k}^{K+1} T_m')$, such that this term is equal to $A' + T_k'$ when there is only the single common-property resource and the outside option per the main text.

HOV lane use. In this case, our main results are conservative in that they bias us towards concluding that HOV lanes are under-consumed.

Let τ_l represent the access cost for the mainline highway and τ_s represent the access cost for a parallel surface street (s). Because mainline highways are a faster travel option in the absence of congestion, then $\tau_l < \tau_s$.[8] Per our theory above (see also Appendix Figure 1), larger access cost on s implies that $n_l > n_s$ in the decentralized equilibrium. If the congestion functions are identical functions of the number of users, convexity of the congestion function and $n_l > n_s$ implies that $T'(n_l) > T'(n_s)$. As such, the congestion relief benefit from a driver leaving the surface street for the HOV lane ($n_s T'(n_s)$) is smaller than the congestion relief benefit for a driver leaving the mainline ($n_l T'(n_l)$). Similarly, any driver leaving a less congested option for the mainline will generate greater congestion cost in the mainline ($n_l T'(n_l)$) than congestion relief on their original route ($n_s T'(n_s)$).

Relaxing the assumption that the congestion functions are identical raises the possibility that congestion relief on surface streets could be larger in magnitude than congestion relief in the mainline, i.e. if $T'_s(n_s) > \frac{n_l}{n_s} T'_l(n_l)$. For this to be true, the marginal change in congestion on the surface street ($T'_s(n_s)$) would have to be large enough relative to the marginal change in congestion in the mainline ($T'_l(n_l)$) to outweigh the fact that $n_l > n_s$. This seems unlikely to be true.[9] Therefore, we view the congestion benefits we calculate in the main text as an upper-bound on the potential congestion relief under the circumstances described above.

A.4 Transaction costs and induced demand

Corollary 2 of Proposition 4 predicts a positive relationship between transaction costs and the level of induced demand for which the decentralized equilibrium is second-best. For ease of exposition we focus on the case without other use-externalities. Appendix Figure 6 illustrates this relationship for a representative route and plots $\alpha^\star$ versus transaction costs τ for the morning and evening peaks of Interstate 605. The dark lines are locally weighted smoothed estimates for each scatterplot. Several features are worth noting. First, the level of induced demand for which the decentralized

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[8] For example, because of higher speed limits, no traffic signals and more direct routes than surface streets.

[9] For example, if there were twice as many users on the mainline highway as on a parallel surface street, then the marginal congestion function for the surface street would need to be twice as steep (despite having half as many users) for our calculation to not represent an upper-bound.

equilibrium is second-best increases with transaction costs as predicted. Second, for low transaction costs the decentralized equilibrium is second-best for relatively small levels of induced demand, in these examples approximately 0.30 and 0.05. This is consistent with our analytical model where the benefit of congestion relief in the mainline is small for low transaction costs and therefore even a small amount of induced demand can negate the benefits of shifting vehicles to the HOV lane.

We examine whether this positive relationship between τ and $\alpha^\star$ exists across routes in our sample by regressing our calculated $\alpha^\star$ on transaction costs τ for each observation in our sample.[10] Appendix Table 1 presents the results of several different specifications. Model 1 is the base model. Model 2 includes route mean effects and Model 3 adds interactions for τ with route-effects. Finally, Model 4 uses robust regression to account for the influence of outliers. In each of these specifications, the correlation between transaction costs and the level of induced demand is positive. This is true for both the pooled estimates and when the relationship is allowed to vary across routes. Focusing on Model 4, for each minute increase in transaction cost, the optimal level of induced demand increases between 0.005 for I-10W and 0.139 for I-105W. These results further support the analytical results in Corollary 2 of Proposition 4.

A.5   Data appendix

Our analysis focuses on 12 highway routes in Los Angeles, California from 2002 through 2011. We exploit detailed traffic data from the Freeway Performance Measurement Systems (PeMS). From PeMS we observe average vehicle speed and hourly flow rates at nearly 600 locations on the citys major highways. We aggregate the individual detector-level data to route-level data to capture traffic patterns and representative commutes. Because we are interested in congestion externalities, we impose both spatial and temporal restrictions on our data to focus on congested periods and locations. Our routes include all freeways that have both mainline and HOV lanes subject to these restrictions.

