The economics of truck toll lanes

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Preliminary draft

July 6, 2006

For presentation at First International Conference on Funding Transportation Infrastructure

Banff, Alberta, August 3, 2006

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 lane access regulations. Several factors are identified as important: the relative volumes of light and heavy vehicles and the congestion costs they impose, lane indivisibilities, values of travel time for light and heavy vehicles, and the potential safety advantages (whether real or imagined) of separating vehicle types.

Key words: truck-only lanes, congestion, accidents, marginal-cost 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 trucks experience reduced traffic volumes on truck-only lanes they will incur less congestion delay and less frequent need for braking, accelerating, and overtaking. Travel time for freight deliveries may also become more predictable (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 surveys indicate 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).

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

[2] 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 segment, 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 improvements in safety and operations from lane restrictions on heavy vehicles, truck drivers do not foresee improvements (Koehne et al. 1996; Douglas 2005).

Noise: Reductions in noise are a potential benefit (Douglas 2005). [5]

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. The 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 median (Reich et al. 2002).

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).

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.

These lists of pros and cons indicate 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

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[5] However, noise levels as well as pollutant emissions may increase near truck lanes.

[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)."

usage restrictions. But most studies use simulation models without describing (at least in 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 delay for travelers in the remaining lanes. Mannering and Hamed (1990) obtain similar results for HOV lanes designed for cars rather than buses.

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.

This 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 developed in Arnott et al. (1992) will be used here. Section 2 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 the analysis should be extended.

2   THE MODEL

To help illustrate the workings of the model it is developed in two steps: first by presenting the general model and then focusing on congestion and accident costs.

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 values of time 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 one must 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

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:

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

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

Formulae (1a,1b) incorporate 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 or lane. 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 components of single-vehicle accident costs that are borne by the individual users. 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 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 for group g 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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dichotomy of types. Second, *Heavies* differ from *Lights* not only in size and maneuverability, but also in terms of accident frequencies and costs, 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

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

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 and not 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 the g_h^g parameters are 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 four cases to consider in total:

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

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

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 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 if $g=H$ then $-g=L$. The marginal social cost of a trip by type g on route r is:

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

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

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) all correspond to externalities, 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 type g to use both routes at the optimum 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 numerical examples 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 compare, 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. 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, with *Lights* on both routes

Assume now that *Lights* use both routes whereas *Heavies* use only Route 2. This case is likely if *Lights* greatly outnumber *Heavies*, and Route 2 is either designed for *Heavies* or identical to Route 1 except possibly for its capacity. Substituting eqn. (1a) into (3a), setting $N_{H1} = 0$, and using the relationships $N_{L2} = N_L - N_{L1}$ and $N_{H2} = N_H - N_{H1}$, 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

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

As a counterpart to the integrated regime of Case 1, it is clear that the route allocations are equal 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. 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 parallel 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, 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 Congestion and accident costs for Light and Heavy Vehicles

Having considered the route allocation patterns that are possible 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

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

and

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

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. The stability condition depends on the relative magnitudes of the own- and cross- cost coefficients, which are considered in the following two subsections.

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 that are embodied in 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 cost 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 on the same facilities as *Heavies*. 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.

2.2.3 Implications for the stability condition

The specification of congestion and accident costs in Table 1 is admittedly crude. But it is amenable for analysis of the stability condition. 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 nevertheless 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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[12] Simulation models are typically used to model pair-wise interactions between vehicle types although there has been some analytical research; e.g. Netter (1971), Newell (1980, Chap. 8), Berglas et al. (1984) and Arnott et al. (1992).

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 is indicated by the standard or "average" PCE factor. Similarly, the accident-cost coefficients tend to be destabilizing if $f_H^L > 1$; i.e. if *Heavies* impose a disproportionate or perceived accident risk on *Lights*.

Of note is that Conditions (15a, 15b) do not depend on either the Passenger Car Equivalent factors, PCE_{cong} and PCE_{acc}, or on 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 intended 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. Consideration is limited to one 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 (standard) 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 estimated or assumed – in part because VOT depends on the type of vehicle and its load, drivers' wage rates, the importance of punctual delivery and other factors. Wilbur Smith Associates (2003) assumes 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."

