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Synergies of combining demand- and supply-side measures to manage congested streets

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ABSTRACT

An agent-based, multichannel simulation of a downtown area reveals the impacts of both time-shifting traffic demand with congestion pricing, and supplying extra capacity by banning left turns. The downtown street network was idealized, and loosely resembles central Los Angeles. On the demand-side, prices were set based on time-of-day and distance traveled. On the supply side, left-turn maneuvers were prohibited at all intersections on the network.

Although both traffic management measures reduced travel costs when used alone, the left-turn ban was much less effective than pricing. When combined with pricing under congested conditions, however, the left-turn ban's effectiveness increased considerably—it more than doubled in some cases. Furthermore, the two measures combined reduced travel costs in synergistic fashion. In some cases, this synergistic effect was responsible for 30% of the cost reduction. This strong synergy suggests that turning bans should be considered as an added option when contemplating congestion pricing.

1. Introduction

Much literature exists on how to manage city-street congestion created by cars. Some measures do this by reducing or reorganizing demand for car travel. Measures of this kind include turn-taking schemes that ration capacity by partitioning cars into groups, and alternating the days when distinct groups are allowed to enter downtowns (Han et al., 2010; Liu et al., 2014; Nie and Yin, 2013; Thomson, 1967; Ayland and Emmott, 1990). Other examples include: use of traffic signals to meter cars entering downtowns (Daganzo, 2007; Hajbabaie and Benekohal, 2011; Lovell and Daganzo, 2000; Rathi, 1991), and schemes to reduce vehicle miles traveled (VMT) by inducing commuters to shift from cars to transit (Bhat, 1997; Guo and Peeta, 2020; Shin, 2020; Zhang, 2006). Congestion pricing is yet another well-known demand-side measure. It can entail tolling cars as they enter a cordoned neighborhood (de Palma and Lindsey, 2011; Eliasson et al., 2009; Meng and Liu, 2012; Zhang and Yang, 2004); or tolling each car according to the distance it travels inside that neighborhood (Daganzo and Lehe, 2015; Liu et al., 2014; Meng et al., 2012). Schemes of the latter type, called VMT-tolling in this paper, are known to be effective in managing congestion. But they, like their simpler cordon-based counterparts, impose additional costs on drivers, and can thus face public opposition (Arnott et al., 1994; Harrington et al., 2001; Hårsman and Quigley, 2010).

Other measures tackle congestion by supplying more capacity to a street network, sometimes by adding to its physical infrastructure (Fields, 2009; Henisz, 2002; Peeta et al., 2010; Sanchez-Robles, 1998), and other times by better managing that infrastructure

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(Cassidy and Rudjanakanoknad, 2005; Fajardo et al., 2011; Yang and Bell, 1997). Prohibiting disruptive turn maneuvers at intersections is a well-known supply-side measure that falls into the latter category (Gayah and Daganzo, 2012; Glass and Ni, 1992; Shin, 1997; Tang and Friedrich, 2016). It is relatively easy to deploy, but can increase a network's VMT, and may curb congestion only modestly (Levitin et al., 2009; Gayah, 2012; DePrator et al., 2017).

The present study simulates the impacts of both a demand- and a supply-side measure deployed on an idealized version of the street network in downtown Los Angeles. For the demand-side, we used the VMT-tolling strategy in Daganzo and Lehe (2015), because this scheme imposes relatively low tolls. (The scheme works by incentivizing long-distance commuters to travel during the earlier and later periods of the rush, and bear unpunctuality costs as a result.) For the supply-side, left-turns were banned at all intersections on the network.

When demands were high enough to severely congest the network, joint deployments of both measures produced synergies; i.e. travel costs saved by deploying both measures together exceeded the sum of the individual savings. These excess savings were well over 10% in half the cases tested, and approached 30% in nearly a quarter of the cases.

The matter was explored more deeply by setting demand so as to roughly emulate LA's morning congestion pattern. Under these conditions, the inclusion of turn prohibitions reduced the unpunctuality costs caused by tolling by more than 40%. Delay collectively encountered on the network fell by more than 14%. Adding turn prohibitions to tolls thus allowed commuters to arrive at their destinations closer to their desired arrival times, while wasting less time on the road.

The methods used to generate these findings are described in section 2; the findings and their explanations in section 3; and practical implications in section 4.

