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Dedicated Lanes, Tolls and ITS Technology

Robin LINDSEY
University of Alberta
Canada

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ABSTRACT

The merits of separating cars and trucks have long been debated. Potential advantages include smoother traffic flows, lower accident rates, improved air quality and reduced maintenance and road infrastructure costs. Large trucks are often banned from urban roads and restricted to certain lanes on many highways but there are no dedicated truck facilities. However, truck-only lanes and truck tollways are now being actively studied. Tolls on cars and trucks are also becoming increasingly common and could be used to distribute car and truck traffic over road networks more efficiently.

This paper reviews the potential benefits from separating cars and trucks onto different lanes or roads while treating road infrastructure as given. U.S. studies of mixed traffic operations, lane restrictions and differential speed limits do not provide consistent evidence whether separating cars and trucks either facilitates traffic flows or reduces accident rates. Analysis with an economic model reveals that the potential benefits depend on the relative volumes of cars and trucks, capacity indivisibilities and the impedance and safety hazard that each vehicle type imposes. Differentiated tolls can support efficient allocations of cars and trucks between lanes. Lane access restrictions are much more limited in effectiveness. Toll lanes that are dedicated to either cars or trucks are a potentially attractive hybrid policy. Intelligent Transportation Systems (ITS) technology can help to improve safety and travel time reliability, and help drivers select between tolled and untolled routes.

1. INTRODUCTION

Most roads can be used by both cars and trucks even though these vehicles can differ greatly in size, weight, maneuverability and other characteristics [1]. Large trucks are often banned from urban roads and restricted to certain lanes on many highways, but there are no dedicated truck facilities. However, a number of truck-only lane and truck tollway projects have been proposed in the U.S. (Reich *et al.*, 2002; Federal Highway Administration, 2003; Transportation Research Board, 2003; Poole, 2007; Killough, 2008; GAO, 2008). Truck-only corridors between the U.S. and Canada, and truck-only road networks in Britain, Italy, and the Netherlands have also been studied.

Many proposed truck facilities would be tolled. Truck tolls are levied on 8,000 km. of U.S. roads, and over 20 European countries impose tolls on Heavy Goods Vehicles (Broaddus and Gertz, 2008). Tolls are imposed for various reasons including demand management, reduction of greenhouse gas emissions and revenue generation, but not specifically to separate light and heavy vehicles. Several potential advantages of separating cars and trucks have nevertheless been identified. Creating more homogeneous traffic flows could alleviate congestion by reducing the need for braking, accelerating, overtaking and changing lanes. Cars would suffer fewer delays from slow-moving trucks and less interference in fields of vision. Reducing congestion would also make travel times more predictable. Accident rates could fall, and fatalities could drop because of fewer crashes between light and heavy vehicles. Air quality would improve with higher and less variable speeds. Truck-only facilities can be designed to accommodate Long Combination Vehicles that exploit economies of vehicle size

(Samuel *et al.*, 2002). And if truck traffic is gradually concentrated on dedicated facilities, other roads will require less maintenance and new roads designed for cars can be built to a lower standard (Holguín-Veras *et al.*, 2003).

Many considerations arise in designing dedicated facilities: car and truck traffic volumes, availability of uninterrupted rights-of-way, locations of entrances and exits, numbers of lanes and lane widths, pavement thickness, speed limits, services such as truck stops and refueling stations, and the possibility of allowing mixed use on some lanes such as High Occupancy Toll lanes (Chu and Meyer, 2008). Deciding whether to toll cars and/or trucks, and setting the levels of tolls by vehicle type, road segment, time of day and so on are also challenges.

This paper does not attempt to address all these design aspects. It concentrates on the benefits of vehicle separation using dedicated lanes or roads and/or tolls. Capital and operating costs of dedicated facilities, costs of levying and enforcing tolls and many other practical considerations are ignored. The analysis focuses on three questions. First, does vehicle separation enhance operations and safety? Second, is the unregulated equilibrium allocation of cars and trucks across lanes and roads optimal? Third, if the allocation is not optimal what is the best means of intervention?

Section 2 reviews the limited empirical evidence on the advantages and disadvantages of separating cars and trucks. Section 3 summarizes a study by De Palma *et al.* (2008) that assesses the benefits of vehicle separation and compares the effectiveness of lane access restrictions, differentiated car and truck tolls, and toll lanes for either cars or trucks. Section 4 follows up by addressing some important considerations left out of the model. Concluding remarks are made in Section 5.

2. MERITS OF VEHICLE SEPARATION: EMPIRICAL EVIDENCE

No dedicated truck lanes or roads yet exist, but studies of mixed traffic, truck lane restrictions and differential speed limits provide some evidence on the advantages and disadvantages of separating cars and trucks.

2.1 Mixed traffic

For several reasons trucks contribute more to congestion than do cars: they occupy more road space, they are slower to accelerate and decelerate and to negotiate turns, and they obscure vision more. A standard procedure to account for the greater impedance of trucks is to use a Passenger Car Equivalent (PCE). Typical PCE values are 1.5-2 for single-unit trucks and 2-3 for combination vehicles. Larger PCE values are used on hilly roads. The PCE factor has two limitations for assessing the merits of separating cars and trucks. One is that the impedance created by a vehicle may depend on the composition of vehicles in the traffic stream (Demarchi and Setti, 2003). Some studies have found that the PCE of trucks is an increasing function of the fraction of trucks (Yun *et al.*, 2005). A second, and more fundamental limitation is that while the PCE measures the overall impedance created by trucks it does not account for their separate effects on cars and trucks. These effects are not yet well understood (Peeta *et al.*, 2004).