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

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 $v^L = \$12/\text{hour}$ and $v^H = \$50/\text{hour}$.

3.4 Congestion cost coefficients

Based on information in FHWA (1997), 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

Based on information in FHWA (1997), Parry (2006, Table 1) assumes external accident costs of \$0.020/mile for *Lights* and \$0.015/mile for *Heavies*. Given the widespread concern about truck accidents and the perceived 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 fraction 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 assumed to be 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.

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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 holds as a strict inequality 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*.

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 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 an equality. The unregulated equilibrium is still integrated[16], 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. As is shown in Figure 1(b) 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. 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 *Lights* and *Heavies* switch routes. The two peak welfare gains occur with *Heavy* proportions of 25% and 57% for 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 lots of road space.[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 congestion PCE of *Heavies* is reduced from 2 to 1.5. The effects of doing so are qualitatively and quantitatively similar to the effects of 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

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[16] If the stability condition is satisfied as an equality there is actually a continuum of equilibria. To assure an integrated equilibrium prevails one can assume that v^H is marginally greater than $15/hr.

[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

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 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. 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 used, 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 VOT 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* as in Variant 2.

In Variant 11, parameter f_H^L is doubled from 1 to 2 to reflect an enhanced danger to *Lights* from 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 now violated, and *Lights* tend to separate themselves from *Heavies* in the unregulated equilibrium – thereby leaving less scope for welfare-enhancing intervention. This is another instance 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 excessively in the unregulated equilibrium, and tolling has a role to play in correcting the bias.[20] As Table 3 indicates, segregation is also beneficial for a modest 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 as in Variant 2, the maximum welfare

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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 intervention.

[19] Differences in travel time 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.

gains from tolling in Variant 15 are about 20% smaller. The reason is that it is efficient to devote the lion's share of road space to the group with the higher travel costs (heavy vehicles) – an option that is not available if the two routes have the same capacities. 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.

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 and the congestion costs they impose, lane indivisibilities, relative values of travel time for *Lights* and *Heavies*, 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 partial 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 degree to which light vehicles suffer disproportionate costs from accidents with heavy vehicles.

This paper provides a preliminary and partial analysis of heavy vehicle facilities. A number of extensions deserve high priority.

1. *Elastic demand*: The numbers of light vehicles and heavy vehicles using the corridor were 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 in the welfare analysis.
2. *Heterogeneity*: The model features just two categories of 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 two heterogeneous user groups. To examine this question empirically in the case of truck facilities it will be necessary to obtain data on trip-timing preferences for light and heavy vehicles.
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 regional or national road networks – 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 account for the effects of building dedicated truck-only lanes on road infrastructure construction and maintenance costs. According to Forkenbrock and March (2005) the costs of truck-only lanes vary widely with several factors: right-of-way availability, topography, the need to reconstruct overpasses to accommodate heavy vehicles, numbers of entrance and exit ramps required, and so on. Consequently, construction cost per lane-km. will have to be carefully 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 (5). The following example demonstrates that the pair are not sufficient:

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

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

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

7   REFERENCES

Arnott, R., A. de Palma and R. Lindsey (1992), "Route choice with heterogeneous drivers and group-specific congestion costs", Regional Science and Urban Economics 22(1), 71-102.

Arnott, R., A. de Palma and R. Lindsey (1998), "Recent developments in the bottleneck model", in K.J. Button and E.T. Verhoef (eds.), Road Pricing, Traffic Congestion and the Environment: Issues of Efficiency and Social Feasibility, Aldershot: Edward Elgar, 79-110.

Bambe, A. and B.S. McMullen (1996), "Measuring the non-pecuniary costs of triple trailer operation in Oregon; A Contingent Valuation Approach", Journal of the Transportation Research Forum.

Barro, R. and P.M. Romer (1987), "Ski-lift pricing, with applications to labor and other markets", American Economic Review 77(5), 875-890.

Berglas, E., D. Fresko and D. Pines (1984), "Right of way and congestion toll", Journal of Transport Economics and Policy 18(2), 165-187.