First, from all the possible highway routes for which we have PeMS data, we identify congested locations by looking at average vehicle speeds at various points along each freeway during the morning and evening commute periods. When congestion occurs, average speeds drop below the

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[10]We calculate τ as the difference in equilibrium travel time between the mainline and HOV lanes $T_l(n_{it}) - T_h(n_{it})$ for each route i at time t.

free flow traffic speed. These areas of reduced speed define the post-mile ranges for the congested routes. In most cases, the congested sections of highway are bounded by features of the road network, typically interchanges. In some cases we are limited by the locations of PeMS detectors. Second, we restrict our sample to weekdays and drop observations for Federal holidays, and the weeks of Christmas, Thanksgiving and Easter. This results in 239 daily observations per route per year. Third, we focus on two commute hours, 8 am for the morning peak and 5 pm for the evening peak period. We classify each route as an am-peak or pm-peak route based on whether the observed average congestion is more severe in the morning or evening. Our analysis of average vehicle speeds confirms that these hours accurately reflect peak commuting times.

Because we are interested in travel time and speed differentials between the mainline and HOV lanes, we match PeMS detectors by type at the post-mile level. We limit our analysis to only those detectors where mainline and HOV traffic are monitored at the same location.[11] Speeds and flows are measured at between 10 and 40 locations along each route. We drop any routes for which we observe traffic conditions at fewer than 10 locations. Following the above criteria, we select the routes shown in Table 1.

For each route we estimate the average travel time and consumption for the mainline and HOV lanes for each day in the sample using the detector-level data. To do this we replicate the procedure traffic engineers term "walking the vector." Beginning at the start of each route, we calculate the route-level travel time as:

$$T_{it} = \sum_{s=1}^{S} (\frac{1}{\overline{speed}_{j,j+1}})(PM_{j+1} - PM_j) \tag{9}$$

for detector j along route i with S total detectors, where $\overline{speed}_{j,j+1}$ is the average speed between detectors j and $j+1$ and PM_j is the recorded postmile for detector j (for notational convenience, the route i subscripts are suppressed). We repeat this procedure for each day and each route in the sample.

To estimate the average density for each route, day and lane type, we first calculate the mile-weighted average hourly flow ($\bar{F}_{it}$) and speed ($\bar{S}_{it}$). Density ($\bar{n}_{it}$) for route i and time t is then calculated using the identity $n_{it} = \bar{F}_{it}/\bar{S}_{it}$. The difference in travel time between the mainline and HOV lanes captures the difference in access costs between these goods and in this case, equals the

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[11]While this restriction is not necessary, it helps to ensure consistency in route distances, average speeds and flows across the lane types.

transaction cost of carpool formation net of fuel savings and other non-congestion related differences between modes.

A.6   Marginal external congestion costs

Appendix Table 2 shows the mean calculated marginal external costs of congestion for mainline and HOV lanes across the twelve routes in our sample. The righthand columns translate congestion costs into net congestion costs under various levels of induced demand taking into account mainline congestion relief.[12] These results have important practical policy implications. Treating the HOV lane as an isolated open access common property resource and ignoring the link to mainline lanes is analogous to $\alpha = 1$, full induced demand. Here, the mean net marginal congestion costs range from $0.42 and $1.33 per mile and policy makers would choose to *discourage* HOV lane use. If instead one were to ignore induced demand, $\alpha = 0$, mean net marginal congestion costs range from -$0.48 to -$2.40 and policy makers would choose to *increase* HOV lane use. Policy makers who evaluate the HOV lane based on these different induced demand assumptions generate the exact *opposite* policy responses. Of course in reality, induced demand may fall between these extremes and likely evolves over time. For example if $\alpha = 0.6$, Table 2 suggests increasing HOV lane use on some routes and decreasing HOV lane use on others.