2. Methods

Inputs to the analyses are described in section 2.1, and the modeling approach in 2.2 and 2.3.

2.1. Experimental Set-Up

The network of major streets in downtown Los Angeles (highlighted in Fig. 1) was idealized as a homogeneous square grid of 20 N-S and 20 E-W streets with pre-timed traffic signals at every intersection. Links were 200 m in length and four lanes wide, with two lanes in each direction. All signals had a 90 s cycle and two equal phases with unprotected left turns. Effective green times were 41 s, and the lost time was 4 s per phase. Offsets were random, meaning that signals were not coordinated on the network.

Trip origins and destinations were uniformly distributed over the network. The physical length of each trip was obtained by randomly generating its origin and destination, and determining the shortest-distance path connecting that O-D pair. For baseline, do-nothing cases, average trip length turned out to be 2.9 km, with a standard deviation of 1.5 km.[1] Demand was studied parametrically, such that the fixed number of car-trips in each simulation ranged from 10,000 to 100,000. All these travelers were assumed to be captive commuters, meaning that their numbers were independent of travel conditions on the network. It was further assumed that all commuters wished to arrive at work at a common time, which was set to zero without loss of generality.

As in Vickrey (1969), penalties were imposed for exiting the network (i.e. arriving at a workplace) earlier or later than wished. Earliness and lateness penalties are denoted e and L, respectively and expressed in units of in-vehicle travel time. They describe how our commuters trade unpunctuality for travel time. (Tolls will also be expressed in units of travel time.) The penalties were set at $e = 0.5$ and $L = 2$, as suggested in Small (1982).

An agent-based model to be described in sec 2.2 relied upon network-wide relations between vehicle accumulation and average speed. Two such relations were required, to separately reflect baseline (do-nothing) conditions and supply-side changes to the network when left turns were prohibited; see Daganzo (2007). Both were estimated using the AIMSUN platform (Casas et al., 2010) to simulate network conditions under parametrically-varying demands. Twenty distinct demands were examined in this fashion, such that network conditions ranged from free-flow to gridlocked. Each demand was simulated until reaching steady state, and accumulation and speed were jointly extracted over the 60-min period that followed. Ten simulations were performed for each demand.

Curves were fit to the values thus obtained in piecewise fashion using least-squares regression. Resulting curves are shown in Fig. 2. Note the effect of turn prohibitions on the relation.

2.2. Equilibrium model

Conditions on the network were simulated using the agent-based, multichannel model in Daganzo and Lehe (2015). The model was coded in-house. It functions in iterative fashion to emulate equilibriums that might occur over the passage of days. Each iteration simulated commuter decision-making in regard to scheduling trips over a single day's morning rush. For each scenario tested, the system was simulated for many days until an approximate equilibrium was reached and maintained for an extended period. The results were then recorded. Details follow.

The network's time-varying travel conditions were estimated during each rush by stepping through time in 1-min increments. Each minute, the number of vehicles with entry times that had already occurred, but that still remained on the network (i.e. the

[1] When left turns were prohibited, average trip length increased to 3.4 km, again with a standard deviation of 1.5 km.

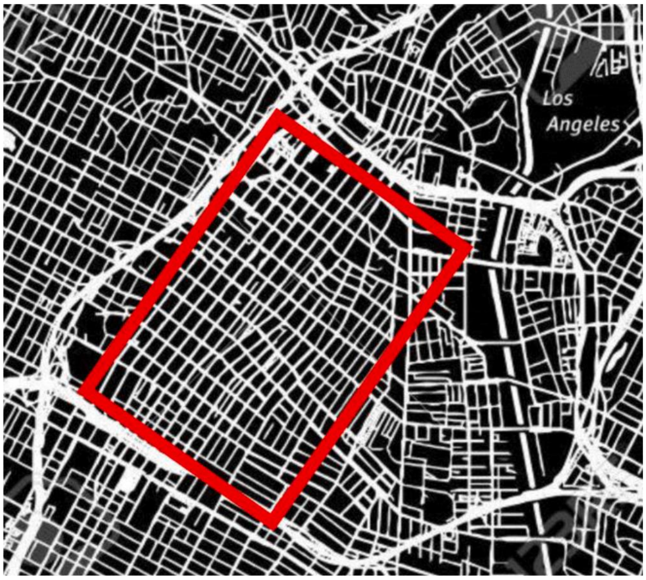

Fig. 1. Street map of downtown Los Angeles. Study site is an idealization of area enclosed in box.