Dahlgren, J. (1998), "High occupancy vehicle lanes: Not always more effective than general purpose lanes", Transportation Research A 32A(2), 99-114.

Dahlgren, J. (2002), "High-occupancy/toll lanes: where should they be implemented?", Transportation Research A 36A, 239-255.

Donaghy, K.P. and L.A. Schintler (1998), "Managing congestion, pollution, and pavement conditions in a dynamic transportation network model", Transportation Research D 3D(2), 59-80.

Douglas, J.G. (2005), "Planning truck facilities on urban highways", 84th Annual Meeting of the Transportation Research Board, Conference CD Paper No. 05-0863.

Evans, Andrew W. (1992), "Road congestion pricing: When is it a good policy?", Journal of Transport Economics and Policy, 213-244.

Federal Highway Administration (2003), "The Freight story: A national perspective on enhancing freight transportation", FHWA-OP-03-004.

Fischer, M.J., D.N. Ahanotu and J.M. Waliszewski (2003), "Planning truck-only lanes: Emerging lessons from the Southern California Experience", 82nd Annual Meeting of the Transportation Research Board, Conference CD Paper No. 002048.

Federal Highway Administration (1997), 1997 Federal Highway Cost Allocation study. Final Report to the United States Congress HPP-10/9-98(3M)E, Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation.

Forkenbrock, D.J. and J. March (2005), "Issues in the financing of truck-only lanes", Public Roads 69(2).

Gan, A. and S. Jo (2003), "Final Report: Operational performance models for freeway truck-lane restrictions", Project No. BD-015-01, Prepared for Office of the State Transportation Planner, Systems Planning Office, State of Florida Department of Transportation, April.

Hedlund, K. (2004), "Truck tollways", 83rd Annual Meeting of the Transportation Research Board, presented at Session 546: Future role of road pricing and tolls in transportation finance.

Janson, B.N. and A. Rathi (2002), "Economic feasibility of exclusive vehicle facilities", Transportation Research Record 1305, 201-215.

Koehne, J., F. Mannering and M. Hallenbeck (1996), "Analysis of trucker and motorist lane evaluation: an exploratory analysis", Transportation Research A 24A(5), 371-379.

Mannering, F. and M. Hamed (1990), "Commuter welfare approach to high occupancy vehicle opinions toward truck-lane restrictions", Transportation Research Record 1560, 73-82.

Middleton and Lord (2005), "Safety and operational aspects of exclusive truck facilities", http://ceprofs.tamu.edu/dlord/Papers/Safety_Truck_Roadways_Middleton-Lord.pdf (Accessed April 1, 2006.)

Middleton, D. and S. Venglar (2006), "Operational aspects of exclusive truck roadways", 85th Annual Meeting of the Transportation Research Board, Washington, D.C., Conference CD Paper No. 06-0928.

Mohring, H. (1979), "The benefits of reserved bus lanes, mass transit subsidies, and marginal cost pricing in alleviating traffic congestion", in P. Mieszkowski and M. Straszheim (eds.), Current Issues in Urban Economics, Baltimore: John Hopkins Press.

Netter, M. (1971), "Equilibrium and marginal cost pricing on a road network with several traffic flow types", in G.F. Newell (ed.), Traffic Flow and Transportation, New York: Elsevier, 155-163.

Newell, G.F. (1980), Traffic Flow on Transportation Networks, Cambridge, MA.: MIT Press.

Organization for Economic Cooperation and Development (OECD) (1992), Scientific Expert Group. Cargo Routes: Truck Roads and Networks. Road Transport Research, Paris.

Parry, I.W.H. (2006), "How should heavy-duty trucks be taxed?", Resources for the Future Discussion Paper 06-23, http://www.rff.org/Documents/RFF-DP-06-23.pdf (Accessed July 3, 2006.)

Parsons, Brinckerhoff, Quade & Douglas (2005), "Truck only toll facilities: Potential for implementation in the Atlanta Region". http://www.i10freightstudy.org/ (Accessed March 31, 2006.)