A.7   Present value of policy interventions in peak and non-peak hours

Our main analysis focuses on the peak commuting hours of 8 am and 5 pm to investigate whether HOV lanes are over or under-consumed.[13] To investigate the implications of our focus on peak hours, we replicate the analysis of Section 5.2 using all hourly observations from 6 am through 8 pm. Late evening and early morning hours are still excluded from the analysis, as without congestion, highway use is non-rival. As in our earlier calculations, we assume a social discount rate of 3% and that induced demand is fully realized after 10 years.

Appendix Table 3 summarizes changes in the present value of social costs due to an increase in

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[12]We assume each carpool consists of two commuters and ignore additional use-externalities to enable the reader to easily compare between the righthand and lefthand columns.

[13]We focus on peak hours to avoid the computational cost associated with analyzing such a large quantity of data. For example, the simulation results for all daytime hours reported below required nearly two weeks of processing time.

HOV lane use for all daytime hours. Qualitatively, the results in Appendix Table 3 are quite similar to our main results. Across the various routes, mean social costs range from $23.60 to $196.50. Median values range from $10.22 to $87.29. While these values are somewhat smaller in magnitude than the peak hour results, social cost changes are more likely to be positive across the daytime hours. For instance, only route I-10 E is negative at the 5th percentile. Intuitively, including off peak hours introduces additional highly congested hours for which increasing HOV lane use raises social costs. It also introduces some less congested hours where increasing HOV lane use is more likely to lower costs, for example if the mainline is congested but the HOV lane is not. To see this, Appendix Table 4 summarizes mean present value social costs for increasing HOV lane use by route and by hour. The mean values are all positive, though values are smaller in magnitude for the off-peak hours on each route. This means the average effects using all congested hours in the data will be smaller compared with our results using only peak hours. However, the total effects across all hours will be larger relative to our main results.

As before, we can estimate the net present value of social cost from increasing vehicle density by one car per mile across the routes in our sample. This equates to approximately $3.4 million using the mean and $1.8 million using the median values. This effect is of course averaged over all the hours of the day. A more interesting calculation is to sum up the effects across the hours of the day. In this case the estimated total effects are approximately $51.5 million and $30.6 million using the mean and median values.
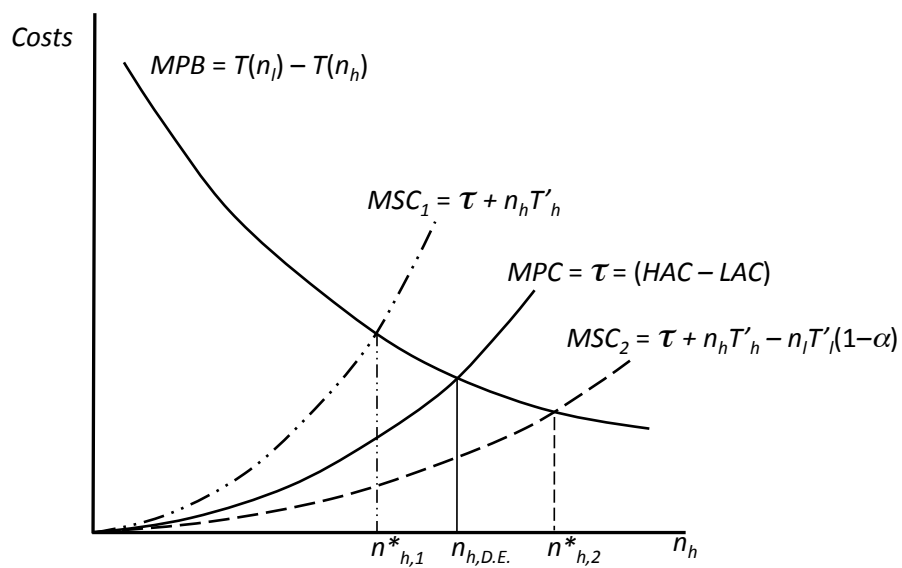
Finally, we can explore the robustness of these results to changes in the social discount rate r and the year in which induced demand is fully realized T. These results are summarized graphically in Appendix Figure 7. As in our main results using only peak hours, increasing HOV lane use is unlikely to lower present value social costs unless the social discount rate is substantially higher, or induced demand rises much more slowly.