In addition to congestion, trucks create safety hazards for other vehicles. Several truck characteristics suggest that these hazards are greater for cars than trucks. Long trucks have extensive blind spots and drivers may have difficulty seeing smaller vehicles beside and behind them. Trucks obscure a wider field of view for car drivers and the blockage is magnified when a column of trucks is traveling in the same lane. Trucks block sight of other vehicles as well as roadside and overhead signs — although the extent of this problem has not been studied (TRB, 2003). On bad roads and in bad weather trucks throw up water and debris that may cause vehicle damage and obscure vision. Trucks create obstacles and hazards when they lose their loads or blow a tire. And trucks with heavy axle loads cause road damage which, over time, may reduce safe driving speeds and increase wear and tear for cars.

Trucks also have features that enhance their safety. Advances in antilock brakes have improved truck braking performance, and on wet surfaces braking distances are comparable to those of cars (TRB, 2003). Because truck drivers sit higher off the road than car drivers they can see further and respond more quickly to safety hazards. Perhaps most important, many truck drivers are experienced professionals with strong incentives to drive safely.

Empirical evidence on car and truck accidents is varied and rather complex. Overall accident rates in the U.S. per 100 million vehicle-miles are lower for large trucks than cars, but fatal crash rates are higher and in collisions involving cars and trucks the car driver is much more likely to be killed (Adelakun and Cherry, 2009). Accidents involving trucks are more likely to be sideswipes and less likely to be truck-into-car rear-ends or run-off-the-road crashes (Golob and Regan, 2004). Road characteristics such as grades, lane widths, lateral sight distances and curves affect truck performance and accident hazards. Traffic volumes are also a factor. According to simulation models (e.g. Garber and Liu, 2007) accident rates per vehicle-mile increase with volume, but costs fall because of reduced accident severity. Lane changes per vehicle-mile — which are correlated with accident rates — increase with the fraction of trucks in the traffic volume up to about 25%, but drop beyond that (Siuhi and Mussa, 2007). Studies differ as to whether variance in speeds contributes to crash rates.

The behaviour of car drivers is affected by the presence of trucks in ways that can affect safety. There is some evidence that car drivers maintain longer headways when following trucks than cars (Yoo and Green, 1999). Car drivers are more inclined to overtake trucks than cars and to overtake them more quickly. Car drivers experience psychological discomfort from the presence of trucks — particularly in bad weather and at intermediate traffic volumes when both the probability and potential severity of collisions is elevated (Peeta *et al.*, 2004).

2.2 Lane restrictions

Large trucks are prohibited on many highways from using certain lanes. Most restrictions in the U.S. apply 24 hours a day to ease enforcement and driver compliance. Restrictions are sometimes voluntary, and many states do not attempt to enforce those that are mandatory (TRB, 2003).

Studies vary on how lane restrictions affect traffic operations. Using simulation software Rakha *et al.* (2005) concluded that providing separate lanes for trucks enhances performance as measured by speeds, fuel consumption and emissions. Not surprisingly, passenger vehicles benefit more from vehicle separation during peak hours when congestion is high (Siuhi and Mussa, 2007; Florida DOT, 2008) and on highway sections with extended upgrades. Lane restrictions are found to be more effective on highways with three or more lanes in each direction than on highways with only two (Stanley, 2009) and on freeways with limited access. Studies differ as to whether trucks should be restricted to the outer lane (Florida DOT, 2008) or inside lane (Adelakun and Cherry, 2009).

Before and after crash data are sometimes not available to assess the safety effects of truck lane restrictions at particular sites, and studies have employed microscopic computer simulations. Both simulation studies and studies with crash data have produced conflicting results and there is no clear evidence that truck lane restrictions have either positive or negative effects on safety (TRB, 2003).

2.3 Differential speed limits

Many highways have different speed limits for cars and trucks. The practice is controversial and arguments are made both for and against differential speed limits. Inferior maneuverability and braking capabilities of trucks militate in favour of lower speeds, at least in mixed traffic, although as noted above truck drivers tend to have superior vision and driving skills that enhance truck safety. Differential limits may increase speed variance and induce more frequent lane changes that increase the rate of car-into-truck rear-end collisions and sideswipes, but reduce other types of accidents such as truck-into-car rear-end collisions (Harkey and Mera, 1994). Evidence on the safety effects of differential speed limits is relatively sparse. There is little difference in overall accident rates or severity between U.S. states with uniform speed limits and differential limits although the types of collisions and the roles of cars and trucks appear to differ (TRB, 2003)

In summary, the evidence from U.S. studies of mixed traffic operations, lane restrictions and differential speed limits does not provide a clear indication whether separating cars and trucks either facilitates traffic flow or reduces accident rates. Findings vary with the composition and overall volume of traffic, type of road and terrain, whether dedicated lanes are located on inside or outside lanes and other factors.

3. MERITS OF VEHICLE SEPARATION: MODELING RESULTS

The potential benefits from separating cars and trucks were recently analyzed by De Palma *et al.* (2008) using a microeconomic model. This section provides a summary of the model and presents the analytical and numerical results of greatest interest.

