The economics of truck toll lanes

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Abstract

Truck-only lanes and truck tollways have been studied and promoted in the U.S. as a potential tool for combating road congestion, enhancing safety and reducing pavement damage. The goal of this paper is to conduct a preliminary and partial economic analysis of truck lanes by considering whether there are advantages in separating light and heavy vehicles, and if so how this can be implemented using tolls or access regulations. Several factors are identified as important: the relative volumes of light and heavy vehicles, lane indivisibilities, values of travel time for light and heavy vehicles, the relative congestion costs they impose, and the potential safety advantages (whether real or imagined) of separating them.

Key words: truck-only lanes, congestion, accidents, pricing, segregation

JEL codes: R41, R48

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1 INTRODUCTION

Truck-only lanes and truck tollways have been extensively studied in the U.S.[1] Although no such facilities have yet been built[2] several U.S. states, including California, Texas and Virginia, have conducted studies (Federal Highway Administration 2003; Transportation Research Board 2003; Hedlund 2004). The Southern California Association of Governments (SCAG) has a plan that calls for an interconnected system of truck-only freeway lanes on four highways that would cost nearly $10 billion. Truck-only lanes were proposed for a North American Free Trade Association (NAFTA) highway between Toronto and Laredo, Texas. The Reason Foundation published a detailed study (Samuel et al. 2002) arguing that an interstate network of private truck tollways could be profitable in the U.S. And Texas has adopted an ambitious plan to build a "Trans Texas Corridor" (Texas Department of Transportation 2002).[3]

Several potential advantages of dedicated truck-only facilities are identified in the literature.

Road design: Trucks require higher road-design standards than do light vehicles as far as pavement thickness, lane widths, road curvature, grades, etc. By restricting trucks to a subset of roads or lanes, the rest of the road network can be built to a lower standard.

Congestion: If the provision of truck-only lanes reduces traffic volumes for trucks, it reduces the congestion delay they incur as well as the frequency of braking, accelerating, and overtaking. It also improves reliability of travel time for freight deliveries (Douglas 2005).

Safety: Although the empirical evidence is not clear-cut, it appears that accident rates are higher in mixed (i.e. heavy and light vehicle) traffic than in homogeneous traffic (Middleton and Lord 2005; Forkenbrock and March 2005). If so, safety is promoted by segregating trucks from cars. And it is generally accepted that automobile drivers dislike trucks and would be willing to pay to avoid them.[4]

Air quality: By supporting higher and less variable speeds, truck-only lanes contribute to better overall air quality (Douglas 2005).[5]

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[1] Reich et al. (2002) provide an extensive literature review up to 2002.

[2] Only two facilities in the U.S. are designed to accommodate trucks while permitting passenger vehicles to access them. One is the New Jersey Turnpike, and the other is a segment of Interstate 5 north of Los Angeles (Middleton and Venglar 2006). The New Jersey Turnpike is a so-called "dual-dual" roadway, defined to be "a system of parallel, grade-separated lanes with trucks restricted from operating in the center, auto-only lanes."

[3] The Trans Texas Corridor will consist of a 4,000-mile network of corridors up to 1,200 feet wide with three road lanes in each direction for passenger vehicles, and two road lanes in each direction for trucks. Road tollways will be designed for an 80 mph speed limit. In addition, the corridors will have one rail track in each direction for each of three types of rail service (freight, commuter rail, and high-speed passenger rail) as well as corridors for utilities. The first Trans Texas Corridor, TTC-35, is under development.

[4] Using contingent valuation analysis Bambe and McMullen (1996) estimated that motorists would be willing to pay about $35 (1995) annually to remove triple-trailer combination trucks from Oregon's highways. (Information taken from Forkenbrock and March 2005, p. 8.) However, while automobile drivers generally perceive an improvement in safety and operations from lane restrictions on heavy vehicles, truck drivers do not foresee improvements (Koehne et al. 1996; Douglas 2005).

[5] However, pollutant emissions and/or noise levels may increase near truck lanes.

Noise: Reductions in noise are a potential benefit (Douglas 2005).

Truck type: Truck-only lanes will facilitate use of so-called Long Combination Vehicles (LCVs) that exploit economies of vehicle size.[6] Use of larger trucks not only reduces transport costs per tonne-km, but also reduces congestion delays for a given amount of freight transported because fewer trucks are on the road.

Truck-only roads or lanes are also recognized to have several potential disadvantages.

Capacity indivisibilities: Building truck-only roads or lanes (or High Occupancy Vehicle (HOV) lanes more generally) is cost-effective only if both truck volumes and total traffic volumes are sufficiently high (OECD 1992; Douglas 2005; Forkenbrock and March 2005). Lane indivisibilities are an important practical consideration that makes it difficult to allocate capacity between vehicle categories in efficient proportions (Small 1983; Dahlgren 1998, 2002; Yang and Huang 1999; Parsons et al. 2005). And to facilitate access in the event of incidents, as well as to provide reliable travel times for truckers, it is advisable to build twin truck lanes (Fischer et al. 2003) which increases the infrastructure costs. Wilbur Smith Associates (2003) assessed various strategies for dealing with congestion on Interstate 10 (I-10), which runs across the southern U.S. from Florida to California. This study concluded that simply adding more general-purpose lanes to I-10 would be more effective than adding truck-only lanes.

Availability of right-of-way: Some intercity travel corridors in the U.S. lack sufficient width to accommodate double truck lanes throughout their length (Poole and Samuel 2004). And many Interstate highways lack an uninterrupted median that would permit an extra lane or lanes to be built in the medium (Reich et al. 2002).

Temporal segregation: Truckers generally avoid traveling during peak commuting periods (Donaghy and Schintler 1998; Fischer et al. 2003). A majority of their trips are made during mid-day (10:00-15:00) and at night. To the extent that auto and trucking trips are segregated temporally they can use the same roads at different times, and building separate facilities is unnecessary.

Lane access considerations: Complete segregation of heavy vehicles from cars is not practical.[7] Truck route or lane restrictions may add to travel distance which militates against truckers using them for short haul trips. And forcing vehicles to use certain lanes may increase the number of lane changes (e.g. if trucks are restricted to left-hand lanes) which contributes to traffic flow turbulence and accident hazards (Gan and Jo 2003).

This list of pros and cons indicates that the optimal design and cost-effectiveness of truck facilities depends on many practical considerations. A large number of facility types have been proposed that differ according to numbers of lanes, conversions vs. additions (including conversion of HOV lanes, and admitting trucks to High Occupancy Toll (HOT) lanes), and usage restrictions. But most studies use simulation models without describing (at least in

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[6] Samuel et al. (2002) conclude that permitting the largest LCVs would increase productivity by $3.04 per vehicle-mile.
[7] As Wilbur Smith Associates (2003, p.35) remarks: "Even in cases where truck separation is applied, there will have to be some degree of car/truck interaction, especially along segments where local traffic merges on/off the freeway system. This presents significant traffic engineering issues (trucks and cars crossing lanes to merge to and from exclusive lanes)."

publicly available documents) how the models work or identifying precisely what factors drive the results.

To the best of our knowledge no formal analytical/economic analysis of truck-only facilities has been conducted to date. Nevertheless, the economics of truck-only facilities resemble in several respects the economics of HOV and HOT lanes which have been studied from an economic perspective. An early and insightful analysis of HOV lanes is found in Small (1977, 1983). Small uses a disaggregate logit model of modal choice to determine whether HOV lanes for buses are cost effective, and how well they perform relative to congestion tolls. He finds that with ideal lane segregation of buses and cars (i.e. when capacity is perfectly divisible), bus priority lanes yield about half the benefits of marginal cost pricing.[8] But when the indivisibility of HOV lanes is accounted for, auto congestion becomes dramatically worse because a full lane has to be allocated to HOV traffic. Only at high volumes of passengers per lane-hour do the positive benefits for HOV lane users outweigh the negative effects of increased auto delay. Mannering and Hamed (1990) obtain similar results for HOV lanes designed for cars.