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B Appendix figures

Appendix Figure 1: Congestion costs and differences in access costs (τ) for the LAC and HAC resources with symmetric congestion cost functions.
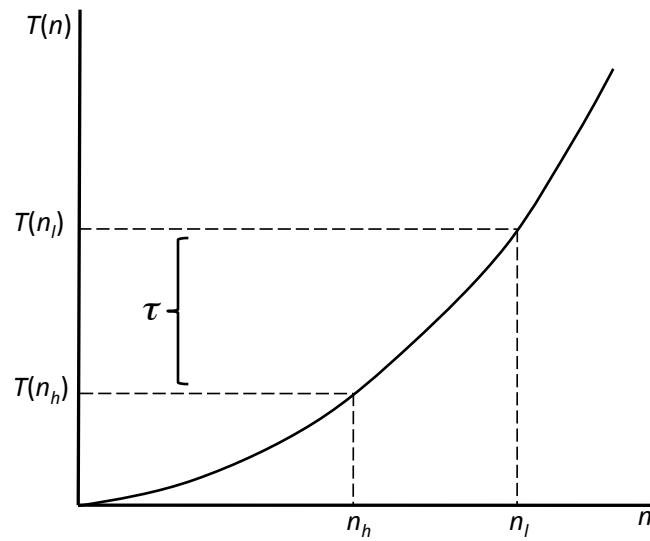
Appendix Figure 2: Private benefits, costs and social costs for the HAC resource.