The model features two vehicle types: light-duty vehicles ("*Lights*", denoted by subscript *L*) and heavy-duty vehicles ("*Heavies*", denoted by subscript *H*) [2]. Fixed numbers of trips by each vehicle type are made from a common origin to a common destination using one of two routes, Route 1 and Route 2, that can be either different roads or parallel traffic lanes of the same road. The total number of trips by type *g* is N_g, and the number of trips by type *g* on route *r* is N_{gr}. The total private cost of a trip by type *g* on route *r* is a linear increasing function of the numbers of vehicles of each type that take the same route:

$$C_r^L = \underbrace{F_r^L}_{(a)} + \underbrace{c_{Lr}^L N_{Lr}}_{(b)} + \underbrace{c_{Hr}^L N_{Hr}}_{(c)} + \underbrace{\tau_r^L}_{(d)},\ r = 1,2\ , \tag{1}$$

$$C_r^H = \underbrace{F_r^H}_{(a)} + \underbrace{c_{Lr}^H N_{Lr}}_{(b)} + \underbrace{c_{Hr}^H N_{Hr}}_{(c)} + \underbrace{\tau_r^H}_{(d)},\ r = 1,2\ . \tag{2}$$

Term (a) in eqns. (1) and (2) is the fixed cost of a trip. Term (b) is the additional cost imposed by *Lights* that use the same route and term (c) is the additional cost imposed by *Heavies*. Coefficients c_{Lr}^{L} and c_{Hr}^{H}, r = 1, 2, specify the external costs imposed by each vehicle on vehicles of the same type using the same route, and are called *own-cost coefficients*. Coefficients c_{Hr}^{L} and c_{Lr}^{H} specify the external costs imposed by each vehicle on vehicles of the other type, and are called *cross-cost coefficients*. Both the own-cost and the cross-cost coefficients depend on the capacities of the routes. Finally, term (d) is the toll (if any). It is assumed that tolls can be differentiated both by vehicle type and route.

In the absence of tolls or lane restrictions, drivers of *Lights* and *Heavies* are free to take either route. Three types of equilibrium usage configurations are possible: an *integrated* equilibrium in which both *Lights* and *Heavies* use each route, a *partially separated* equilibrium in which one type uses both routes and the other type uses only one route, and a *segregated* equilibrium in which each type uses only one route. Which of the three configurations prevails depends on the numbers of each vehicle type, N_L and N_H, and on the magnitudes of the cost coefficients, c_{hr}^{g}, which in turn depend on route capacities. Define $c_{h\bullet}^{g} \equiv c_{h1}^{g} + c_{h2}^{g},\ g = L, H,\ h = L, H$. De Palma *et al.* (2008) show that a necessary condition for an *integrated* equilibrium is:

$$\frac{c_{H\bullet}^{L}}{c_{L\bullet}^{L}} < \frac{c_{H\bullet}^{H}}{c_{L\bullet}^{H}}. \tag{3}$$

Condition (3) stipulates that the ratio of the external cost imposed on a *Light* vehicle by a *Heavy* vehicle to the cost imposed on a *Light* vehicle by another *Light* vehicle ($c_{H\bullet}^{L} / c_{L\bullet}^{L}$) must be smaller than the corresponding ratio of costs imposed on a *Heavy* vehicle ($c_{H\bullet}^{H} / c_{L\bullet}^{H}$). If condition (3) holds, *Lights* prefer to travel on a route with *Heavies* and *Heavies* prefer to travel on a route with *Lights*. Condition (3) can be satisfied even if individual *Heavy* vehicles impose much higher congestion, accident and other external costs than do individual *Light* vehicles. What matters is the **relative** costs that *Light* and *Heavy* vehicles impose on each other.

Since travel demand is assumed fixed, the optimal allocation of drivers between routes is one that minimizes total social costs. Similar to the unregulated equilibrium, the optimum can be integrated, partially separated or segregated. However, the social cost of a trip by either vehicle type differs in two respects from the private cost given in eqns. (1) and (2). First, it excludes the toll because this is a transfer. Second, it includes the external costs of emissions, noise, vibration and pavement damage that are (mostly) borne by the population at large rather than by road users. For brevity these costs are referred to as *environmental* costs.

For several reasons the optimal allocation of vehicles to routes differs from the unregulated equilibrium. One is that drivers ignore the environmental costs of their trips, and another is that drivers are biased towards taking the route with lower fixed costs [3]. Since environmental and fixed costs are likely to be similar — if not identical — for lanes of the same road, these biases may not apply. However, the external costs reflected by the own-cost and cross-cost coefficients generally do not balance out between routes even for lanes of the same road. De Palma *et al.* (2008) show that a necessary condition for the optimal allocation to be integrated is:

$$c_{L\bullet}^{L} c_{H\bullet}^{H} > c_{H\bullet}^{L} c_{L\bullet}^{H} + \frac{1}{4}\left(c_{H\bullet}^{L} - c_{L\bullet}^{H}\right)^{2}. \tag{4}$$

Rearranging Condition (3) the corresponding condition for the unregulated equilibrium to be integrated is:

$$c_{L\bullet}^{L} c_{H\bullet}^{H} > c_{H\bullet}^{L} c_{L\bullet}^{H} . \tag{5}$$

Since the quadratic term on the right-hand side of condition (4) is positive, condition (4) is more stringent than condition (5) and the optimal allocation may be partially separated or segregated even if the unregulated equilibrium is integrated. To see why, suppose that $c_{H\bullet}^{L} > c_{L\bullet}^{H}$. Heavies then impose higher external costs on Lights than Lights impose on Heavies. Heavies are therefore biased towards traveling with Lights and it is optimal to keep Heavies away from Lights. Similarly, if $c_{H\bullet}^{L} < c_{L\bullet}^{H}$ Lights are biased towards traveling with Heavies and it is advantageous to keep Lights away from Heavies. Unless the capacities of the routes are roughly commensurate with the numbers of Light and Heavy vehicles it is not efficient to eliminate conflicts between Lights and Heavies by segregating them, but partial separation is still warranted.