These and other studies convey two important lessons that carry over to truck-only facilities. One is that the benefits from dedicated facilities depend critically on the volume of traffic that will use them. The second lesson is that lane- or route-access restrictions are second-best policies compared to efficient pricing.

The current paper will focus on one aspect of the economics of truck-only facilities: how existing road space should be allocated between light vehicles and heavy vehicles. This question has been partially addressed by Berglas et al. (1984) and Arnott et al. (1992) *inter alios*, and the model used developed in Arnott et al. (1992) will be used here. Section 2 following summarizes the model and derives some general results concerning traffic allocation in the unregulated equilibrium and the social optimum. Section 3 describes the setting for the numerical examples, and Section 4 describes the results. Finally, Section 5 summarises the main findings of the study and identifies various ways in which it should be extended.

2   THE MODEL

To help illustrate the workings of the model it is developed in two steps.

2.1   The general model

The general model is adopted from Arnott et al. (1992). There are two routes or sets of traffic lanes indexed by r, $r=1,2$. And there are two types or groups of vehicles, indexed by g, $g=L,H$, where subscripts L and H refer to light vehicles (henceforth *Lights*) and heavy vehicles (henceforth *Heavies*) respectively. [9] The number of trips taken by *Lights* is N_L, and the

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[8] Evans (1992) obtains a similar result using a deterministic model with travellers who differ in their VOT and willingness to pay to make a trip. Like Small, Mohring (1979) emphasizes the benefits of reserved bus lanes as a second-best instrument when road pricing is precluded.

[9] With two discrete groups it is necessary to contend with a number of possible group-to-route allocations (Arnott et al. 1992; Small and Yan 2001). This complication can be avoided by using a model with a continuum of traveller types (e.g. as in Verhoef and Small 2004). The discrete typology is adopted here for two reasons. First, it is suitable for a study of truck toll lanes in which there is a natural dichotomy of types and access regulations. Second, *Heavies* differ from *Lights* not only in size

number of trips by *Heavies* is N_H. N_L and N_H are fixed; i.e. independent of the cost of a trip. Trips on the two routes are perfect substitutes. The cost incurred by type g for a trip on route r is a linear[10] increasing function of the number of vehicles of each type using the same route:

$$C_r^L = \underbrace{c_{Lr}^L N_{Lr}}_{(1)} + \underbrace{c_{Hr}^L N_{Hr}}_{(2)} + \underbrace{F_r^L}_{(3)} + \underbrace{t_r^L}_{(4)}, \ r = 1, 2, \tag{1a}$$

$$C_r^H = \underbrace{c_{Lr}^H N_{Lr}}_{(1)} + \underbrace{c_{Hr}^H N_{Hr}}_{(2)} + \underbrace{F_r^H}_{(3)} + \underbrace{t_r^H}_{(4)}, \ r = 1, 2. \tag{1b}$$

In writing formulae (1a,1b) we use the convention that a superscript denotes the user type that incurs the cost in question, and a subscript denotes the group that creates the cost. Term (1) in each expression is the cost imposed by *Lights* that use the same route. Term (2) is the analogous cost imposed by *Heavies*. Following Arnott et al. (1992) the coefficients c_{Lr}^L and c_{Hr}^H, r=1,2, will be called *own-cost coefficients*, and the coefficients c_{Hr}^L and c_{Lr}^H, r=1,2, will be called *cross-cost coefficients*. Term (3) includes costs that are independent of usage including vehicle operating costs, free-flow travel time costs, and the internalized component of single-vehicle accident costs. Finally, term (4) is the toll (if any). It is assumed that tolls can be differentiated by vehicle type and route, which is typical practice on tolled facilities around the world.

2.1.1 Unregulated equilibrium

In the absence of tolls or lane-access restrictions, three types of equilibrium route allocations are possible (Arnott et al. 1992; Small and Yan 2001): integrated equilibria, partially separated equilibria and segregated equilibria. In an integrated equilibrium both *Lights* and *Heavies* use each route. In a partially separated equilibrium, one type uses both routes and the other type uses only one route. And in a segregated equilibrium each type uses only one route.

If type g uses both routes then, by Wardrop's first principle, the costs must be equal:

$$C_1^g = C_2^g. \tag{2}$$

The necessary and sufficient conditions for an integrated equilibrium are:

$$C_1^L = C_2^L, \tag{3a}$$

$$C_1^H = C_2^H, \tag{3b}$$

$$N_{L1} > 0, \ N_{L2} > 0, \ N_{H1} > 0, \ N_{H2} > 0. \tag{4}$$

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and maneuverability, but also in terms of accident frequencies, emissions, road damage costs, values of time and other characteristics. Constructing an empirically accurate and tractable joint frequency distribution of these dimensions would be a challenge, and it would preclude analytical results.

[10] Linear functions are chosen mainly for tractability. Most road traffic studies assume that travel time (and travel time cost) is a strictly convex function of usage. These functions are typically specified in terms of instantaneous flows. When specified in terms of trips the functional relationship can be approximately linear. In the case of Vickrey's bottleneck queuing model with identical travelers and linear schedule delay cost functions, the relationship is exactly linear; see Arnott et al. (1998) and Small and Verhoef (2006, Chapter 4).

Substituting (1a) into (3a), and (1b) into (3b), yields a pair of linear reaction functions of the form $N_{L1} = f^L(N_{H1})$ and $N_{H1} = f^H(N_{L1})$. By the usual stability criterion an integrated equilibrium can obtain only if $(\partial f^L / \partial N_{H1})(\partial f^H / \partial N_{L1}) < 1$. Given eqns. (1a) and (1b) the stability condition works out to

$$\left(c_{L1}^L + c_{L2}^L\right)\left(c_{H1}^H + c_{H2}^H\right) > \left(c_{H1}^L + c_{H2}^L\right)\left(c_{L1}^H + c_{L2}^H\right). \tag{5}$$

Stability requires that the own-cost coefficients on the two routes be larger (in a sense defined by condition (5)) than the cross-cost coefficients. One might think that Condition (5) is guaranteed to hold if the following two inequalities are satisfied:

$$c_{Lr}^L c_{Hr}^H > c_{Hr}^L c_{Lr}^H, \ r=1,2. \tag{6}$$

In fact, this is not the case as Appendix A illustrates with a numerical example. This demonstrates that stability is a property of pairs of routes rather than routes in isolation. However, it is trivial to show that the two conditions in (6) imply Condition (5) if the routes satisfy the so-called similarity property[11]:

(Similarity property) $$\frac{c_{L2}^L}{c_{L1}^L} = \frac{c_{H2}^L}{c_{H1}^L} = \frac{c_{L2}^H}{c_{L1}^H} = \frac{c_{H2}^H}{c_{H1}^H} \tag{7}$$

The similarity property will be invoked later in this section. It will hold if the cost coefficients have the functional form

$$c_{hr}^g = \frac{g_h^g}{s_r}, \ g = L, H, \ h= L, H, \ r=1,2,$$

where s_r is the flow capacity of Route r and g_h^g is independent of r.

It should be emphasized that Condition (5) is a necessary, but not sufficient, condition for an integrated equilibrium. In addition, the nonnegativity conditions (4) must be satisfied. As Arnott et al. (1992, 83-84) explain, there are three cases to consider:

1. Stability condition satisfied, but nonnegativity conditions violated. In this case there is a unique equilibrium that is either partially separated or segregated.
2. Nonnegativity conditions satisfied, but stability condition violated. Two equilibria exist, each of which can be partially separated or segregated.
3. Stability and nonnegativity conditions both violated. There is a unique equilibrium that is either partially separated or segregated.