Poole, R.W., Jr. and P. Samuel (2004), "Corridors for toll truckways: Suggested locations for pilot projects". Reason Public Policy Institute Policy Study 316.

Reich, S., J. Davis, M. Catalá, A. Ferraro and S. Concas (2002), "The potential for reserved truck lanes and truckways in Florida", Center for Urban Transportation Research, University of South Florida.

Samuel, P., R.W. Poole, Jr. and J. Holguin-Veras (2002), "Toll truckways: A new path toward safer and more efficient freight transportation", Reason Public Policy Institute http://www.rppi.org.

Small, K.A. (1977), "Priority lanes on urban radial freeways: An economic-simulation model", Transportation Research Record 637, 8-13.

Small, K.A. (1983), "Bus priority and congestion pricing on urban expressways", in T.E. Keeler (ed.), Research in Transportation Economics 1, Greenwich, Conn.: JAI Press, 27-74.

Small, K.A. and E.T. Verhoef (2006), Urban Transportation Economics, second edition. Chapters 2 and 3 available at http://www.socsci.uci.edu/~ksmall/research_page.htm (Accessed May 3, 2006.)

Small, K.A. and J. Yan (2001), "The value of "value pricing" of roads: Second-best pricing and product differentiation", Journal of Urban Economics 49(2), 310-336.

Texas Department of Transportation (2002), Crossroads of the Americas: Trans Texas Corridor Plan, www.dot.state.tx.us/ttc/ttc_home.htm (Accessed March 31, 2006.)

Transportation Research Board (2003), "Freight capacity for the 21st century".

Verhoef, E.T., P. Nijkamp and P. Rietveld (1996), "Second-best congestion pricing", Journal of Urban Economics 40(3), 279-302.

Verhoef, E.T. and K.A. Small (2004), "Product differentiation on roads: Constrained congestion pricing with heterogeneous users", Journal of Transport Economics and Policy 38(1), 127-156.

Wilbur Smith Associates (2003), The National I-10 Freight Corridor Study: Summary of Findings, Strategies and Solutions http://www.i10freightstudy.org/ (Accessed July 3, 2006.)

Yang, H. and H.-J. Huang (1999), "Carpooling and congestion pricing in a multilane highway with high-occupancy-vehicle lanes", Transportation Research A 33A(2), 139-155.

Yun, S., W.W. White, D.R. Lamb and Y. Wu (2005), "Accounting for the impact of heavy truck traffic in volume/delay functions within transportation planning models", 84th Annual Meeting of the Transportation Research Board, Conference CD Paper No. 05-2163.

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

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

Source: Authors' construction

Routes			
Characteristic		Route 1	Route 2
Capacity		4,000 PCE /hour	2,000 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			
Road damage		$0.0000/mile[1]	$0.0740/mile[1]
Local pollution		$0.0133/mile[1]	$0.0857/mile[1]
Global pollution		$0.0080/mile[1]	$0.0286/mile[1]
Noise		$0.0010/mile[1]	$0.0270/mile[1]
Sum	e_{gr}	$0.0214/mile[1]	$0.2150/mile[1]

Table 2: Base-case parameter values for numerical example

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: $t_2^\bullet - t_1^\bullet$				Maximum welfare gains	Frac. of Heavies in traffic mix for which segregation beneficial (steps of 0.01)
			Light		Heavies			
			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]
2	v^H = $75/hr	Satisfied	-$2.54	$1.86	-$6.01	$4.40	$7,128	[0.11,0.18]
(b) Congestion-cost parameters								
3	PCE_{cong}=1.5	Satisfied	-$2.53	$1.98	-$4.18	$3.28	$7,275	[0.14,0.24]
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 miles	Satisfied	$0.00	$1.43	-$0.08	$3.01	$2,233	[0.15,0.21]
14	Rte 2 length 35 miles	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., v^H = $75/hr	Satisfied	-$2.16	$2.13	-$5.11	$5.04	$5,569	[0.20,0.31]