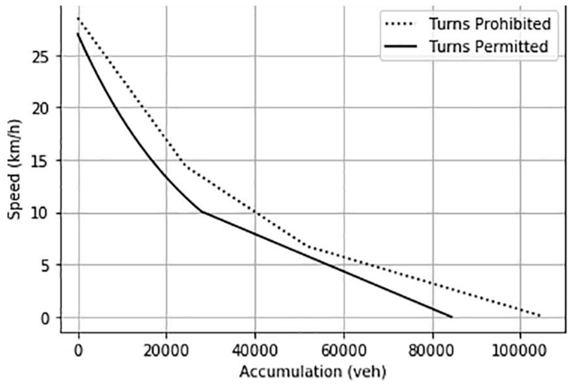

Fig. 2. Speed-Accumulation relations for the network with and without left-turn prohibitions.

accumulation) was determined. This accumulation dictated the network's average speed during that minute, as per the relations in Fig. 2. This, in turn, determined the distance traveled by each accumulated vehicle over the minute. A vehicle arrived at its destination upon reaching the travel distance assigned to it from the beginning, and was thereupon removed from the network.

The resulting travel cost to each i^{th} commuter, C_i , was then evaluated. It was expressed in units of time, and is the sum of i's time spent traveling on the network, and the penalties incurred, P_i. The latter include an unpunctuality penalty for arriving early or late to work, plus a monetary penalty due to the toll. All these values were dynamic and depended upon entry and exit times. The formulas are given in the next section.

Once all simulated trips during a rush were completed and all C_i determined, a random sample of 10% of the commuters was assumed to evaluate their C_i vis-a-vis those of other entry times. The sampled commuters shifted their entry times on the following day to the best times possible for each. The simulation was then repeated for the next day; and for ensuing days in this iterative fashion until reaching a quasi-equilibrium in which similar conditions persisted on the network for 100 days or more thereafter.[2]

2.3. Cost formulas

Formulas for C_i are given below. The section can be skipped without loss of continuity.

Let $t_{e,i}$ and $t_{a,i}$ be the exit and entry times of commuter i. Then, the commuter's in-vehicle travel time is $(t_{e,i} - t_{a,i})$, and the schedule penalty is max{$-et_{e,i}$, $Lt_{e,i}$ }. If τ_i denotes the toll paid (in units of in-vehicle time), the commuter's total cost becomes:

[2] Those scenarios that did not result in gridlock were found to reach a quasi-equilibrium state within roughly 50 days.

$$C_i = t_{e,i} - t_{a,i} + \tau_i + \max\{-et_{e,i}, Lt_{e,i}\}.$$

The toll, τ_i, also depends dynamically on $t_{e,i}$ in the way described in Daganzo and Lehe (2015). The formula for the toll is given below. It allows a commuter to arrive at work close to the ideal time by paying a higher toll, or paying less by arriving further from the ideal. The formula is:

$$\tau_i = \max\left\{\frac{eW_i}{(e+L)V_r} - \max\{-et_{e,i}, Lt_{e,i}\}, 0\right\},$$

where W_i and V_r are known constants. The former is the cumulative distance collectively traveled by all vehicles with trip distances less than that of commuter *i*. It is calculated by sorting all trips by their physical lengths, and summing the values that are less than that of *i*. The V_r is the maximum rate at which the network processes vehicle-miles. It can be calculated by finding the maximum product of accumulation and the corresponding speed given by Fig. 2; see Daganzo and Lehe (2015) for further explanation.

3. Findings

The morning commute was modeled under four control measures: (i) a baseline, do-nothing case; (ii) a global left-turn ban; (iii) the tolling scheme just described; and (iv) measures (ii) and (iii) together. Synergies are unveiled in sec. 3.1 by varying demand parametrically and observing the resulting total travel costs in each scenario. Causal mechanisms are uncovered in sec. 3.2 by examining the components of total cost under conditions roughly akin to those in downtown Los Angeles.