2.1.2   The social optimum

Following the usual practice, welfare will be measured using social surplus, *W*. Let e_{gr} denote the external cost of a trip by type *g* on route *r* that is not borne by users of the route collectively. Parameter e_{gr} includes the costs of emissions, noise, pavement damage and so

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[11] This term is introduced in Arnott et al. (1992, §2.1).

on; for brevity it will be called the *environmental cost*. Since tolls are a transfer from users to the toll-road authority, toll revenues net out of social surplus and W is given by the formula

$$W = \sum_{r=1,2} \left(c_{Lr}^L N_{Lr} + c_{Hr}^L N_{Hr} + F_r^L + e_{Lr} \right) N_{Lr} + \left(c_{Lr}^H N_{Lr} + c_{Hr}^H N_{Hr} + F_r^H + e_{Hr} \right) N_{Hr}. \quad (8)$$

Let $-g$ be the index for the type other than g; i.e. if $g=L$ then $-g=H$, and vice versa. Differentiating W with respect to N_{gr} one obtains the marginal social cost of a trip by type g on route r:

$$MSC_r^g \equiv \frac{\partial W}{\partial N_{gr}} = 2c_{gr}^g N_{gr} + \left(c_{-gr}^g + c_{gr}^{-g} \right) N_{-gr} + F_r^L + e_{gr},$$

$$= \underbrace{C_r^g}_{(1)} + \underbrace{c_{gr}^g N_{gr}}_{(2)} + \underbrace{c_{gr}^{-g} N_{-gr}}_{(3)} + \underbrace{e_{gr}}_{(4)}, \, g = L, H, r = 1,2. \quad (9)$$

Term (1) in eqn. (9) is the private cost net of toll borne by a user of group g on route r. Term (2) is the external cost imposed on users of the same type on route r. Term (3) is the external cost imposed on users of the other type. And Term (4) is the environmental cost imposed on non-users. Terms (2-4) are disregarded by the user, and hence are a potential source of inefficiency in the unregulated regime.

The social or first-best optimum achieves a maximum of W. A necessary condition for it to be optimal for type g to use both routes is that the marginal social costs are equal:

$$MSC_1^g = MSC_2^g. \quad (10)$$

Condition (10) is the counterpart to Condition (2) for the unregulated equilibrium. Similar to the unregulated equilibrium, the optimum may entail integration, partial separation or segregation of the two user types.

2.1.3   Comparison of social optimum and unregulated equilibrium

For two reasons it is not straightforward to compare the optimum and unregulated equilibrium. First, the route allocation patterns may differ. For example, the unregulated equilibrium allocation may be integrated whereas the optimum is partially separated or segregated. As the simulations in Section 4 will demonstrate, this will tend to be the case if one type has much higher cost coefficients than the other type so that it is optimal to give the high-cost type exclusive access to one of the routes. Second, despite the simple linear structure of the model the formulae for the route splits are unwieldy, and it is not easy to compare the route splits even if the optimum and unregulated equilibrium allocation patterns are the same.

To provide some insights into how the optimum and unregulated equilibrium regimes may differ, we will consider two cases.

Case 1: Optimum and unregulated equilibrium both integrated

Suppose both regimes are integrated. It is straightforward to show that the route splits are equal (and hence the optimum and unregulated equilibrium are identical) if the following three conditions are satisfied:

1. Free-flow travel costs are the same on the two routes: $F_1^g = F_2^g$, $g = L, H$.
2. The environmental costs are the same on the two routes: $e_{g1} = e_{g2}$, $g = L, H$.
3. The similarity property (7) holds.

Condition 1 is familiar from the literature on two parallel routes with homogeneous travelers (e.g. Barro and Romer 1987; Verhoef et al. 1996) where it is shown that the shorter or lower-cost route is used excessively in the unregulated equilibrium. Condition 1 rules this bias out. The reason for Condition 2 is obvious: environmental costs are disregarded by users in the unregulated equilibrium, but if environmental costs are the same on the two routes there is no bias.

Case 2: Optimum and unregulated equilibrium both partially separated; *Lights* on both routes

Assume now that *Lights* use both routes whereas *Heavies* use only Route 2. This case is likely if *Lights* outnumber *Heavies* and Route 2 is either designed for *Heavies* or identical to Route 1 except possibly for capacity. Substituting eqn. (1a) into (3a), setting $N_{H1} = 0$, and using the relationships $N_{L2} = N_L - N_{L1}$ and $N_{L2} = N_L - N_{L1}$, one obtains for the unregulated equilibrium (denoted by superscript e):

$$N_{L1}^e = \left(c_{L1}^L + c_{L2}^L\right)^{-1}\left(c_{L2}^L N_L + c_{H2}^L N_H + F_2^L - F_1^L\right). \tag{11}$$

The optimum is derived in the same way as the unregulated equilibrium except with the condition $MSC_1^L = MSC_2^L$ in place of Condition (3a):

$$N_{L1}^o = \left(c_{L1}^L + c_{L2}^L\right)^{-1}\left(c_{L2}^L N_L + \frac{c_{H2}^L + c_{L2}^H}{2} N_H + \frac{F_2^L - F_1^L}{2} + \frac{e_{L2} - e_{L1}}{2}\right). \tag{12}$$

Subtracting (12) from (11) one obtains

$$N_{L1}^e - N_{L1}^o = \left(c_{L1}^L + c_{L2}^L\right)^{-1}\left(\underbrace{F_2^L - F_1^L}_{(1)} + \underbrace{e_{L1} - e_{L2}}_{(2)} + \underbrace{\left(c_{H2}^L - c_{L2}^H\right) N_H}_{(3)}\right). \tag{13}$$

As a counterpart to the integrated regime of Case 1, it is clear that the route splits are equal in Case 2 if the following three conditions are satisfied:

1. Free-flow travel costs are the same for *Lights* on the two routes: $F_1^L = F_2^L$.
2. The environmental costs of *Lights* are the same on the two routes: $e_{L1} = e_{L2}$.
3. The two cross-cost coefficients on Route 2 are equal: $c_{H2}^L = c_{L2}^H$.

Conditions 1 and 2 are intuitive, and closely resemble Conditions 1 and 2 of Case 1. According to Condition 3 the external cost that a *Light* incurs from each *Heavy* on Route 2 (c_{H2}^{L}) must match the external cost that the *Light* imposes on each *Heavy* (c_{L2}^{H}). If the external cost borne by the *Light* is larger than the cost that it inflicts, then too few *Lights* use Route 2 in the unregulated equilibrium and too many use Route 1. Correspondingly, if the external cost borne by the Light is less than the cost it inflicts, then the unregulated equilibrium results in too few *Lights* on Route 1.

2.2 The truck lane model with Light and Heavy Vehicles

Having considered the route usage patterns that can occur in the general model we now break out the cost coefficients into components. Congestion and accidents are the two main costs that are external to individual users (partially in the case of accidents), but internal to users as a group, and affect the cost coefficients. The cost coefficients are therefore written:

$$c_{hr}^{g} = cong_{hr}^{g} + acc_{hr}^{g}, \; g = L, H; \; h = L, H; \; r = 1, 2$$

where $cong_{hr}^{g}$ and acc_{hr}^{g} are congestion and accident coefficients respectively. Define

$$cong_{h\bullet}^{g} = cong_{h1}^{g} + cong_{h2}^{g}, \; g = L, H; \; h = L, H \; ,$$

and

$$acc_{h\bullet}^{g} = acc_{h1}^{g} + acc_{h2}^{g}, \; g = L, H; \; h = L, H \; .$$

The stability condition (5) can then be written

$$\left(cong_{L\bullet}^{L} + acc_{L\bullet}^{L}\right)\left(cong_{H\bullet}^{H} + acc_{H\bullet}^{H}\right) > \left(cong_{H\bullet}^{L} + acc_{H\bullet}^{L}\right)\left(cong_{L\bullet}^{H} + acc_{L\bullet}^{H}\right). \tag{14}$$

By reasoning parallel to that in Section 2.1, one might expect Condition (14) to be satisfied if it holds for the congestion and accident coefficients separately; i.e. if:

$$cong_{L\bullet}^{L}.cong_{H\bullet}^{H} > cong_{H\bullet}^{L}.cong_{L\bullet}^{H} \tag{15a}$$

and

$$acc_{L\bullet}^{L}.acc_{H\bullet}^{H} > acc_{H\bullet}^{L}.acc_{L\bullet}^{H} . \tag{15b}$$

But Conditions (15a) and (15b) are neither necessary nor sufficient for stability. This can be shown by example as in Appendix A, and the lack of necessity will be apparent in the numerical examples of Section 4.