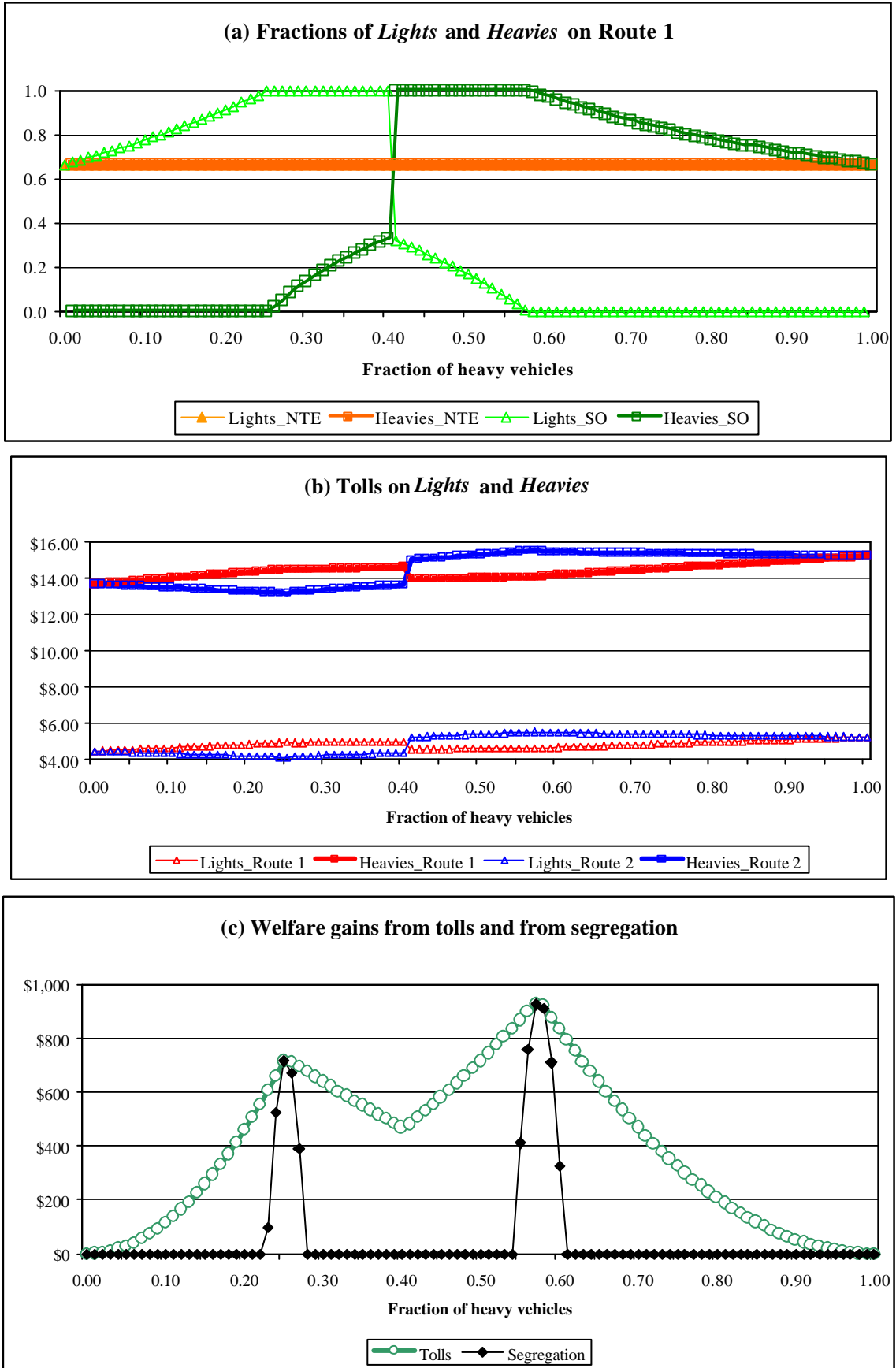**Table 3: Sensitivity analysis**

Source: Authors' construction

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

Legend: Lights_NTE — Heavies_NTE — Lights_SO — Heavies_SO

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