When the unregulated equilibrium distribution of *Light* and *Heavy* vehicles between the routes is not optimal various traffic control measures can be considered. Three such measures are considered here: lane access restrictions, tolls on both vehicle types and both lanes, and a toll lane restricted to one vehicle type. Because *Light* and *Heavy* vehicles impose different external and environmental costs on each route undifferentiated tolls are inadequate to support the optimum. But tolls that are differentiated by both vehicle type and route do suffice [4].

The scope for lane restrictions to support an efficient distribution of traffic turns out to be rather limited. If the optimum is segregated it can be supported simply by restricting each type to its designated route. But lane restrictions clearly don't work if the optimum is integrated. Moreover, if the optimum is partially separated lane restrictions typically don't work either because, while one vehicle type can be restricted to its designated route, the other vehicle type will not allocate itself between routes in optimal proportions. Indeed, if the unregulated equilibrium is integrated a lane restriction on one type can actually increase total travel costs [5].

The third policy instrument, a toll lane, entails dedicating one route to one vehicle type and levying a toll on it. A toll lane is therefore a hybrid of a lane restriction and a toll. A single toll lane cannot support the optimum if it is integrated. However, under certain conditions a single toll lane can decentralize the optimum if it is segregated or partially separated [6]. To consider one case, suppose the optimum is partially separated with only *Lights* using Route 1. Making Route 1 a toll lane for *Lights* supports the optimum if *Lights* are biased against using Route 2 (i.e., if $c_{H2}^{L} > c_{L2}^{H}$) because this bias can be offset by imposing a positive toll on *Lights* using Route 1. However, if *Lights* are biased against using Route 1 (i.e., if $c_{H2}^{L} > c_{L2}^{H}$) imposing a toll on Route 1 would only exacerbate the misallocation.

To examine more closely the potential benefits from lane separation, comprehensive tolls and toll lanes, De Palma *et al.* (2008) developed a specific version of the general model in which the external costs of travel are due to congestion and accidents: $c_{hr}^{g} = cong_{hr}^{g} + acc_{hr}^{g}$, $g = L, H$; $h = L, H$; $r = 1, 2$, where $cong_{hr}^{g}$ and acc_{hr}^{g} are congestion and accident cost coefficients respectively. The relative congestion costs imposed by *Heavies* on *Lights* and *Lights* on *Lights* are assumed to be:

$$\frac{cong_{Hr}^{L}}{cong_{Lr}^{L}} = \lambda_{H}^{L} PCE_{cong} , \; r = 1, 2 , \tag{6}$$

where PCE_{cong} is a generic PCE for congestion created by *Heavies* and $\lambda_H^L \geq 1$ is a scale factor to reflect the greater impedance that *Heavies* may imposed on *Lights* for reasons discussed in Section 2. The relative accident costs imposed by *Heavies* on *Lights* and *Lights* on *Lights* are given by an analogous expression:

$$\frac{acc_{Hr}^L}{acc_{Lr}^L} = \phi_H^L PCE_{acc},\ r = 1,2, \tag{7}$$

where PCE_{acc} is a generic PCE for accident costs created by *Heavies*, and $\phi_H^L \geq 1$ is a scale factor to account for the disproportionate safety hazard or fear that *Heavies* may impose on *Lights*. Base-case values of the parameters are given in Table 1. They describe a three-lane road with two lanes comprising Route 1 and the remaining lane comprising Route 2. The $cong_{Lr}^L$ and acc_{Lr}^L coefficients are calibrated so that in the unregulated equilibrium the marginal external congestion cost of a *Light* vehicle is about $0.10/mile (€0.044/km) on each route, and the marginal external accident cost is about $0.02/mile (€0.009/km) [7].

De Palma *et al.* (2008) compute unregulated equilibria and optima for a wide range of parameter values. Attention is restricted here to a few alternatives that illustrate the lessons of greatest policy interest. As a first alternative the value of time (VOT) for *Heavies* is set to $75/hr (€53/hr). Condition (3) is satisfied and the unregulated equilibrium is integrated, but condition (4) is violated so that the optimum is not integrated. Since the VOT for *Heavies* is over six times the VOT of $12/hr for *Lights*, the main benefit from intervention is to reduce congestion delay for *Heavies* by allocating lots of road space to them.