Consider now the relative magnitudes of the own- and cross- cost coefficients.

2.2.1 Relative congestion costs

For several reasons *Heavies* have a greater impact than *Lights* on highway speeds: they occupy more road space, they take longer to accelerate and decelerate, and they obscure visibility more. These considerations are usually accounted for by using a Passenger Car

Equivalent (PCE) factor. Typical PCE values are 1.5-2 for buses and single-unit trucks, and 2-3 for combination vehicles. It is common practice to adjust the PCE factor upwards with the percentage grade and the fraction of road length that is hilly (Middleton and Lord 2005). And some studies have found that the PCE factor is an increasing function of the fraction of *Heavies* in the traffic stream (e.g. Janson and Rathi 1991; Yun et al. 2005): a consideration that cannot be treated with the linear functions in (1a,1b).

Less well documented or understood are the relative magnitudes of the congestion effects between vehicle types as captured by the own- and cross-congestion coefficients in eqns. (1a,1b).[12] To provide some flexibility in the specification, the formulation shown in panel (a) of Table 1 is adopted. Parameter PCE_{cong} is a generic Passenger Car Equivalent for *Heavies*. Parameter $l_H^L \geq 1$ is an adjustment factor to account for the possibility that *Heavies* impose a disproportionately large delay or impedance on *Lights*. And v^g is the value of time for type g. For simplicity it is assumed that the relative magnitudes of the coefficients are the same on the two routes.

2.2.2 Relative accident costs

Relative accident costs are treated qualitatively the same way as relative congestion costs as described in panel (b) of Table 1. Parameter PCE_{acc} is a generic Passenger Car Equivalent for *Heavies* that describes the expected accident costs imposed by a *Heavy* as a multiple of the cost imposed by a *Light*. Parameter $f_H^L \geq 1$ is an adjustment factor to account for the "fear" that drivers of *Lights* may have of *Heavies* and the associated psychological distress that they experience from driving near them. Finally, m^H is the cost borne by a *Heavy* in an accident with a *Light* as a multiple of the cost borne by a *Light* in an accident with a *Light*. The empirical value of m^H is unclear. On the one hand a *Heavy* vehicle and its driver may suffer little damage or injury in a collision with a *Light* vehicle. On the other hand the value of the vehicle and cargo at risk is typically much greater for a *Heavy*, and the opportunity cost of time spent dealing with the accident is also likely to be higher. Admittedly this formulation is quite crude. But it is easily implemented, and it is amenable for analysis of the stability condition to which we now turn.

As noted above, it is not possible to check the stability condition (7) by examining the congestion-cost and accident-cost coefficient conditions, (15a, 15b), independently. But an examination of the two conditions is still instructive. Given the relative congestion cost coefficients in Table 1(a) one has

$$cong_{L\bullet}^L cong_{H\bullet}^H - cong_{H\bullet}^L cong_{L\bullet}^H \overset{s}{=} 1 - l_H^L \, ,$$

and

$$acc_{L\bullet}^L acc_{H\bullet}^H - acc_{H\bullet}^L acc_{L\bullet}^H \overset{s}{=} 1 - f_H^L \, ,$$

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where $\overset{s}{=}$ means "has the same sign as". Congestion therefore tends to be destabilizing of an integrated equilibrium if $l_H^L > 1$; i.e. if *Heavies* tend to impede *Lights* more than by the standard or average PCE factor. Similarly, the accident-cost coefficients tend to be destabilizing if $f_H^L > 1$; i.e. if drivers of *Lights* are distressed by the presence of *Heavies*.

Of note is that Conditions (15a, 15b) do not depend on the Passenger Car Equivalent factors, PCE_{cong} and PCE_{acc}, or the values of time of the two types, v^L and v^H.

3   PARAMETER VALUES USED FOR NUMERICAL EXAMPLES

The travel corridor featured in the numerical examples is designed to be representative of limited-access highways which serve most of the medium-to-long urban truck trips in the U.S. Base-case parameter values are listed in Table 2.

3.1   Routes

The travel corridor has three traffic lanes in each direction. Route 1 comprises two lanes with an aggregate capacity of 4,000 (standard) PCEs per hour, and Route 2 comprises one lane with a capacity of 2,000 PCEs per hour. Free-flow travel speed on each route is 65 mph, which is the speed limit on a majority of Interstate highways. Both routes are 32.5 miles long so that free-flow travel time is 30 mins.

3.2   Travel demand

Total trip demand ($N_L + N_H$) is fixed at 40,000 trips per day. The proportion of *Heavies* is varied parametrically from 0% to 100%.[13]

3.3   Volume-independent user costs

The value of travel time (VOT) for automobile drivers has been estimated in numerous studies. Small and Verhoef (2006, p. 3-56) use a value of \$9.14/hr for U.S. metropolitan areas in 2003. Some recent studies assume rather higher values. For heavy vehicles a wide range of values for VOT have been used – in part because VOT depends on the type of vehicle and its load, drivers' wage rates, the importance of punctual delivery and numerous other factors. Wilbur Smith Associates (2003) assume a VOT of \$25/hr for trucks while acknowledging that this is a very conservative value. According to Forkenbrock and March (2005, p.7):

> "The value of time used by FHWA is \$25.24 per vehicle-hour for large trucks, compared to \$15.71 for small cars. In other studies in the United States and Europe, estimated values of time for trucking range as high as \$193.80, with a median value among the studies of \$40 and a mean of \$51.80. The value of reliability (that is, the cost of unexpected delay) is another 50 to 250 percent higher than these values of time."

These figures suggest that the average VOT for *Heavies* is several times the average VOT for *Lights*. For the base-case values it is assumed that $v^L = \$12$/hour and $v^H = \$50$/hour.

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[13] Typical percentages are 20% or lower, but it is instructive to consider the full potential range.

3.4 Congestion cost coefficients

Parry (2006, Table 1) assumes a PCE for congestion of 1.9 for single-unit trucks and 2.2 for combination trucks. The value for PCE_{cong} of 2.0 used here is an (approximate) weighted average for the two truck types. The *Light-Light* congestion cost parameters, $cong_{Lr}^{L}$, $r = 1, 2$, are chosen so that the marginal external congestion cost of a *Light* is about $0.10/mile on each route in the base-case example.

3.5 Accident cost coefficients

Using data from FHWA (1997), Parry (2006, Table 1) assumes external accident costs of $0.02/mile for *Lights* and $0.015/mile for *Heavies*. Given the widespread concern about truck accidents, and the dangers that trucks impose on light vehicles, the relatively small value for *Heavies* is surprising. One possible explanation is that truck drivers are better drivers on average than automobile drivers, and less prone to causing accidents.[14]

3.6 External costs

Parry (2006, Table 1) reports pollution costs per gallon. The values in Table 2 are converted to costs per mile by dividing by his values for vehicle fuel economy.