Costs

$MPB = T(n_l) - T(n_h)$

$MSC_1 = \tau + n_h T'_h$

$MPC = \tau = (HAC - LAC)$

$MSC_2 = \tau + n_h T'_h - n_l T'_l (1-\alpha)$

$n^*_{h,1}$ $n_{h,D.E.}$ $n^*_{h,2}$ n_h

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Appendix Figure 3: Congestion costs, alternative option costs and induced demand effects.
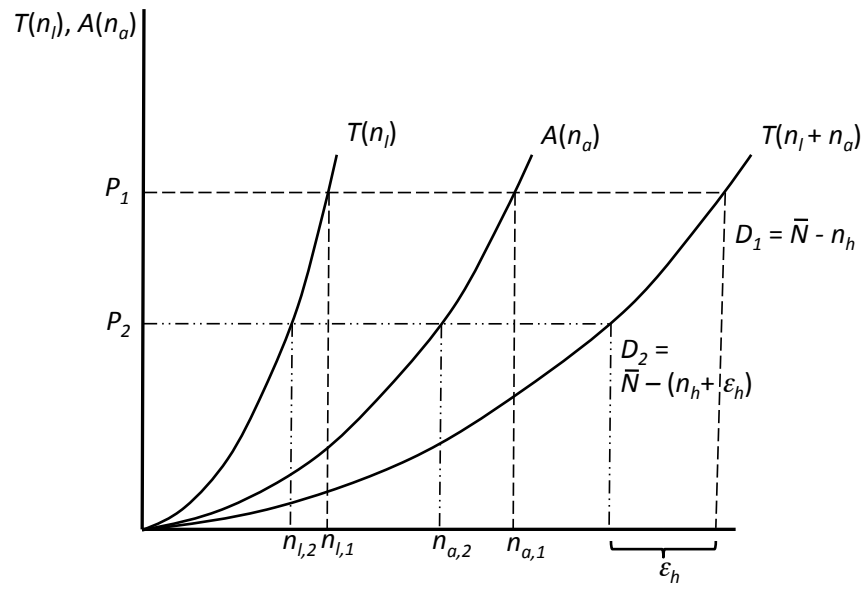
Appendix Figure 4: Inefficiency of decentralized equilibrium illustrated with a production framework.
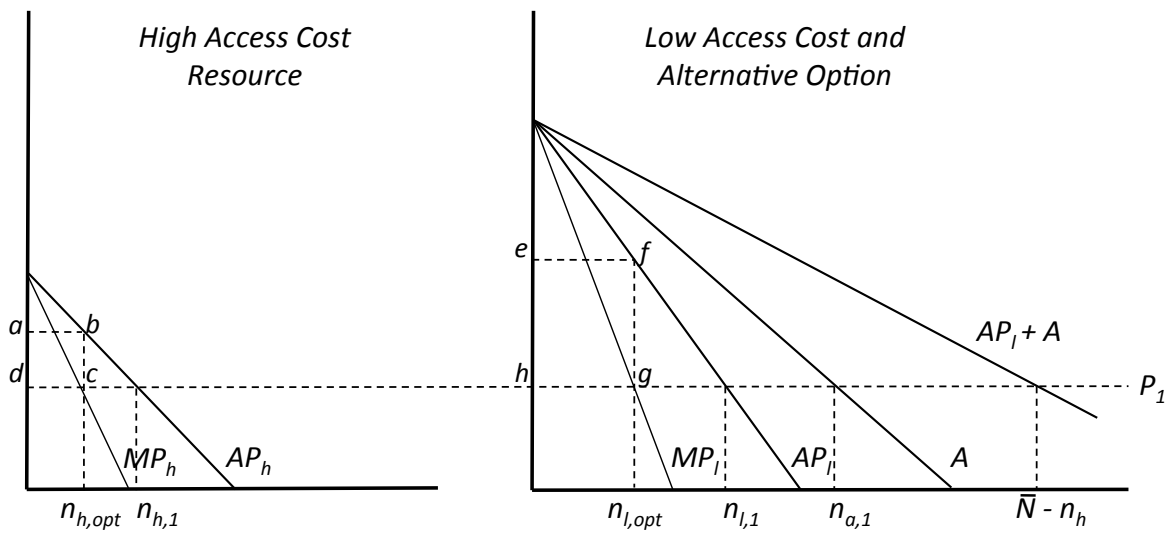
Appendix Figure 5: Welfare effects and induced demand in a production framework.
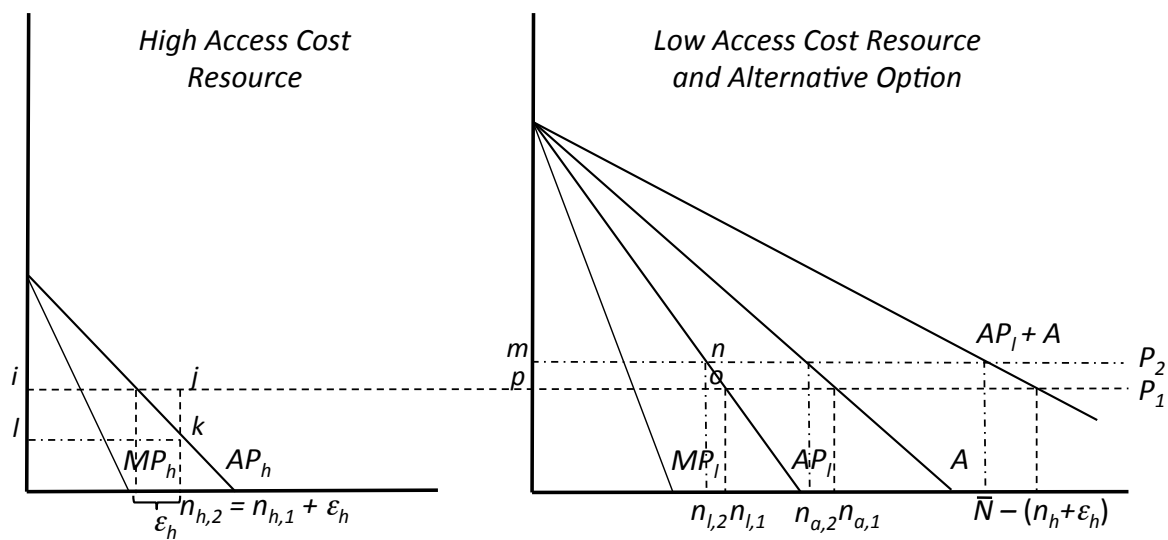
Appendix Figure 6: Representative relationships between the critical level of induced demand and access costs.