Legend: Lights_Route 1 — Heavies_Route 1 — Lights_Route 2 — Heavies_Route 2

(c) Welfare gains from tolls and from segregation

Legend: Tolls — Segregation

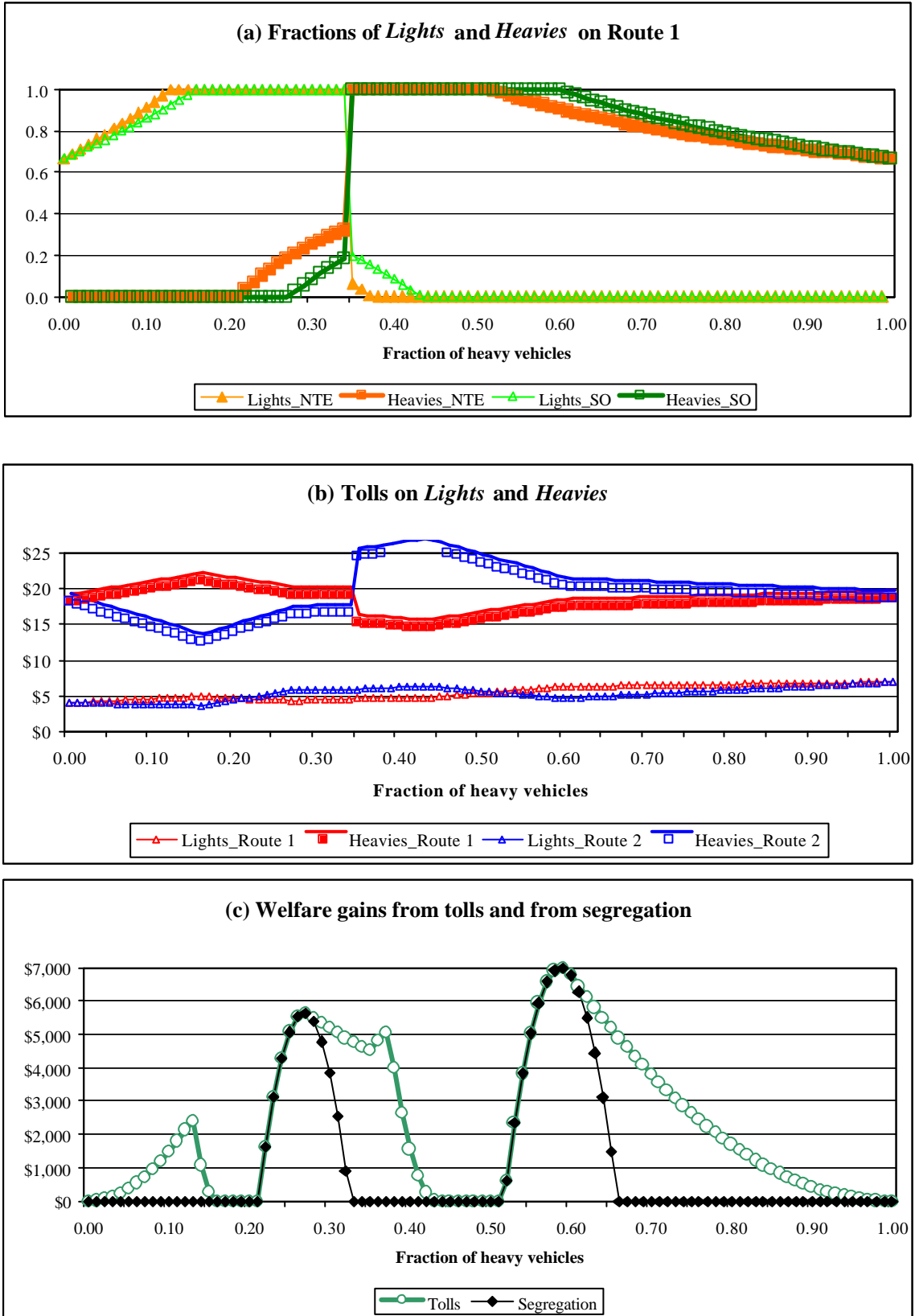**Figure 1: Results for Variant 1:** $v^{H} = \$15/hr$

Figure 2: Results for Variant 6: $l_H^L = 2$, $v^H = \$25/hr$