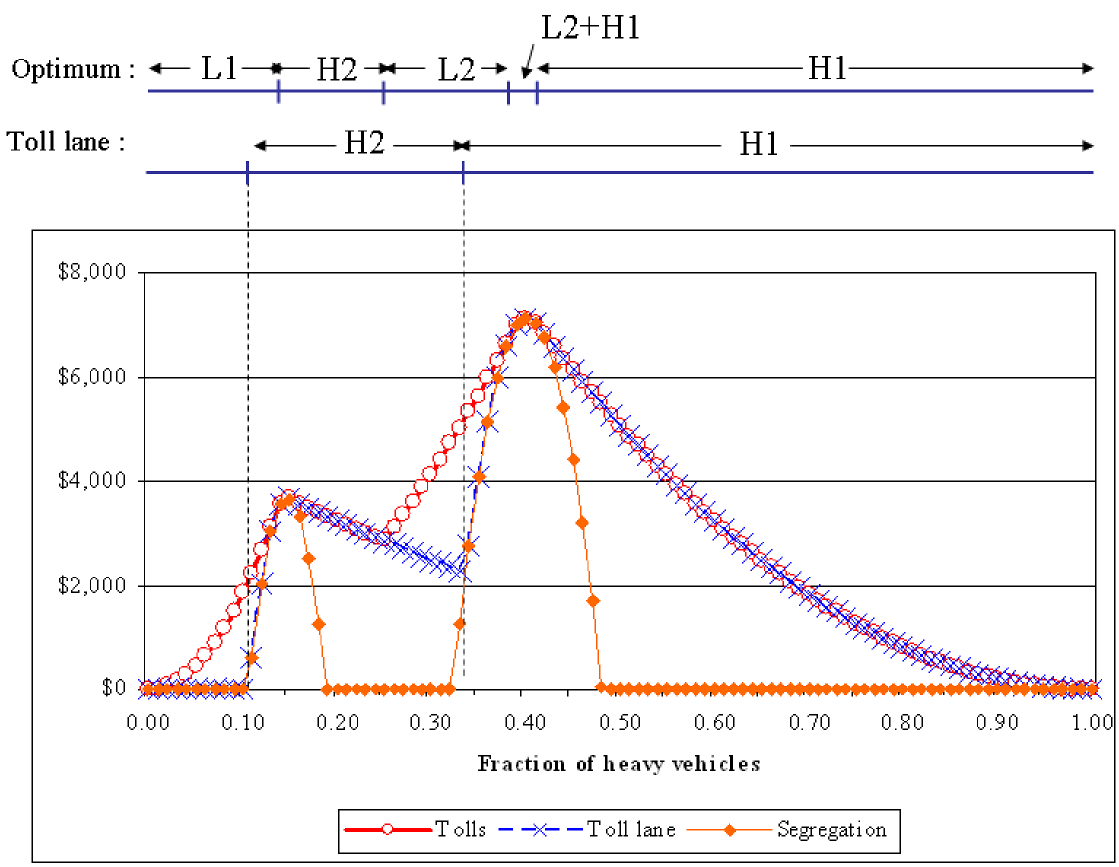
Table 1. **Base-case parameter values**

	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
Total trips		40,000
Proportion of *Heavies*		Range 0-100%
Travel costs	***Light* vehicles**	***Heavy* vehicles**
Fixed costs	$0.194/mile	$0.42/mile
Values of time	$12/hour	Range
Congestion PCE for *Heavies* (PCE_{cong})		2
Relative impedance of *Lights* by *Heavies* (λ_H^L)	1	
Accident PCE for *Heavies* (PCE_{acc})		0.75
Relative crash hazard for Lights (ϕ_H^L)	1	
Relative cost of accident for *Heavies*		1
Environmental costs	$0.0223/mile	$0.2153/mile

Source: De Palma *et al.* (2008)

As shown at the top of Figure 1 by the label "L1", if the fraction of *Heavies* in the traffic mix, call it *f*, is below about 0.14, Route 1 (with two thirds of total capacity) is dedicated to *Light* vehicles and *Heavies* are confined to Route 2. For $f \in (0.14, 0.24)$, Route 2 is dedicated to *Heavies* (H2) and *Lights* are confined to Route 2. For $f \in (0.24, 0.39)$, Route 2 is dedicated to *Lights* (L2). Within the narrow range $f \in (0.39, 0.41)$ segregation is optimal with Route 2 dedicated to *Lights*, and Route 1 dedicated to *Heavies* (L2+H1). Finally, for $f > 0.41$ Route 1 is dedicated to *Heavies* (H1) and *Lights* are confined to using the one lane on Route 2. As *f* varies from 0 to 1, the optimal allocation pattern of traffic to routes changes four times which highlights the importance of the proportion of *Heavy* vehicles in determining efficient use of road space [8]. As noted above, the optimum can be decentralized using differentiated tolls. The benefit, shown in Figure 1, exhibits a double peak with a local minimum at *f*=0.24 where *Heavies* are shifted from Route 2 to Route 1 and the allocation of vehicle types to routes is relatively less important.

Figure 1. **Benefit from tolls, toll lane and segregation vs. fraction of *Heavy* vehicles**