(a) Route I-605 South am Peak
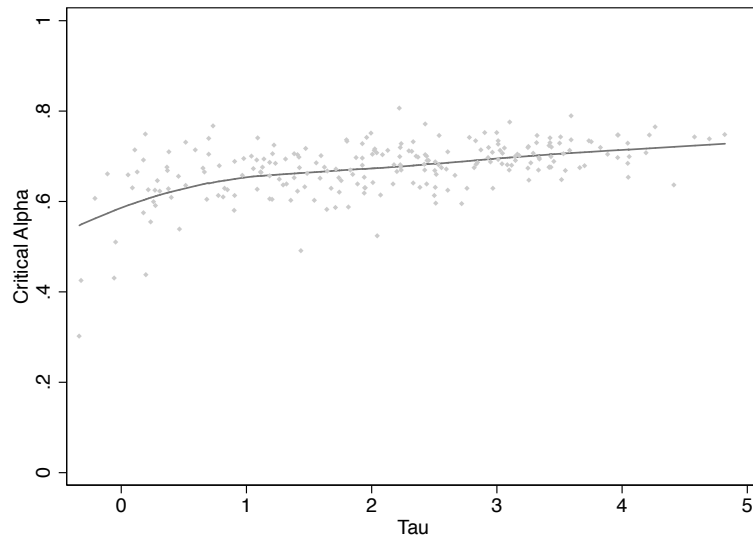
(b) Route I-605 North pm Peak

Appendix Figure 7: Parameter space for the social planner simulation and the probability of a decrease in the present value of social costs using traffic data for all hours from 6 am through 8 pm.

C Appendix tables

Appendix Table 1: Models for the relationship between transaction costs and the critical induced demand.
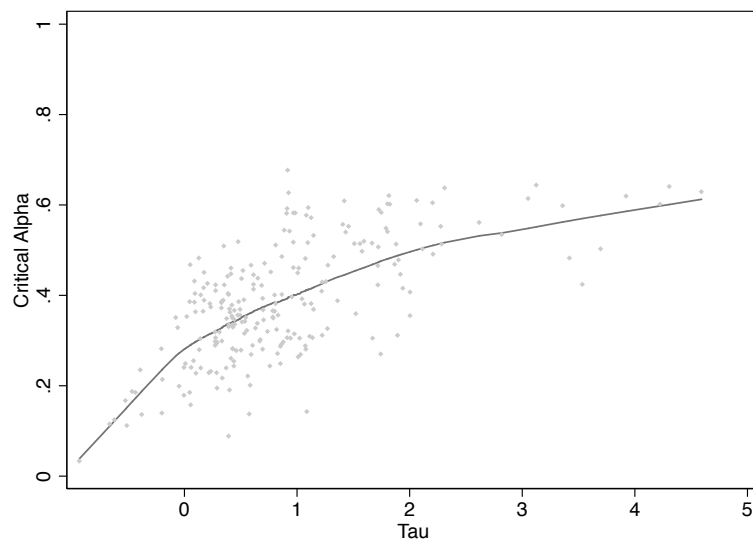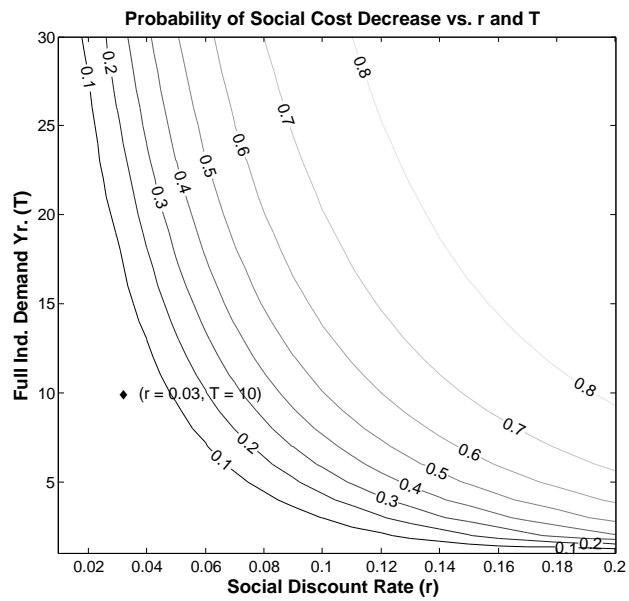
Models for Critical Induced Demand as a Function of Transaction Cost				
	Model 1	Model 2	Model 3	Model 4
Transaction Cost (τ)	0.025***	0.021***	0.092***	0.080***
	(0.0050)	(0.0040)	0.0000	(0.0020)
Transaction Cost (τ) X D_{105W}			0.001***	0.003
			0.0000	(0.0030)
Transaction Cost (τ) X D_{10E}			-0.074***	-0.064***
			0.0000	(0.0020)
Transaction Cost (τ) X D_{10W}			-0.086***	-0.075***
			0.0000	(0.0020)
Transaction Cost (τ) X D_{210E}			-0.052***	-0.044***
			0.0000	(0.0020)
Transaction Cost (τ) X D_{210W}			-0.079***	-0.068***
			0.0000	(0.0020)
Transaction Cost (τ) X $D_{405N\ north}$			-0.050***	-0.038***
			0.0000	(0.0020)
Transaction Cost (τ) X $D_{405N\ south}$			-0.081***	-0.069***
			0.0000	(0.0020)
Transaction Cost (τ) X $D_{405S\ north}$			-0.076***	-0.069***
			0.0000	(0.0020)
Transaction Cost (τ) X $D_{405S\ south}$			-0.072***	-0.059***
			0.0000	(0.0020)
Transaction Cost (τ) X D_{605N}			-0.020***	-0.013***
			0.0000	(0.0020)
Transaction Cost (τ) X D_{605S}			-0.071***	-0.059***
			0.0000	(0.0020)
Route Effects	No	Yes	Yes	Yes
Observations	28812	28812	28812	28812
Adj. R-Squared	0.28	0.56	0.63	0.67

