EFFECTS OF SEGREGATING BUSES AND CARS IN A CONGESTED, NON-STEADY-STATE STREET NETWORK

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Much of the literature on exclusive bus lanes pertains to how these lanes might induce shifts in mode choice by prioritizing bus travel, sometimes at the expense of degrading travel by car; e.g. (1). A separate line of research theorized that the conversion of regular-use lanes to bus-only lanes can, in certain circumstances, improve travel for cars as well buses, even in the absence of modal shifts (2). By removing buses from queues and putting them in their own, faster-moving lanes, target service frequencies can be maintained with fewer buses; which mean that fewer bus lanes are needed; which mean that more lanes can be left for the exclusive use of cars.

However, these Pareto improvements were predicted in (2) only when converted lanes enjoyed rather high bus flows; and only by relying upon a so-called "smoothing effect" which describes the network capacity gained when distinct travel modes are segregated into their own lanes. With this segregation, disruptive vehicular interactions are diminished, which can generate higher bottleneck capacities (3,4). In efforts to garner the kinds of high-level insights that can guide large-scale planning decisions, street networks were modeled in (2) as rotationally-symmetric, closed-loop beltways operating in the steady-state.[1]

The present work follows lines of thought that are similar to those in (2), in that it too: models the impacts of converting regular lanes to bus lanes on rotationally-symmetric beltways; and assumes that travel demands for buses and cars are not subject to shifts from one mode to the other. However, the present work recognizes that rush periods are invariably characterized by non-steady-state conditions; i.e. the early part of a rush is typically characterized by travel demand that exceeds beltway capacity, such that beltway queues expand; while the later part is characterized by demand that falls below capacity, such that queues gradually disappear. It turns out that these non-steady-state realities can be favorable to bus lanes, meaning that lane conversions can sometimes improve travel for buses and cars, even if one ignores the smoothing effect.

ASSUMPTIONS AND METHODS

We assume now a set of conditions that might describe the operation of jitney buses in a city within the developing world, albeit in idealized fashion. Contrary to (2), it is assumed that the number of bus trips made during the rush is fixed, irrespective of whether some lanes are given to buses. Each bus: enters a beltway network during the rush; serves assigned portions of the network; then exits. The points from which buses and cars enter the beltway are uniformly distributed over its boundary. When buses and cars share the same lanes, both modes compete for available road capacity to enter and circulate through the beltway. When some lanes are instead set-aside for buses, those buses enter and circulate without delay,

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[1] The beltway is a good representation of a congested downtown street network. For example, the beltway's on- and off-ramps can represent the downtown's access and egress points: the shorter the downtown's block lengths, the greater the number of beltway ramps. And the beltway's circumference can be selected so as to account for the downtown's total available road space.

and cars are left with fewer lanes on the beltway for their use. The number of bus lanes to be used on the beltway, N, must be integer valued such that $1 \leq N \leq N_T - 1$, where N_T is the beltway's total number of lanes available to serve traffic in each travel direction. The upper bound guarantees that at least 1 lane is available in each direction to serve cars. Very importantly, once all rush-period bus tours are completed, all N_T lanes are thereafter made available to cars.

It is further assumed that: prior to the start of a rush at time $t = 0$, there is a fixed demand in passenger car equivalents (pce) that is less than beltway capacity; from $t = 0$ to $t = t_r$, there is a fixed demand that exceeds the previous rate by the amount λ (in pce/h) and this high demand exceeds beltway capacity; and at $t > t_r$, demand returns to the initial low rate that occurred prior to $t = 0$.

For simplicity, we work with the average speed and the average distance traveled on the beltway by all pce. The implicit assumption is that the variances in speed and in distance traveled are not large, neither when measured across vehicles of the same class, or across the two distinct classes.

Beltway traffic is described using a triangular-shaped Macroscopic Fundamental Diagram (MFD) that relates total flow on the network (in pce/h) to network-wide density (pce/km), much as in (5). Knowing the beltway's physical size and the vehicle trip length on it, the MFD is rescaled to a Network Exit Function (NEF) that relates the total vehicle accumulation on the beltway, n (pce), to the rate that vehicles complete their trips on it, f (pce/h). The maximum trip-completion rate is f_m and the corresponding accumulation is n_m.