4 RESULTS OF THE NUMERICAL EXAMPLES

4.1 Base case

With the base-case parameter values, the stability condition holds[15] and the unregulated equilibrium is integrated with two-thirds of both *Lights* and *Heavies* taking Route 1. If *Heavies* account for 20% of traffic (a representative proportion for urban portions of the Interstate Highway System) the private cost of a trip is $10.39 for *Lights* and $28.40 for *Heavies*. Perhaps surprisingly, the social optimum is also integrated. Moreover, since all three of the conditions identified in Section 2 (Case 1) for congruence of the optimum and unregulated equilibria are satisfied, the two regimes coincide and nothing can be gained from either tolling or lane access restrictions. Naturally, this would not be true if travel demand were elastic. With 20% Heavies in the vehicle mix the Pigouvian tolls are $4.62 for *Lights* and $13.98 for *Heavies*: likely high enough to induce diversion of some trips to alternative routes or modes.

4.2 Sensitivity analysis

There is considerable uncertainty about the "true" values for several of the parameters, and thus sensitivity analysis is warranted. Table 3 summarizes the results for four parameters or

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[14] Consistent with this view, Forkenbrock and March (2005, p.6) write: "According to FHWA [Federal Highway Administration], in 71 percent of two-vehicle fatal crashes involving a large truck and another vehicle, police reported 'one or more errors or other factors' related to the behavior of the passenger vehicle driver and none for the truck driver."

[15] The stability condition is satisfied despite the fact that Conditions (15a) and (15b) for the congestion-cost and accident-cost coefficients hold as equalities rather than inequalities. The reason for this is that relative to *Heavies*, *Lights* inflict more congestion than accident costs, whereas relative to *Lights*, *Heavies* are more averse to congestion than to accidents. Consequently, *Heavies* prefer to travel with *Lights* and *Lights* prefer to travel with *Heavies*.

sets of parameters: (a) the value of time for heavy vehicles, (b) the congestion-cost parameters, (c) the accident-cost parameters, and (d) characteristics of the routes.

(a) Value of time for heavy vehicles

The base-case value of the VOT for *Heavies* is $v^H = \$50$/hr. If this is drastically reduced to just $15/hr (Variant 1 in Table 3) the stability condition is satisfied only as a weak inequality. The unregulated equilibrium is still integrated, but in the social optimum *Lights* and *Heavies* are partially separated throughout the range of traffic mix as shown in Figure 1(a). Separation is advantageous because *Heavies* create much more congestion than do *Lights*, but value travel time only slightly more. It is therefore appropriate to keep *Heavies* away from *Lights* to the extent possible. When the proportion of *Heavies* reaches 41%, all the *Heavies* are moved onto Route 1 (with the higher capacity) and the majority of *Lights* are shifted onto Route 2.[16] At this point the Pigouvian tolls on Route 1 take a small downward jump, the tolls on Route 2 take a small upward jump, and the toll differentials reverse sign as shown in Figure 1(b). The welfare gains from tolling (i.e. the increase in *W*) exhibit a double peak (Figure 1(c)) with a local minimum at the point where *Heavies* switch routes. The two peak gains occur with *Heavy* proportions of 25% and 57% at which segregation is optimal. Consequently, at these points a lane-access rule to segregate the two types would be as effective as tolling. However, segregation is beneficial only within a narrow range of traffic mix about each peak, whereas tolling yields appreciable benefits for most of the range.

If the VOT for *Heavies* is raised part way back up to $25/hr. the base-case pattern reappears in which the social optimum and unregulated equilibrium coincide. However, if the VOT is raised further to 150% of the base-case value (Variant 2), behaviour similar to that of Variant 1 appears but with much higher welfare gains. The prime motivation for separation now is to minimize congestion for *Heavies* by giving them more road space than *Lights*.[17] Because of the high VOT for *Heavies*, the two segregation points occur at much lower *Heavy* proportions than in Variant 1 (14% and 39% vs. 25% and 57%).

(b) Congestion-cost parameters

For Variant 3 the PCE of *Heavies* is reduced from 2 to 1.5. The effect is qualitatively and quantitatively similar to raising v^H in Variant 2. By contrast, if the PCE of *Heavies* is raised from 2 to 3 (Variant 4) the unregulated equilibrium remains optimal as in the base case.

In Variant 5, parameter l_H^L is doubled from 1 to 2 to reflect greater interference of *Lights* from *Heavies*. This upsets the stability condition, and the unregulated equilibrium[18] becomes partially separated or segregated as the *Lights* try to avoid the *Heavies*. Simultaneously doubling l_H^L and halving v^H (Variant 6) has a much more pronounced effect. Significant

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[16] No restriction is imposed that some *Heavies* always use Route 2 (e.g. the right-hand lane of a three-lane highway).

[17] This is an instance of the principle noted in Section 2 that, if one type has much higher cost coefficients than the other type, it is optimal to give the first type preferential access.

[18] As explained in Section 2, if the stability condition is violated and the nonnegativity conditions are satisfied (as they are for certain values of the traffic mix), there are two unregulated equilibria. The equilibrium with the lower total social costs is assumed to prevail here and in other cases where the stability condition fails. Naturally, this biases downwards the potential inefficiency of the unregulated equilibrium and the potential benefits from tolling.

differences between the unregulated equilibrium and optimal route allocations are apparent (Figure 2(a)) and the toll differentials on the two routes exhibit a relatively complicated pattern as the traffic mix changes (Figure 2(b)). The welfare gains are substantial (Figure 2(c)), and segregation is welfare-improving for an appreciable range of traffic mixes (Figure 2(c)). It is interesting to note that either halving v^H alone, or doubling l_H^L alone, creates little or no scope for welfare-enhancing intervention, whereas adjusting the two parameters together does have an appreciable effect. Even in the simple model, parameter values can interact in rather complex ways.

(c) Accident-cost parameters

Raising the accident externality of *Heavies* (parameter PCE_{acc}) as in Variants 7 and 8 does not upset the stability condition. But the optimum becomes separated and the pattern of tolls and welfare gains is broadly similar to that of reducing the value of time for *Heavies*. Halving the costs of accidents for *Heavies* (Variant 9) does not affect the results of interest, but doubling the costs (Variant 10) creates a pattern similar to raising the VOT of *Heavies* (Variant 2).

In Variant 11, parameter f_H^L is doubled from 1 to 2 to reflect a fear of accidents with *Heavies*. The effect of this change is nearly identical to doubling the costs of accidents for *Heavies* (Variant 10). Surprisingly, doubling f_H^L again from 2 to 4 dampens the welfare gains. The reason for this is that the stability condition is violated, and *Lights* tend to separate themselves from *Heavies* in the unregulated equilibrium – thereby leaving less scope for welfare-enhancing intervention. This is another illustration of non-monotonic behaviour in the model.

(d) Route characteristics

For Variants 13 and 14 the two routes are assumed to differ in length, and consequently in free-flow travel times.[19] As discussed in Section 2, the shorter route is used to excessive in the unregulated equilibrium, and tolling has a role to play in correcting the bias.[20] As Table 2 indicates, segregation is also beneficial for a limited range of traffic mix.

Finally, for Variant 15 the two routes are assumed to have equal capacities of 3,000 vehicles/hour, and the VOT for *Heavies* is raised to $75/hr as in Variant 2.[21] Despite the fact that the total capacity of the two routes is the same, the maximum welfare gains from tolling in Variant 15 are about 20% smaller than in Variant 2. The reason is that it is efficient to devote the lion's share of road space to the group with the higher travel costs – an option that is not available if the two routes are the same size. This illustrates a lesson, developed at greater length in Arnott et al. (1992), that the benefits from road pricing depend not only on the flexibility of the tolling scheme, but also on the scope for allocating road space between vehicle types in efficient proportions.

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[19] Differences in travel time can also arise because of differences in speed limits. However, since vehicle operating costs and externality costs are assumed to be proportional to distance these costs change if the lengths of the routes are changed. Differences in speed limits are therefore not equivalent to commensurate differences in route length.

[20] However, the gains are diluted by the fact that the environmental costs of travel are less on the shorter route.

[21] If only the capacities are changed, the social optimum remains identical to the unregulated equilibrium.