Notes: The dependent variable in each regression is the the critical level of induced demand ($\alpha\star$) for which the decentralized equilibrium is second-best. Standard errors are clustered at the route level. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels, respectively. Model 4 uses robust regression to account for the influence of outliers.

Appendix Table 2: Mean calculated marginal congestion costs to mainline and HOV lane commuters in $ per car-mile. Mean marginal net external cost for HOV lane commuters at various levels of induced demand α in $ per car-mile.

Route	n	$n_l T'_l$	$n_h T'_h$	HOV Lane Mean Net MEC ($/car-mile)			
				$\alpha = 0$	$\alpha = 0.1$	$\alpha = 0.6$	$\alpha = 1$
105 E (PM Peak)	2,401	0.75	0.39	-0.71	-0.56	0.19	0.78
105 W (AM Peak)	2,401	0.60	0.36	-0.48	-0.36	0.24	0.71
10 E (PM Peak)	2,401	1.12	0.47	-2.40	-2.07	-0.39	0.94
10 W (AM Peak)	2,401	0.84	0.27	-1.98	-1.73	-0.47	0.54
210 E (PM Peak)	2,401	0.91	0.67	-0.50	-0.31	0.60	1.33
210 W (AM Peak)	2,401	0.76	0.36	-0.80	-0.65	0.11	0.72
405 N North Rt. (PM Peak)	2,401	0.80	0.32	-0.98	-0.82	-0.01	0.63
405 N South Rt. (AM Peak)	2,401	0.62	0.27	-0.71	-0.58	0.04	0.53
405 S North Rt. (AM Peak)	2,401	0.99	0.40	-1.18	-0.98	0.01	0.80
405 S South Rt. (PM Peak)	2,401	0.92	0.54	-0.76	-0.58	0.34	1.08
605 N (PM Peak)	2,401	0.76	0.47	-0.59	-0.44	0.33	0.94
605 S (AM Peak)	2,401	0.68	0.21	-0.94	-0.80	-0.12	0.42

Notes: Mean mainline ($n_l T'_l$) and HOV lane ($n_h T'_h$) marginal congestion costs calculated per vehicle.
HOV lane net marginal external costs assume 2 riders per carpool. For comparison across columns we ignore additional vehicle related use-externalities.

Appendix Table 3: Points on the distribution of the present value of social cost changes for increasing HOV use using all hours from 6 am through 8 pm. Preferred estimates: r = 0.03 and T = 10.