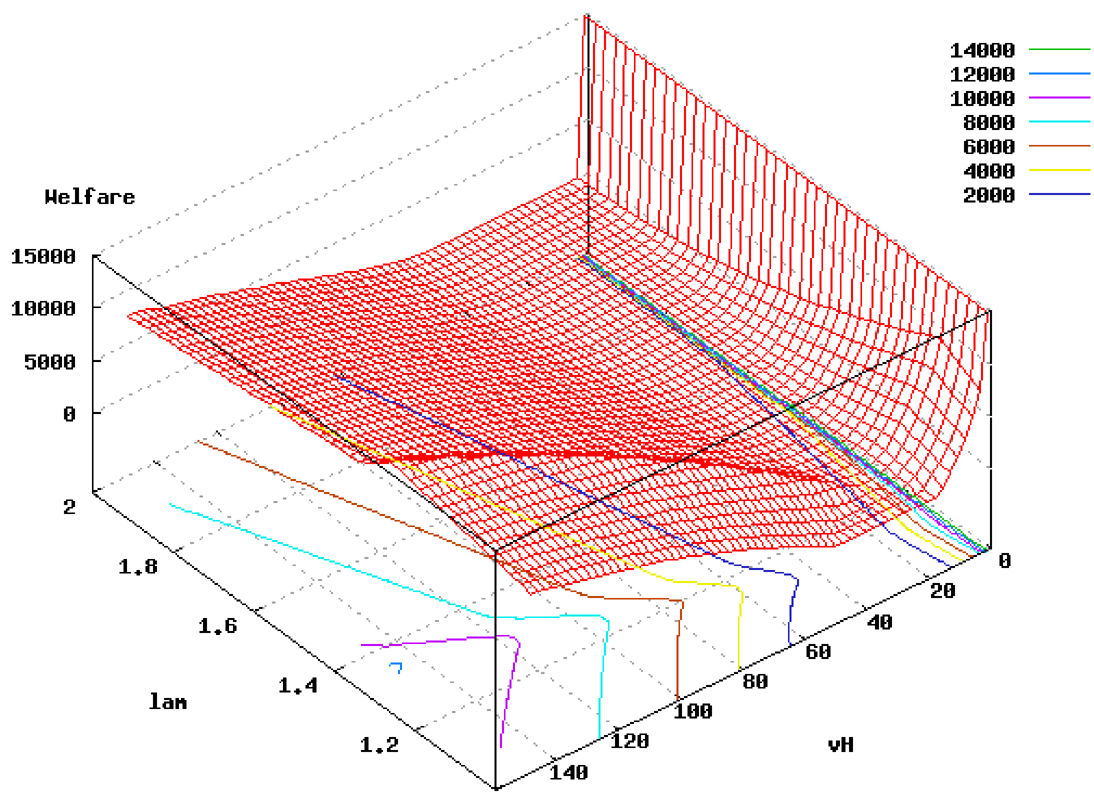


Source: Author's construction

The most effective toll lane configuration is identified just below the optimal pattern near the top of Figure 1. For *f*<0.10 there are two few *Heavies* to justify a toll lane. For $f \in (0.10, 0.33)$ a toll lane for *Heavies* on Route 2 is beneficial (H2), and for *f*>0.33 a toll lane on Route 1 (H1) is best. The toll lane configuration coincides with the optimal configuration over two subintervals of *f* and the toll lane supports the optimum over much of this range. By contrast, segregation is optimal only within the narrow range $f \in (0.39, 0.41)$ identified above, and segregation is beneficial (but not optimal) only for two relatively small intervals $f \in (0.11, 0.18)$ and $f \in (0.33, 0.48)$ within which the proportion of heavy vehicles is roughly commensurate with the capacity of either Route 2 or Route 1.

Figure 2 shows the results of a second experiment in which the value of travel time for *Heavies* (denoted by v^H) and the relative impedance of *Heavies* (λ_H^L) are simultaneously varied while holding the fraction of *Heavies* fixed at 20%. The benefit from intervention is a roughly U-shaped function of v^H . For low values of v^H it is beneficial to keep *Heavies* away from *Lights*, whereas for large values of v^H (such as $75/hr. in the first experiment) it is advantageous to keep *Lights* away from *Heavies*. For intermediate values of v^H in the neighborhood of $25/hr. Condition 4 is satisfied and both the optimum and unregulated equilibrium are integrated. Since fixed trip costs and environmental costs are the same for the two routes in the numerical example, the equilibrium allocation of traffic is unbiased and there is no scope for beneficial intervention. This region shows up in Figure 2 where the surface is flat and the benefit is zero.

Figure 2. **Benefit from intervention vs. VOT for *Heavies* and relative impedance of *Lights* (20% *Heavies*)**



Source: De Palma *et al.* (2008)

Turning attention to the effect of parameter λ_H^L it is apparent from the ridge on the surface in Figure 2 that the benefit of intervention is greatest when λ_H^L is slightly greater than one and falls off on either side. As λ_H^L begins to increase above 1 the cross-congestion-cost coefficients, $cong_{Hr}^L$, rise and so does the benefit from separating *Heavies* from *Lights*. But when λ_H^L exceeds a threshold value, the unregulated equilibrium becomes separated and moves closer to the optimal traffic allocation. This illustrates that the benefits from intervention depend on both the unregulated and optimal traffic allocation configurations. Varying parameter ϕ_H^L, the relative crash hazard for *Light* vehicles, has a similar inverse V-shaped effect on the benefits.

The model in De Palma *et al.* (2008) conveys at least two important policy lessons regarding vehicle separation. One is that lane-access or route-access restrictions are generally less effective than comprehensive tolls and may provide no benefit at all. The second and related lesson is that lane capacity indivisibilities make it difficult to allocate capacity between vehicle types in efficient proportions. Building dedicated truck facilities is cost-effective only if truck volumes are sufficiently high: a lesson that also applies to High Occupancy Vehicle (HOV) lanes for passenger transportation (Small, 1983; Dahlgren, 1998).

4. FURTHER CONSIDERATIONS

The model used in Section 3 is limited to driver's choice of lane or route on a corridor with fixed travel demand, and disregards various potentially important practical considerations such as travel time uncertainty and trip timing. Some of these factors are reviewed in this section.

4.1 Values of travel time, values of reliability and uses of information technology

Values of travel time

As the analysis in Section 3 makes clear, values of travel time for passenger and freight trips are key parameters in determining the benefits of separating cars and trucks. The VOT for automobile travel has been estimated in numerous studies [9]. It varies with trip purpose, vehicle occupancy, income and other factors. In order to do an accurate assessment of a specific project it is necessary to determine the proportions of trips made for business, commuting and leisure as well as the socioeconomic characteristics of the traveling population.