5   CONCLUDING REMARKS

Truck-only lanes and truck tollways have been promoted in the U.S. as a potential tool for combating road congestion, enhancing safety and reducing pavement damage. This paper has conducted a preliminary and partial economic analysis of truck lanes by focusing on how cars and trucks (or, more generally, light and heavy vehicles) choose between alternative traffic lanes or routes, and on whether the allocation can be improved by tolling or access regulations. Several factors were identified as important: the relative volumes of light and heavy vehicles, lane indivisibilities, relative values of travel time for Lights and Heavies and the relative congestion costs they impose, and the potential safety advantages (whether real or imagined) of separating Lights and Heavies.

One perhaps unexpected conclusion is that there is no presumption that Lights and Heavies should be separated or segregated. Indeed, with the base-case parameter values the two types are integrated in both the unregulated equilibrium and the optimum, and neither tolling nor lane-access regulations can improve the outcome. Nevertheless, for many plausible alternative parameter values separation or segregation is desirable, and it can be achieved using tolls that are differentiated by route and vehicle type. Another finding is that the welfare gains from tolling vary non-monotonically with some key parameters – including the proportion of heavy vehicles in the traffic mix, the value of time for heavy vehicles, and the fear that light vehicle drivers may have of accidents with heavy vehicles.

This paper provides just a first, halting, step in the analysis of heavy vehicle facilities. A number of extensions can be identified that deserve high priority.

1. *Elastic demand*: The number of Lights and Heavies using the corridor was treated as given. With price elastic demand the number of vehicles and the vehicle mix would become endogenous. In addition to route or lane choices, tolls and access regulations would affect trip generation and mode choice decisions that would have to be accounted for.
2. *Heterogeneity*: The model features just two categories of identical vehicles. In reality of course both light vehicles and heavy vehicles differ in numerous characteristics such as size, safety, operating costs, emissions and so on, that are relevant to whether they choose to be, or should be, integrated or segregated on the road network.
3. *Trip-timing preferences*. As noted in the Introduction, light and heavy vehicles tend to make trips at different times of day. Arnott et al. (1992) provide a simple theoretical analysis of when temporal segregation is a cost-effective alternative to spatial segregation with heterogeneous users. To examine this question empirically in the case of truck facilities it would be necessary to obtain data on light- and heavy-vehicle flows by time of day and, preferably, their actual trip-timing preferences.
4. *Vehicle characteristics*: Vehicle characteristics are exogenous in the model. This is a reasonable assumption for analysis of a single travel corridor since trucking firms would have little incentive to modify their vehicle fleets. The assumption sits less well for study of a regional or national road network – particularly since substantial productivity gains may be possible from using large combination vehicles (Samuel et al. 2002).
5. *Road design*: Finally, and perhaps most important, it is desirable to extend the analysis to account for road construction and maintenance costs and the merits of building dedicated truck-only lanes. According to Forkenbrock and March (2005) the cost of truck-only lanes varies considerably with respect to several factors: right-of-way availability, topography, any need to reconstruct overpasses to accommodate heavy vehicles, numbers of entrance

and exit ramps needed, etc. Consequently, construction cost per lane-km. can be expected to vary widely and will have to be assessed on a case-by-case basis.

6 APPENDIX

The pair of inequalities $c_{Lr}^L c_{Hr}^H > c_{Hr}^L c_{Lr}^H$, $r=1,2$, is neither necessary nor sufficient to satisfy the stability condition (6). To see that the pair are not sufficient, consider the example:

$$\begin{bmatrix} c_{L1}^L & c_{H1}^L \\ c_{L1}^H & c_{H1}^H \end{bmatrix} = \begin{bmatrix} 1 & 2.2 \\ 0.9 & 2 \end{bmatrix}, \begin{bmatrix} c_{L2}^L & c_{H2}^L \\ c_{L2}^H & c_{H2}^H \end{bmatrix} = \begin{bmatrix} 1 & 1.3 \\ 1.5 & 2 \end{bmatrix} \Rightarrow \begin{bmatrix} c_{L1}^L + c_{L2}^L & c_{H1}^L + c_{H2}^L \\ c_{L1}^H + c_{L2}^H & c_{H1}^H + c_{H2}^H \end{bmatrix} = \begin{bmatrix} 2 & 3.5 \\ 2.4 & 4 \end{bmatrix}.$$

The two routes feature the same own-cost coefficients but dissimilar cross-cost coefficients. By inspection it is clear that $c_{L1}^L c_{H1}^H > c_{H1}^L c_{L1}^H$ and $c_{L2}^L c_{H2}^H > c_{H2}^L c_{L2}^H$, but

$$\left(c_{L1}^L + c_{L2}^L\right)\left(c_{H1}^H + c_{H2}^H\right) < \left(c_{H1}^L + c_{H2}^L\right)\left(c_{L1}^H + c_{L2}^H\right).$$

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(a) Congestion coefficients		
$cong_{Hr}^{L} / cong_{Lr}^{L},\ r = 1,2$	$cong_{Lr}^{H} / cong_{Lr}^{L},\ r = 1,2$	$cong_{Hr}^{H} / cong_{Lr}^{L},\ r = 1,2$
$l_{H}^{L} PCE_{cong}$	v^{H} / v^{L}	$\left(v^{H} / v^{L} \right) PCE_{cong}$
(b) Accident coefficients		
$acc_{Hr}^{L} / acc_{Lr}^{L},\ r = 1,2$	$acc_{Lr}^{H} / acc_{Lr}^{L},\ r = 1,2$	$acc_{Hr}^{H} / acc_{Lr}^{L},\ r = 1,2$
$f_{H}^{L} PCE_{acc}$	m^{H}	$m^{H} PCE_{acc}$

Table 1: Relative magnitudes of congestion cost and accident cost coefficients

Source: Authors' construction

Routes			
Characteristic		Route 1	Route 2
Capacity		2,000 PCE /hour	4,000 PCE /hour
Speed limit		65 mph	65 mph
Length		32.5 miles	32.5 miles
Demand			
$N_L + N_H$		40,000 trips per day	
Proportion of *Heavies*		Range 0-100%	
Volume-independent user costs			
Component	Symbol in model	*Light* vehicles	*Heavy* vehicles
Operating & maint. (incl. fuel tax)		$0.131/mile[2]	
Variable component of vehicle capital cost		$0.063/mile[2]	
Sum		$0.194/mile[2]	$0.42/mile[3]
Values of time	v^g	$12/hour[4]	$50/hour[4]
Congestion cost coefficients			
Component	Symbol in model	*Light* vehicles	*Heavy* vehicles
Light-Light coeff.	$cong_{Lr}^L$	See text[4]	
PCE, *Heavies*	PCE_{cong}		2[1]
Relative impedance of *Lights* by *Heavies*	l_H^L	1[4]	
Accident cost coefficients			
Component	Symbol in model	*Light* vehicles	*Heavy* vehicles
Light-Light coeff.	acc_{Lr}^L	$0.02/mile[1]	
PCE, *Heavies*	PCE_{acc}		0.75[1]
Relative cost of accident for *Heavies*	m^H		1[4]
Fear factor	f_H^L	1[4]	
External costs			
Noise		$0.001/mile[1]	$0.027/mile[1]
Road damage		$0.000/mile[1]	$0.074/mile[1]
Local pollution		$0.0133/mile[1]	$0.0857/mile[1]
Global pollution		$0.008/mile[1]	$0.0286/mile[1]
Sum	e_{gr}	$0.0214/mile[1]	$0.215/mile[1]

Table 2: Base-case parameter values

Sources: [1] Parry (2006, Table 1), [2] Small & Verhoef (2006, Table 3.3), [3] Poole & Samuel (2004, Table 4-3), [4] Authors' judgment