Route	n	mean	min.	p5	p10	p50	p90	p95	max.
105 E (PM Peak)	3,585,000	32.52	-39.20	4.87	6.06	15.12	79.42	111.19	298.35
105 W (AM Peak)	3,585,000	38.18	-39.42	8.64	10.49	27.13	77.47	112.75	771.52
10 E (PM Peak)	3,585,000	50.18	-262.95	-5.01	0.02	15.92	149.45	242.04	3,240.40
10 W (AM Peak)	3,585,000	43.41	-188.43	0.02	6.93	30.83	85.37	131.94	987.94
210 E (PM Peak)	3,585,000	196.50	-48.63	23.56	27.25	63.30	569.19	767.15	2,864.30
210 W (AM Peak)	3,585,000	138.07	-27.84	27.93	33.03	82.49	334.07	467.74	1,608.00
405 N Northern Route (PM Peak)	3,585,000	23.60	-71.77	3.76	4.59	10.22	61.76	80.56	312.97
405 N Southern Route (AM Peak)	3,585,000	106.68	-11.54	30.21	37.36	87.29	197.83	258.38	901.00
405 S Northern Route (AM Peak)	3,585,000	96.80	-382.82	9.29	14.48	53.91	227.14	333.03	2,542.10
405 S Southern Route (PM Peak)	3,585,000	154.14	-114.11	20.06	25.00	64.53	406.57	577.39	2,307.20
605 N (PM Peak)	3,585,000	52.55	-58.45	3.78	6.47	27.05	137.01	185.83	658.29
605 S (AM Peak)	3,585,000	44.57	-44.54	5.13	7.51	31.64	93.72	124.65	1,356.80

Appendix Table 4: Mean values for the present value of social cost changes for increasing HOV use by route and hour.

Hour	105 E (PM Peak)	105 W (AM Peak)	10 E (PM Peak)	10 W (AM Peak)	210 E (PM Peak)	210 W (AM Peak)	405 N North Rt. (PM Peak)	405 N South Rt. (AM Peak)	405 S North Rt. (AM Peak)	405 S South Rt. (PM Peak)	605 N (PM Peak)	605 S (AM Peak)
6	25.51	50.30	42.53	50.37	145.00	193.72	19.46	129.31	131.16	109.66	41.85	62.59
7	26.78	69.42	44.33	59.30	154.68	238.69	19.72	166.84	193.98	112.69	46.59	89.33
8	25.96	55.70	39.18	45.11	146.77	176.94	18.92	143.73	145.05	115.68	44.00	53.15
9	24.97	37.87	39.28	52.32	150.19	134.57	19.08	120.20	95.64	108.25	42.89	29.92
10	26.74	32.03	39.25	41.37	153.22	120.98	18.81	100.88	76.37	111.59	43.23	20.19
11	26.24	30.10	38.70	36.28	148.25	116.92	19.44	92.53	73.09	117.55	41.46	15.60
12	25.72	28.58	43.11	36.36	157.59	112.48	19.77	91.30	73.02	118.96	42.09	17.99
13	28.19	30.48	43.69	36.84	166.74	112.72	19.50	90.76	75.91	128.97	47.45	24.24
14	34.77	30.61	52.63	40.57	205.54	118.37	21.25	95.13	83.48	159.24	54.11	42.32
15	42.40	35.09	71.28	44.46	264.15	124.89	30.30	99.61	92.76	210.27	66.68	70.28
16	45.82	35.57	77.09	46.56	309.82	130.95	40.59	102.83	92.27	267.79	77.01	86.29
17	48.10	37.90	66.98	45.97	327.24	139.10	38.24	105.98	94.17	283.24	79.85	83.66
18	45.63	38.02	59.50	43.58	269.87	130.21	28.59	96.74	86.18	209.98	68.49	47.68
19	33.94	32.05	53.27	38.29	193.76	113.34	20.16	84.50	73.04	143.71	47.93	16.32
20	26.98	28.93	41.89	33.79	154.76	107.17	20.15	79.90	65.90	114.51	44.70	8.95