We view the beltway network as being composed of a series of identical building blocks, like the building block shown for a single travel direction in Fig. 1. When the beltway is congested, we have $\alpha_j > \beta_j$, where α_j is the proportion of pce that enter the block j from outside the beltway, and β_j is the proportion of the block's pce that exit the beltway. Hence for every pce that enters a block via the beltway, there are $(1 + \alpha_j)$ that traverse the block and remain on the beltway. Given that the blocks are identical and that the beltway is rotationally symmetric, we aggregate α_j and β_j across all the beltway blocks. Hence $\alpha = \Sigma_j \alpha_j$ and $\beta = \Sigma_j \beta_j$ represent the proportion of pce that enter and exit the beltway in total. The merge model of Daganzo (5) is used to estimate the block entry flows at short time steps.

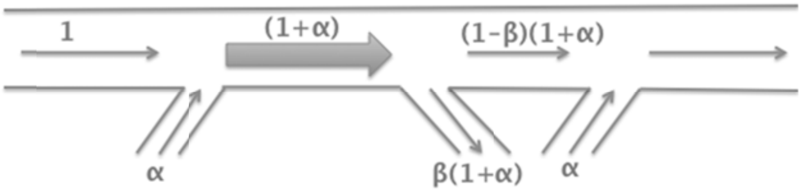

FIGURE 1 Building Block of the Beltway.

With entry and exit flows thusly obtained for a point in time, t, the NEF is used to determine the accumulation in the beltway, n(t). We can then incrementally construct a queueing diagram, like the one in Fig. 2, to estimate delays.

The diagram in Fig. 2 was constructed for the case in which buses and cars share the same lanes. (The fixed flow at $t < 0$ and $t > t_r$ is treated as a background rate and was subtracted from the cumulative count curves.) When bus lanes are used to segregate buses and cars, the analysis is performed using the demand for car travel (only), since buses are no longer subject to delays. The merge model and the NEF are rescaled to account for the diminished space that remains available to car traffic.

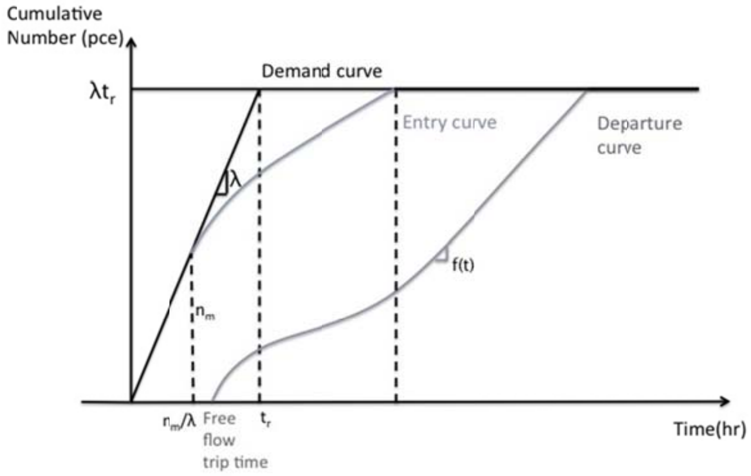

FIGURE 2 Cumulative Total Demand, Entry and Departure Curves.

Parametric analysis featuring comparisons of segregated and non-segregated cases unveil certain insights. Examples follow.

EXAMPLE FINDINGS

Fig. 3 presents analysis outcomes for ranges of t_r (normalized by average vehicle free-flow trip time on the network) and λ (normalized by f_m). Other key inputs to the analysis are noted in the figure caption. Most of these were borrowed from (6).