Variant	Parameters	Stability condition	Toll differential: $t_2 - t_1$				Maximum welfare gains	Fraction of Heavies for which segregation beneficial (Computed in steps of 0.01)	
			Light		Heavy				
			Min	Max	Min	Max			
	Base case	Satisfied	$0.00	$0.00	$0.00	$0.00	$0	None	
	(a) Value of time for heavy vehicles								
1	v^H = $15/hr.	Knife edge	-$0.81	$0.92	-$1.32	$1.50	$931	[0.23,0.27]	[0.55,0.60]
2	v^H = $75/hr.	Satisfied	-$2.54	$1.86	-$6.01	$4.40	$7,128	[0.11,0.18]	[0.33, 0.48]
	(b) Congestion-cost parameters								
3	PCE_{cong}=1.5	Satisfied	-$2.53	$1.98	-$4.18	$3.28	$7,275	[0.14,0.24]	[0.39,0.56]
4	PCE_{cong}=3	Satisfied	$0.00	$0.00	$0.00	$0.00	$0	None	
5	$?^L_H$=2	Violated	-$2.81	$2.27	-$4.19	$5.98	$66	0.13	0.38
6	$?^L_H$=2, v^H = $25/hr.	Violated	-$1.60	$1.60	-$8.46	$11.37	$6,982	[0.22,0.32]	[0.52,0.65]
	(c) Accident-cost parameters								
7	PCE_{acc}=1	Satisfied	-$1.47	$1.10	-$3.60	$2.68	$802	[0.15,0.17]	[0.42,0.46]
8	PCE_{acc}=1.5	Satisfied	-$1.48	$1.12	-$3.29	$2.48	$2,747	[0.14,0.19]	[0.39,0.48]
9	μ^H = 0.5	Satisfied	$0.00	$0.00	$0.00	$0.00	$0	None	
10	μ^H = 2	Satisfied	-$1.94	$1.46	-$4.12	$3.11	$4,782	[0.13,0.19]	[0.37,0.49]
11	f^L_H=2	Satisfied	-$1.65	$1.24	-$3.29	$2.48	$4,634	[0.14,0.20]	[0.38,0.50]
12	f^L_H=4	Violated	-$2.00	$1.54	-$2.39	$1.85	$3,002	[0.14,0.20]	[0.38,0.50]
	(d) Route characteristics								
13	Rte 2 length 30 km	Satisfied	$0.00	$1.43	-$0.08	$3.01	$2,233	[0.15,0.21]	
14	Rte 2 length 35 km	Satisfied	-$1.77	$0.00	-$3.88	$0.08	$2,480	[0.14,0.16]	[0.41,0.50]
15	Rte capacs 3,000/hr., vH = $75/hr.	Satisfied	-$2.16	$2.13	-$5.11	$5.04	$5,569	[0.20,0.31]	

Table 3: Sensitivity analysis

(a) Fractions of *Lights* and *Heavies* on Route 1

Lights_NTE ▲ Heavies_NTE ■ Lights_SO △ Heavies_SO □

(b) Tolls on *Lights* and *Heavies*

Lights_Route 1 △ Heavies_Route 1 ■ Lights_Route 2 △ Heavies_Route 2 □

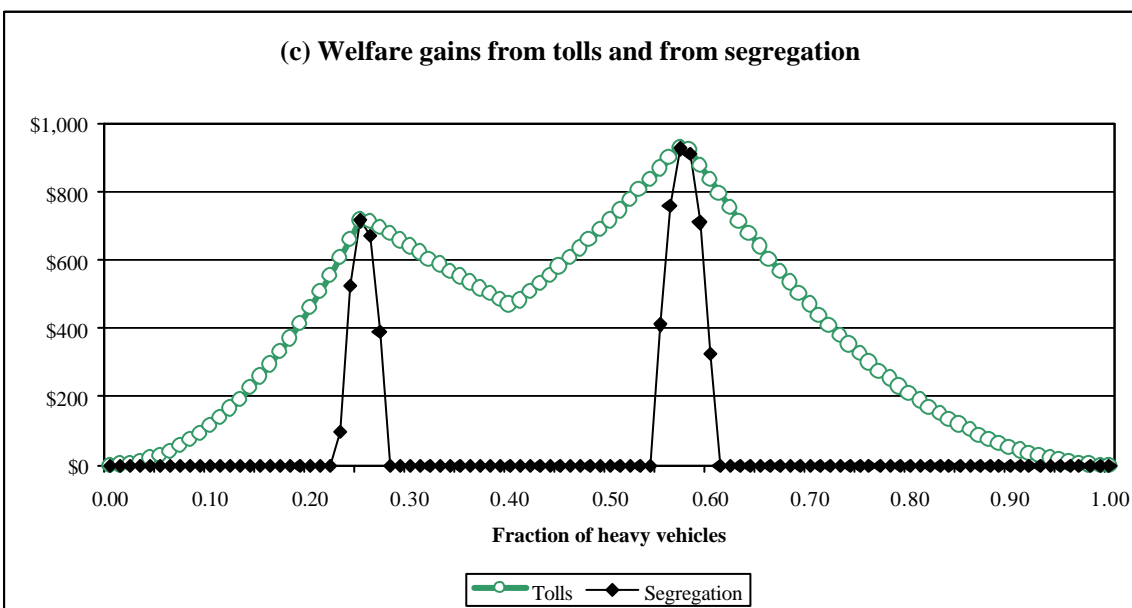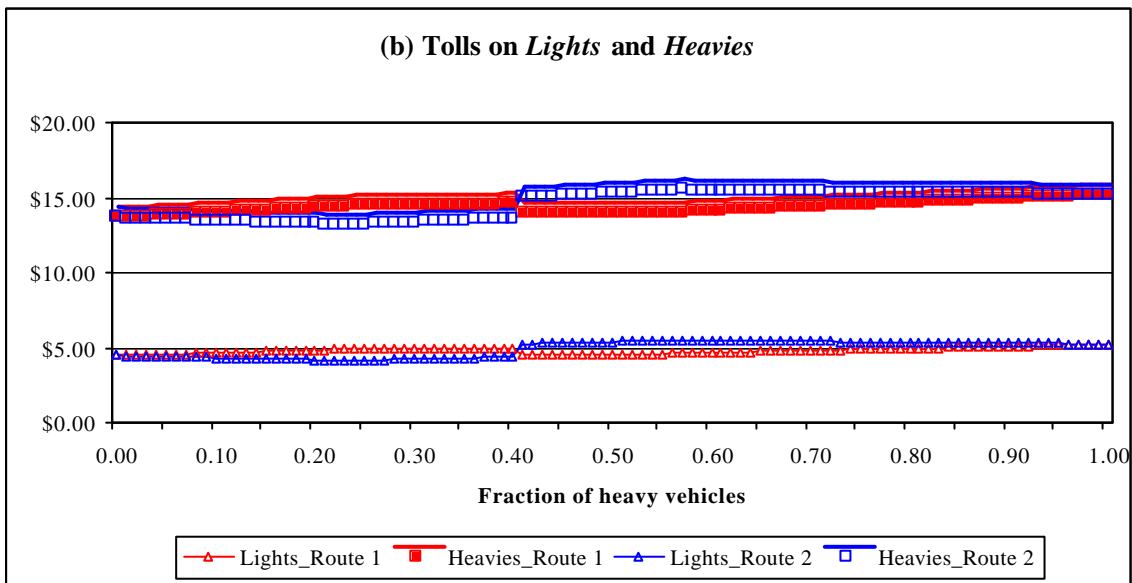**(c) Welfare gains from tolls and from segregation**