3.1. Parametric analysis

Total costs of travel are presented for each scenario in Fig. 3 as functions of demand.[3] Demand for car-trips were varied from 10,000 to 100,000 in increments of 10,000. Each data point was obtained by averaging outcomes across 25 separate equilibrium analyses of the kind described in sec. 2.2. Each of these analyses entailed a distict set of commuters with a distict set of origins and destinations. The upward-bending trend in each curve reveals that marginal costs increase with increasing demand.

The figure's bold, solid curve shows that travel costs are virtually always highest by doing nothing. The bold, dotted curve unveils how turn prohibitions (alone) tended to produce only modest cost savings, even when demands were high and the network was congested. The light, solid curve shows that substantially greater savings came via sole deployment of congestion tolling once demand reached about 50,000 car-trips, an amount that severely congested the network and dropped speeds to as low as 9 Km/h. Not surprisingly perhaps, the light, dotted curve shows that cost savings were greatest when the two measures were implemented jointly.

Further note from Fig. 3 that the vertical displacements between the light, solid curve and the light, dotted one are appreciably larger than the displacements between the two remaining (dark) curves. Consideration shows that these pairwise features of the curves unveil the synergies at play when the demand- and supply-side measures were deployed in combination. The differences in vertical displacements were more than double for demands in the range of 70,000 to 90,000. Thus we see that, for this range of demands, the effectiveness of turn prohibitions more than doubled when deployed in combination with tolling.

These synergies are made more evident in Fig. 4. Its curves display the percent differences in travel costs incurred relative to baseline, do-nothing cases. Note that the figure provides: two curves that reflect separate deployments of each measure; a third curve that sums the two; and a fourth curve reflecting joint deployments of both measures combined. Visual inspection shows that for demands greater than about 50,000 car-trips, the travel costs saved by combining both measures exceed the savings summed across the separate deployments of each; i.e. the whole is greater than the sum of its parts. Note how the synergy was highest for a demand of roughly 70,000. In that case, the synergistic gain over the sum of separate deployments is 30%. This synergy and the turn prohibition were responsible for a 60% increase in benefits as compared to tolling (alone).

3.2. Case study

We next explore the mechanisms that gave rise to the above findings. To add a touch of realism, the network was loaded with a demand of 100,000 car-trips. This produced congestion that persisted on the network for nearly 2 h, which is roughly commensurate with what occurs each weekday morning in downtown Los Angeles (Burger and Kaffine, 2009).

The bar graph in Fig. 5 presents cost components for: the baseline, do-nothing case; separate deployments of each measure; and joint deployment of both.[4] Note how in this realistic case the best result was still obtained when combining both measures. Also note from the cost reductions relative to the baseline that there continued to be significant synergies. These reductions were: 1,410 hrs for turn prohibitions alone; 8,510 hrs for pricing alone; and 10,955 hrs for the deployment of both measures combined. The rest of this section examines how the various components of generalized cost varied across strategies.

We start with turn prohibitions. These caused speeds to increase on the network, as previously shown in Fig. 2. The network's free-flow speed rose from 27 Km/h for the baseline case, to 28.5 Km/h under the turn ban. Average trip distance also rose, however, by 16%. The net effect of these two changes: free-flow travel time on the network grew by 1000 h. This was treated as an increase in delay.

[3] Total costs to commuters entail only travel time, unpunctuality penalties and tolls, as per sec. 2.3.
[4] Average cost per user can be obtained by dividing total costs in Fig. 5 by the demand (100,000 car trips).

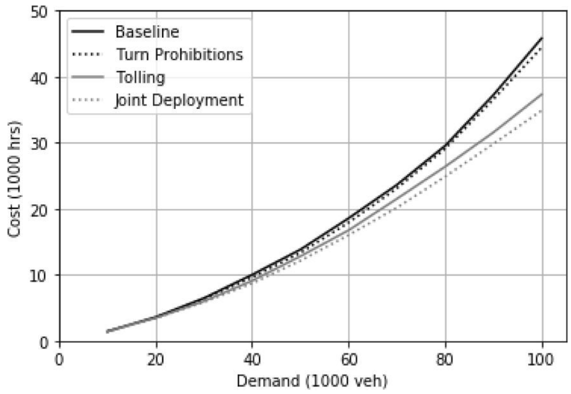

Fig. 3. Total travel costs as functions of demand.