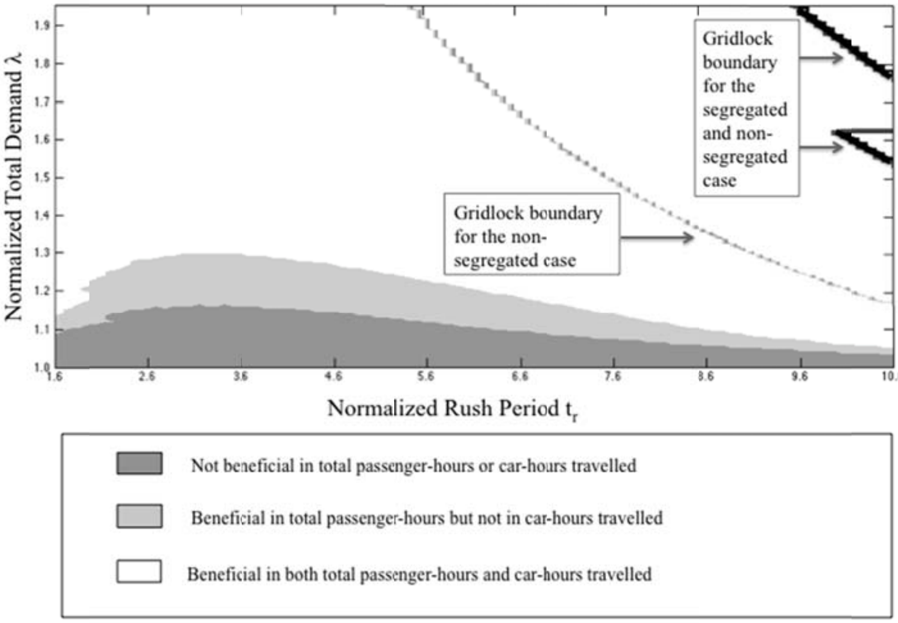

FIGURE 3 Delay Reduction Map for a Bus Demand Proportion of 20%, a Number of Lanes of 3, $\boldsymbol{f_m = 15660}$ pce/h, $\boldsymbol{n_m = 3000}$ pce, $\boldsymbol{\alpha = 0.2}$, $\boldsymbol{\beta = 0.14}$, a Maximum On-Ramp Capacity of $\boldsymbol{2f_m}$ and a Maximum Total Accumulation of 6500 pce

The boundary lines near the graph's upper-right corner delineate where combinations of t_r and λ create gridlock on the beltway network. Tellingly, the gridlock region is smaller for the segregated case, where one or more beltway lanes are given over to buses.

The darker-shaded area at the bottom of the graph highlights the combinations of t_r and λ for which bus lanes increase the person-hours traveled by car on the network, and even the total person-hours traveled by both modes combined, as compared against not setting aside any lanes for bus-use only. The finding comes despite the advantages that bus lanes extend to bus travelers. The lighter-shaded region directly atop denotes combinations for which the bus lanes still increase the person-hours traveled by car, but diminish the total hours traveled via both modes combined. Very importantly, the large unshaded portion of the graph shows where bus lanes diminish not only the combined total hours traveled but the hours traveled by cars as well.

Car-hours diminish in these latter cases because by enabling buses to travel faster, the bus lanes mean that the total collection of bus tours will end earlier in the rush. Thereafter, all lanes are given over for car travel, and cars no longer compete with rush-period buses for beltway capacity[2].

The findings are even more favorable to bus lanes when one considers the smoothing effect. Other illustrative analyses and other insights are offered in the full paper.

REFERENCES

(1) Basso, L. J., Guevara, C. A., Gschwender, A., & Fuster, M. (2011). Congestion pricing, transit subsidies and dedicated bus lanes: Efficient and practical solutions to congestion. *Transport Policy*, 18 (5), 676 - 684.
(2) Cassidy, M. J., Daganzo, C. F., Jang, K., & Chung, K. (2009). Spatiotemporal Effects of Segregating Different Vehicle Classes on Separate Lanes. In W. H. Lam, S. C. Wong, & H. K. Lo (Eds.), *Transportation and Traffic Flow Theory 2009: Golden Jubilee* (pp. 57-74). Springer US.
(3) Menendez, M., Daganzo, C.F., 2007. Effects of HOV lanes on freeway bottleneck. *Transportation Research Part B 41*, 809–822.
(4) Cassidy, M. J., Jang, K., & Daganzo, C. F. (2010). The smoothing effect of carpool lanes on freeway bottlenecks. *Transportation Research Part A: Policy and Practice*, 44 (2), 65 - 75.
(5) Daganzo, C. F. (1996). The Nature of Freeway Gridlock and How to Prevent It. (J.-B. Lesort, Ed.) *Proceedings of the 13th International Symposium on Transportation and Traffic Theory* , 629-646.
(6) Geroliminis, N., & Daganzo, C. F. (2007). Macroscopic Modeling of Traffic in Cities. *Transportation Research Board 86th Annual Meeting.* Washington DC.

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[2] The bus lanes are not Pareto improving in these cases because car travelers during the early part of the rush incur greater delays owing to the fewer number of beltway lanes available to them. Happily, these added delays are more than compensated by the delay savings that cars enjoy later in the rush.