Valuation of travel time not been studied as thoroughly for freight transport as it has for passenger transport although its importance is now widely recognized. Truck VOTs depend on many factors: vehicle type and load, importance of punctual delivery, whether the truck is operated in-house or for-hire, truck drivers' wage rates and working hours, etc. VOTs tend to be higher for shippers than transporters and depend on whether receivers have an input into the scheduling of deliveries (Hensher and Puckett, 2008). VOT estimates range over an order of magnitude in developed countries and are highly skewed (Kawamura, 2000).

There has been a longstanding debate in the literature on whether VOT depends on trip duration and the size of travel time savings: relevant questions for trips on dedicated facilities which could range in length from a few kilometers to hundreds of kilometers on interstate or international road networks. In theory VOT could either rise with distance due to fatigue or boredom, or fall because trips many not be scheduled as tightly for long hauls [10]. The value attached to small travel time savings depends, *inter alia*, on whether the amount saved is enough to make an additional delivery during a driver's shift. This will vary from trucker to trucker and may average out in the aggregate.

Values of reliability

Variability in travel time is absent from the deterministic model used in Section 3. A study by Cambridge Systematics (2005) [11] identified the sources of highway congestion as bottlenecks (40%), traffic incidents (25%), workzones (10%), bad weather (15%), poor signal timing (5%), and special events & other sources (5%). Depending on the information available to travelers about incidents, weather and so on, between roughly one quarter and one half of congestion delays are unpredictable.

Although the literature on travel time reliability has advanced greatly in the last decade there are still no generally accepted monetary values for the value of reliability (VOR). In travel demand studies VOR is often estimated by the coefficient on the standard deviation of travel time and VOT by the coefficient on mean travel time. The reliability ratio, ρ, is defined by the ratio of VOR to VOT. If the coefficient of variation (*CV*) of travel time is assumed to be constant the effect of variability in travel time can be accounted for simply by scaling up the VOT by the factor $1+\rho * CV$ (Institute for Transport Studies, 2008, p.21). A problem with this approach is that *CV* tends to increase with congestion because congestion magnifies the effects of incidents and other disturbances. Another problem is that *CV* tends to decline with trip length (Arup, 2003). These findings would suggest that reliability accounts for a smaller portion of total trip costs on longer and less congested roads. To the extent that lane restrictions and/or tolls reduce congestion the unit value of the resulting travel time savings are reduced as well: an obvious complication for project and policy evaluation.

Uses of information technology

The cost of travel time unreliability depends on how well system operators can control travel conditions and on what drivers know when they make their travel decisions. Intelligent Transportation Systems (ITS) technology is advancing in both directions (TRB, 2003). Ramp metering is an established and relatively simple technology that alleviates congestion by controlling the inflow rate onto limited-access highways. Slowly changing variable speed limits help to smooth traffic flows and reduce the incidence of rear-end collisions. Dynamic truck restrictions involve the use of dynamic message signs and specialized ramp metering to direct large trucks onto certain traffic lanes, and operate in some ways similarly to conventional lane restrictions. ITS is also contributing to truck safety with warning systems for long downgrades and curves, and on-board collision avoidance systems.

As far as driver aids dynamic message signs have long been used to provide en route trip guidance. Pre-trip information is also becoming increasingly available by phone, on the Internet and at public places. ITS can also be used in conjunction with tolling to inform travelers about toll levels and travel times on tolled and untolled facilities (FHWA, 2009). In the future, drivers may be able to program onboard navigation aids to select a route with the shortest distance, shortest expected travel time or lowest expected generalized cost (Chorus and Timmermans, 2008).

4.2 Route choice

The model in Section 3 is limited to two routes or sets of lanes in the same travel corridor and the only choice for drivers is which route or lane to take. In many settings other routes will be available. A potential drawback of restricting trucks to certain lanes and/or levying high truck tolls is that truckers may divert to secondary roads or city streets that are not designed to handle heavy vehicles and where congestion, accident and environmental externalities are worse. Traffic diversion has not been a major problem for the German Heavy Goods Vehicle (HGV) toll because many potential alternate routes are closed to trucks (Broaddus and Gertz, 2008). And some freeways — such as many in Atlanta — have no good alternative routes (Chu and Meyer, 2008). However, traffic diversion has been a problem in some countries such as France. Setting tolls when substitute or complementary roads are not tolled is a classic problem in second-best pricing. It requires rather detailed information on travel demands and costs even on simple road networks and the consequences of setting tolls at nonoptimal levels can be severe [12].

4.3 Trip timing

The model in Section 3 is static and implicitly assumes that cars and trucks travel at the same time. To the extent that they can use the same roads at different times, dedicated lanes or facilities are not actually needed to separate them. Passenger and freight traffic flows do follow different daily and weekly time patterns (Rakha *et al.*, 2005) and truckers naturally prefer to avoid commuting periods (Fischer *et al.*, 2003). However, truckers are limited as to when they can travel. Hours of service regulations, maritime terminal operating hours, neighborhood curfews and union-negotiated hours of operation impose constraints.

Shippers' hours are another important constraint on truck delivery times (Vilain and Wolfrom, 2001). Just-in-time inventory management systems require that deliveries be made at certain times, and time-sensitive goods such as express services call for immediate delivery. Many receivers with traditional operating hours would incur additional labour costs to accept deliveries during off-hours, and since truckers often make deliveries to several businesses on a single tour the additional labour costs of off-hours would be magnified (Holguín-Veras, 2005). As a consequence, time-of-day price elasticities tend to be lower for trucks than for cars. For example, when the Port Authority of New York and New Jersey introduced a peak-period congestion charge in 2001, only 6 percent of truckers shifted operations to off-peak hours. Two thirds of the truckers who continued to drive during the peak cited shippers' hours as the reason for not switching (Congressional Budget Office, 2009). Tillema *et al.* (2008) report similar results from a survey of Dutch firms. This suggests that the scope for temporal separation of cars and trucks is rather limited.