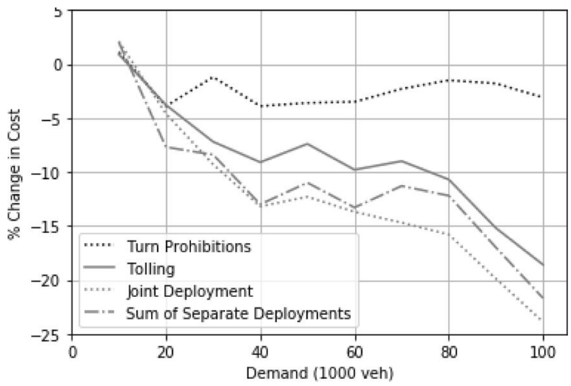

Fig. 4. Costs saved relative to baseline.

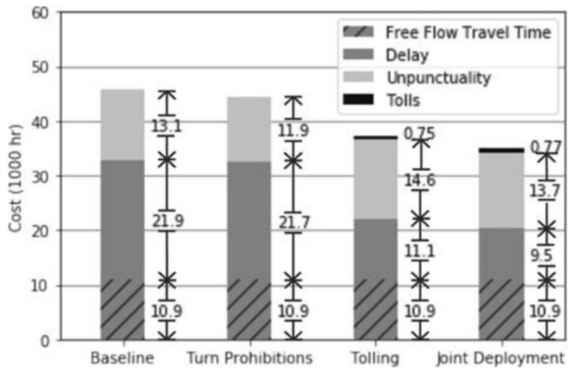

Fig. 5. Cost breakdowns under four scenarios.

Nevertheless, the higher speeds achieved under the turn ban had the net effect of diminishing network-wide delay by a modest 200 h. Moreover, the lowest speed measured over the network rose from 5.4 Km/h for the baseline, to 6 Km/h with turn prohibitions.

The higher speeds motivated commuters to schedule trips closer to workplace start time. This had the perverse effect of raising network accumulations, which drove down speeds; along with the favorable effect of lowering unpunctuality costs, which fell by roughly 1,200 h from the baseline.

For its part, tolling alone reduced baseline total cost by a more substantial 8,510 h. This came via a reduction in delay of 49.5% (10,740 h), coupled with a partially-offsetting rise in unpunctuality cost (of 1,480 h) and the initiation of tolls (collectively equivalent to 750 h). All this because tolling brought about the pattern of trip scheduling shown by the dark-shaded data in Fig. 6. These collectively denote each commuter's toll-induced equilibrium values of workplace arrival time and trip distance in a single rush. Note from Fig. 6 how long-distance trips occurred further from the work start time than did short-distance trips. The rearrangement of trips caused the lowest-measured speed on the network to rise from the baseline rate of 5.4 Km/h to 8.5 Km/h. Unpunctuality rose by 20% for commuters with trip distances greater than the mean; and dropped for commuters with shorter trip distances. Though both long- and short-distance commuters saw reductions in total cost, the reductions were greater for those with shorter trips.

Returning to the bar chart in Fig. 5, we turn attention to the joint deployment of both measures. Total travel cost in this case fell by 10,955 h from the baseline, an additional cost savings of 29%, compared to what was achieved by tolling alone. The sum of the total cost reductions separately achieved from each measure (1,410 h + 8,510 h) can account for 9,920 h of this drop. The remaining savings of 1,035 h (10%) is the synergistic effect of combining the two measures together.

This synergy was manifest as a reduction in baseline delay. It fell by approx. 12,400 h (56.4%). The value exceeds the sum of the delay reductions separately achieved from each measure (200 h + 10,800 h) by 1,400 h. This extra savings was partially offset by tolling and unpunctuality costs associated with joint deployment. Additionally, the lowest speed measured over the network rose to 11.3 Km/h, an increase greater than the sum of those achieved by each measure separately (0.6 Km/h + 3.1 Km/h = 3.7 Km/h).