Tolls ○ Segregation ◆
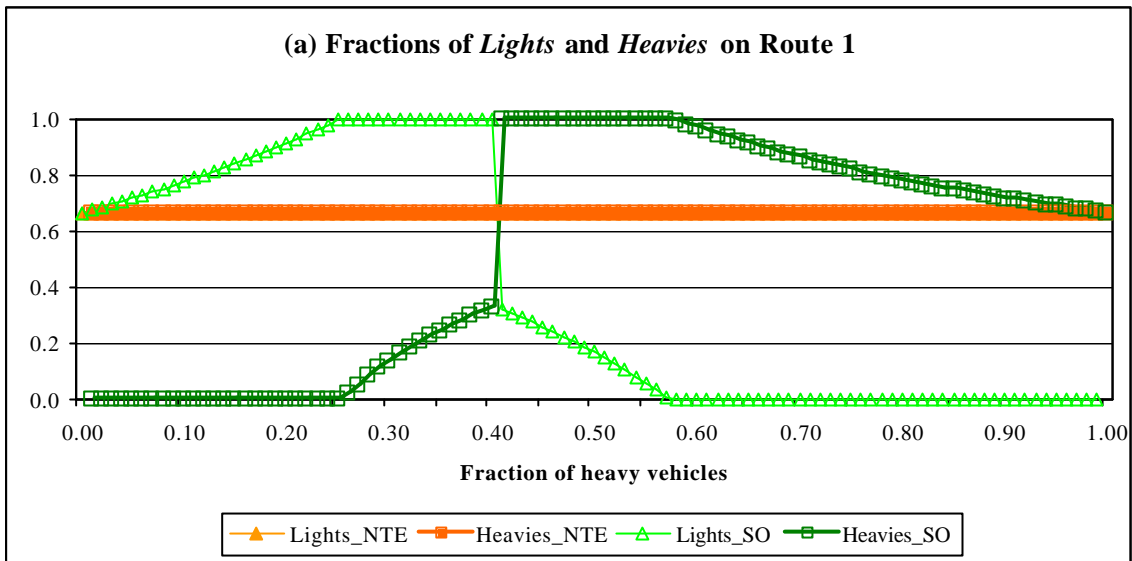
Figure 1: Results for Variant 2: $v^H = \$15/hr$

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(a) Fractions of *Lights* and *Heavies* on Route 1

(b) Tolls on *Lights* and *Heavies*
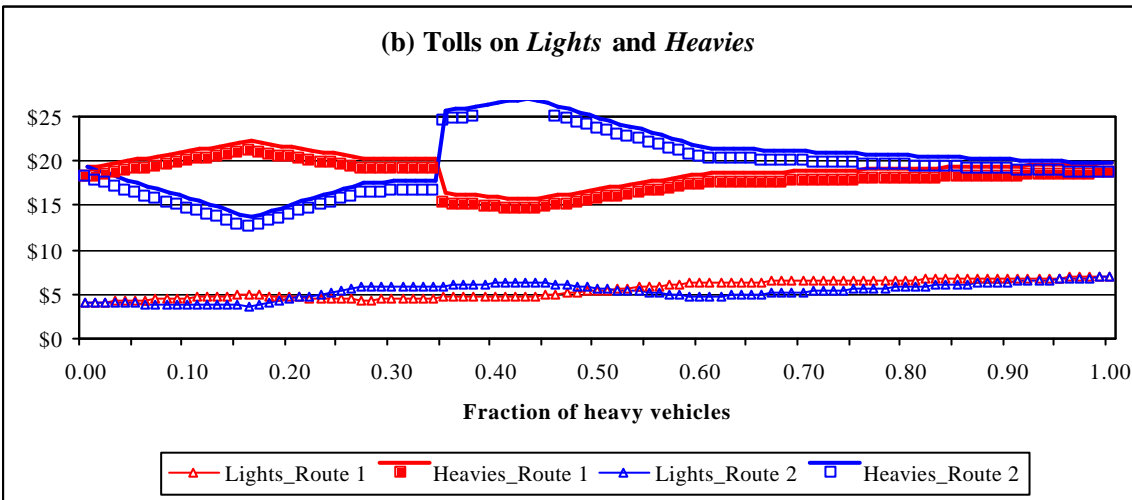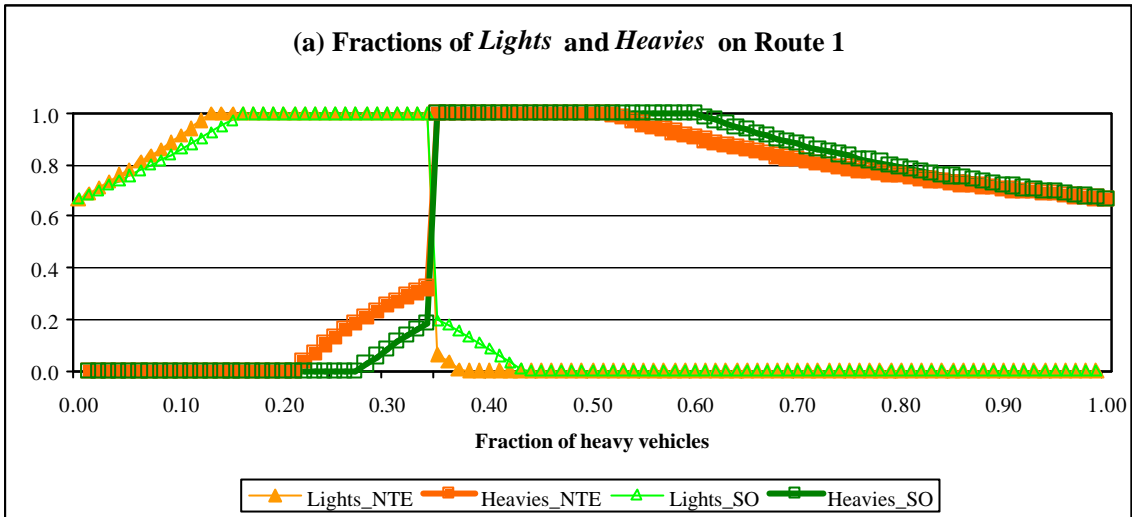
(c) Welfare gains from tolls and from segregation
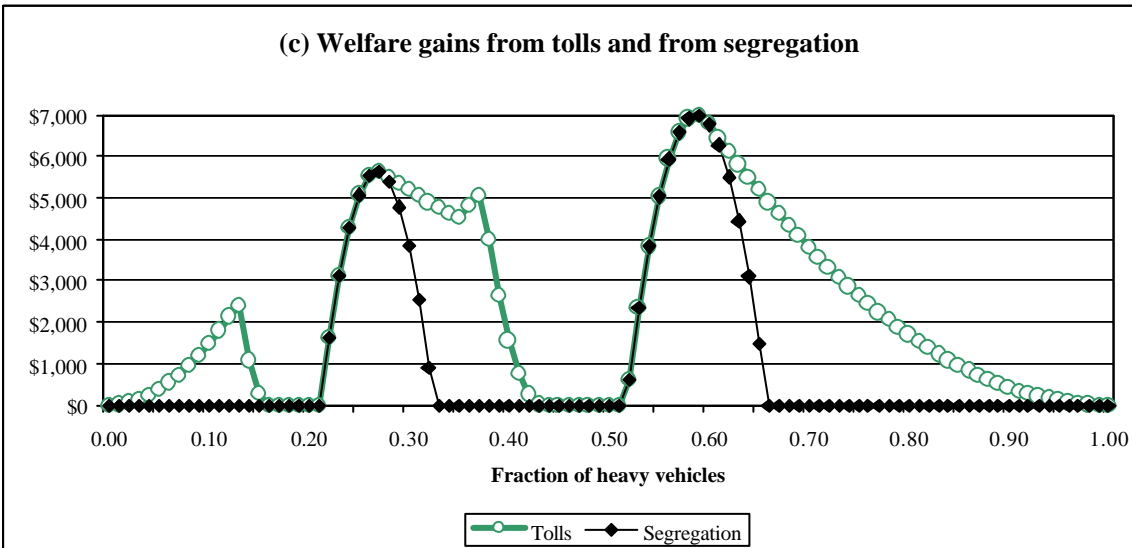
Figure 2: Results for Variant 6: $l_H^L = 2$, $v^H = \$25/hr$