4.4 Vehicle type, logistics and location choices

Most trucking firms would have little incentive to modify their vehicle fleets if truck-only facilities or tolls were established on a single travel corridor. For regional or national road networks, however, there may be substantial productivity gains from using large combination vehicles (Samuel *et al.*, 2002). The Swiss HGV tolling scheme, introduced in 2001, is levied on all roads. It has had a dramatic impacts on truck volumes and has induced a shift towards larger and heavier vehicles (Broaddus and Gertz, 2008). The German HGV charge, which varies with vehicle emissions class, has induced shifts towards environmentally friendly vehicles. It has also encouraged a sharp reduction in the proportion of empty trips. To the extent that tolls and future truck-only facilities succeed in reducing congestion delays freight companies may be able to make more deliveries per day with each vehicle and require fewer vehicles to conduct business (Hensher and Puckett, 2008).

Another possible long-run response of firms to the introduction of truck-only facilities and tolls is to change the locations of their businesses and transfer terminals. Such adjustments would, in turn, affect firms' accessibility to input suppliers, customers and employees and trigger further location shifts (Tillema *et al.*, 2008). Little is yet known about the potential magnitude of these shifts or their effects on truck flows over road networks (Roorda *et al.*, 2009). Nevertheless, as long as first-best conditions hold elsewhere these complications do not invalidate the analysis in Section 3 of given volumes of car and truck trips on a single corridor.

5. CONCLUSIONS

Truck-only lanes and roads have been proposed as a way to alleviate traffic congestion, enhance safety and reduce other external effects of traffic. This paper focuses on the potential benefits of separating cars and trucks while taking road infrastructure and operating costs as given. Because no truck-only facilities have yet been built there is no experience with their operational and safety benefits. However there is evidence on the advantages and disadvantages of separating cars and trucks from studies of mixed traffic, truck lane restrictions and differential speed limits. The evidence from U.S. studies is varied and suggests that the effects of separation are sensitive to car and truck traffic volumes, type of road and terrain, location of dedicated traffic lanes on multilane highways and other factors.

To examine when vehicle separation is beneficial a simple economic model is used in which car and truck drivers choose between two lanes or routes. Routes can differ in fixed, environmental and external (i.e. own- and cross-) costs and each difference can distort the unregulated equilibrium allocation of traffic between routes. If the external cost imposed by cars on trucks differs from the external cost imposed by trucks on cars intervention calls for partially separating or segregating cars and trucks. The optimal allocation can be decentralized using tolls that are differentiated by vehicle type and route. Lane access restrictions are less flexible and, because of capacity indivisibilities, may be unwarranted. For example, a dedicated truck lane is unlikely to be cost effective if trucks account for only a small fraction of total traffic. Toll lanes — a hybrid of lane restrictions and tolls — are generally more effective than access restrictions because they offer a continuous rather than discrete degree of control.

As road transport technology advances, and other changes occur, the economics of dedicated facilities may strengthen or weaken. In most developed countries truck traffic has been growing more rapidly than passenger traffic and this strengthens the economics of building new, dedicated truck facilities or reserving lanes on existing roads for heavy vehicles. However, continuing improvements in vehicle safety could lower accident rates and reduce the safety hazard posed by trucks on lighter vehicles. In the longer term, automated roads could dramatically increase road capacity and reduce both congestion and accidents [13].

A further consideration is that comprehensive road pricing for both cars and trucks may be introduced in the coming years. The German HGV charge uses satellite-based technology to toll heavy trucks on federal motorways and could be extended to other roads, lighter trucks and passenger vehicles. In 2008, the Dutch Parliament approved a national distance-based system of user charges for passenger and freight vehicles. The fee per kilometer will vary by time of day and with vehicle emissions. The technology would permit tolling by vehicle type, lane, time of day and current road conditions and would facilitate vehicle separation using tolls as suggested here.

NOTES

[1.] Passenger vehicles range from small electric cars to sports utility vehicles, vans and pickup trucks and vary widely in their characteristics as well. Freight vehicles vary even more. The generic terms “cars” and “trucks” are used here for ease of reference.

[2.] *Lights* and *Heavies* correspond to cars and trucks in the rest of this paper.

[3.] This bias is well known in the literature; see Verhoef *et al.* (1996).

[4.] See Proposition 3 in De Palma *et al.* (2008). This result remains valid if travel demand is elastic. However, tolls do not internalize all decisions, such as driving speed and weaving between lanes, and a role remains for speed limits and other traffic laws to control these facets of driver behaviour.

[5.] See De Palma *et al.* (2008), Proposition 5.

[6.] See De Palma *et al.* (2008), Propositions 6 and 7.

[7.] For details see De Palma *et al.* (2008), Sections 3 and 4.

[8.] More complicated allocation patterns can occur; see De Palma *et al.* (2008).

[9.] For recent literature reviews see Small and Verhoef (2007) and Intervistas Consulting Inc. (2008).

[10.] For freight transport average VOTs may increase with distance because a greater fraction of trucks have two drivers.

[11.] This information is taken from Congressional Budget Office (2009, Figure 1-1).

[12.] See Small and Verhoef (2007, Section 4.2).

[13.] To the extent that automated roads would operate more effectively with homogeneous vehicles this reinforces, rather than weakens, the argument for vehicle separation.

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