Inspection of the two right-most bars in Fig. 5 reveals how joint deployment of both measures changed things relative to tolling alone. On the downside, tolls slightly increased (collectively by an equivalent of just 20 h) when accompanied by turn prohibitions. The rise is so small as to be barely visible in the figure, and tolls still only comprised about 3% of total travel cost. The small rise occurred because joint deployment of both measures motivated commuters to schedule trips closer to their work start time; refer again to Fig. 6 and compare its lightly-shaded data (for joint deployment) with the dark-shaded data (for tolling alone). On the upside, Fig. 5 reveals that delay under joint deployment diminished by 1,600 h relative to tolling alone, a reduction of more than 14%. Unpunctuality fell by 900 h, a reduction of just over 6%. This reduction offset the increase in unpunctuality due to tolling by more than 40%. These favorable outcomes were again due to the change in trip scheduling noted above with the aid of Fig. 6.

Finally, we note that the average times when commuters departed from home varied little across cases. For example, joint deployment of both measures enabled commuters to leave their homes later than did tolling alone. Yet, the average difference was little more than 1 min in duration, and likely too small to be noticed by most commuters.

4. Conclusions

Idealizations of the street network in downtown Los Angeles were used to explore impacts of demand- and supply-side measures for congestion management. Analyses confirm that either measure deployed on its own can produce favorable outcomes.

By supplying added capacity to the network, left-turn prohibitions favorably altered network-wide traffic relations, as shown in Fig. 2. This raised vehicle speeds. Total travel costs on the network diminished as a result, albeit modestly.

By managing demand, the VMT-tolling scheme of Daganzo and Lehe (2015) reduced total costs more substantially. It incentivized commuters to adjust their travel schedules in ways that diminished the network's vehicle accumulation during the heart of the rush.

By applying both measures together, savings increased; see Figs. 3, 4 and 5. This is not surprising, because the supply-side measure favorably changed the shape of a network-wide traffic relation in Fig. 2, and the demand-side measure shifted the network's traffic states to more favorable positions along the relation. More importantly for policy development is the finding that combined use of both measures produced synergies as high as 30%.

Despite these overall improvements, both measures impact some commuter metrics unfavorably. Turn prohibitions can add to trip distances, and thus to network VMT. The effect was small in this instance, however. The negative effects of tolling were greater. For the strategy studied here, the problem was less the (relatively low) tolls themselves, than the unpunctuality penalties from arriving earlier or later at work. These penalties increase disproportionately for commuters with longer distance trips. This might cause some public opposition, despite tolling's effectiveness in curbing congestion and reducing total costs.[5]

This is one reason why the synergies found in this study could be important. By contributing to the reduction in travel costs by as much as 30%, the synergies could make tolling more acceptable to the public. Improved acceptance could be good news for cities that are presently strangled by congestion and its externalities.

Notwithstanding our efforts to infuse a real-world flavor of downtown Los Angeles, the present analyses are idealized, both in terms of driver behavior and network structure. However, these idealizations may actually *diminish* the beneficial effects of our measures, rather than exaggerate them. For example, drivers' real-world tendencies to adaptively route themselves around congestion can lessen the negative impacts of turn prohibitions on trip distances. This could give a modest boost to the synergistic effects presently observed. We also suspect that synergies are more likely to occur under OD patterns that are typical of mono- or multi-centric cities with varying worktimes, as opposed to the spatially-uniform patterns and common worktime studied here.

The above matters should be explored further. Future work should also consider the synergies of turn bans with more commonly used tolling schemes such as cordon pricing. While cordon pricing does not rearrange trips in the same way that VMT-based pricing does, our preliminary studies find that synergies also arise in this case, once certain congestion thresholds are reached.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[5] Opposition to cordon-based tolling schemes might be even greater, owing to the higher tolls that these simpler schemes tend to levy.

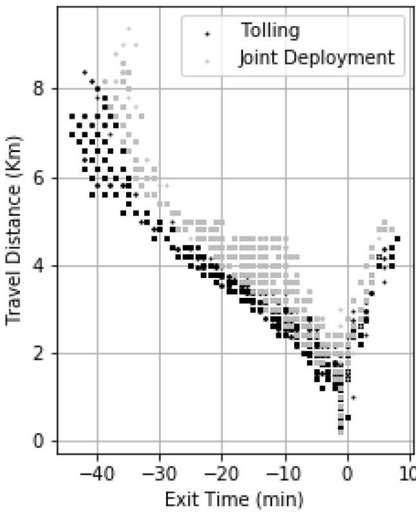

Fig. 6. Workplace arrival times and trip distances.

Acknowledgements

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