RESEARCH REPORT

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Synergies of Combining Demand- and Supply-Side Measures to Manage Congested Streets

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August 2021

Berkeley Institute of
Transportation Studies

Report No.: : UC-ITS-2020-28 | DOI: 10.7922/G2ZP44DF

Technical Report Documentation Page

1. Report No.
UC-ITS-2020-28

2. Government Accession No.
N/A

3. Recipient's Catalog No.
N/A

4. Title and Subtitle
Synergies of Combining Demand- and Supply-Side Measures to Manage Congested Streets

5. Report Date
August 2021

6. Performing Organization Code
ITS Berkeley

7. Author(s)
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8. Performing Organization Report No.
N/A

9. Performing Organization Name and Address
Institute of Transportation Studies, Berkeley
109 McLaughlin Hall, MC1720
Berkeley, CA 94720-1720

10. Work Unit No.
N/A

11. Contract or Grant No.
UC-ITS-2020-28

12. Sponsoring Agency Name and Address
The University of California Institute of Transportation Studies
www.ucits.org

13. Type of Report and Period Covered
Final Report (July 2019 – February 2021)

14. Sponsoring Agency Code
UC ITS

15. Supplementary Notes
DOI:10.7922/G2ZP44DF

This project was delivered in partnership with the National Institute for Congestion Reduction.

16. Abstract
An agent-based, multichannel simulation of a downtown area reveals the impacts of both redistributing traffic demand with time-dependent 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.

17. Key Words
Traffic congestion, congestion pricing, demand, left turns, travel costs, traffic management, traffic simulation

18. Distribution Statement
No restrictions.

19. Security Classification (of this report)
Unclassified

20. Security Classification (of this page)
Unclassified

21. No. of Pages
23

21. Price
N/A

Form Dot F 1700.7 (8-72)

Reproduction of completed page authorized

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Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project. This project was delivered in partnership with the National Institute for Congestion Reduction at the University of South Florida (nicr.usf.edu).

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Executive Summary

This study developed agent-based simulations of traffic flow in an urban network resembling downtown Los Angeles to explore synergies when congestion pricing and left-turn prohibitions are jointly deployed. Traffic was simulated for different scenarios representing a morning commute, each with a fixed number of travelers and a given traffic management strategy. In each simulation, travelers choose when to depart their homes in order to minimize the combination of unpunctuality at work and in-vehicle delay due to congestion. Our performance metric was the sum of these two costs across all travelers.

In our simulations, the total travel cost saved by joint deployment of the two management strategies often considerably exceeded the sum of what each strategy saved without the other — by about 30 percent of the total in the most extreme cases. Both the unpunctuality and in-vehicle-delay components of cost improved. These synergies arise because our two strategies combined influence in a good way both, the demand- and supply-sides of network performance, which are mutually reinforcing phenomena. Although more research is needed, our findings suggest that turn prohibitions should be considered as an added option when contemplating congestion pricing.

Contents

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 (e.g. Thomson (1967), Ayland and Emmott (1990), Han et al. (2010), Nie and Yin (2013);, Liu et al. (2014). Other examples include: use of traffic signals to meter cars entering downtowns (e.g. Rathi, 1991; Lovell and Daganzo, 2000; Daganzo 2007; Hajbabaie and Benekohal, 2011)). and schemes to reduce vehicle miles traveled (VMT) by inducing commuters to shift from cars to transit (e.g. Bhat, 1997; Zhang, 2006; Guo and Peeta, 2020; Shin, 2020)). Congestion pricing is yet another well-known demand-side measure. This can entail tolling cars as they enter a cordoned neighborhood (e.g. Zhang and Yang, 2004; Eliasson et al., 2009; de Palma and Lindsey, 2011; Meng and Liu, 2012)); or tolling each car according to the distance it travels inside that neighborhood (e.g. Meng et al., 2012; Liu et al.,2014; Daganzo and Lehe, 2015). 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 monetary costs on drivers, and can thus face public opposition ; e.g. 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 (e.g. Sanchez-Robles, 1998; Henisz, 2002; Fields et al., 2009; Peeta et al., 2010)), and at other times by better managing that infrastructure ; e.g.(Yang and Bell (1997), Cassidy and Rudjanakanoknad (2005), Fajardo et al. (2011). Prohibiting disruptive turn maneuvers at intersections is another well-known supply-side measure that falls into the latter category ; e.g.(Shin (1997); Glass and Ni (1992), Gayah and Daganzo (2012);, 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 measures 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 travel demand was high enough to severely congest the network, joint deployment 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 percent in half the cases tested, and approached 30 percent 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 percent. Delay collectively encountered on the network fell by more than 14 percent. Thus, adding turn prohibitions to tolls allowed commuters to arrive at their destinations closer to their desired arrival times, while wasting less time on the road.

The following sections describe the methods used to generate these findings, the findings, their explanations and some practical implications.

Methods

Inputs to the analyses and the modeling approach are described in the following subsections.

Experimental Set-Up

The network of major streets in downtown Los Angeles (highlighted in Figure 1) was idealized as a homogeneous square grid of 20 North-South and 20 East-West streets with pre-timed traffic signals at every intersection. Links were 200m in length and four lanes wide — with two lanes in each direction. All signals had a 90 second cycle with two equal phases and unprotected left turns. Effective green times were 43 seconds, and the lost time was four seconds per cycle.

For each simulation, trip origins and destinations were uniformly distributed over the network. The physical length of each trip was determined by randomly generating its origin and destination, and determining the shortest-distance path connecting that O-D pair. For the baseline case (no actions taken), the 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 from10,000 to 100,000 vehicle trips. 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 shorter travel time. Tolls will also be expressed in units of travel time, so the tradeoffs can be compared. The penalties were set at $e = 0.5$ and $L = 2$, as suggested in Small (1982).

Analyses were performed using AIMSUM simulations (Casas et al. 2010), with logic to be described in the next section. The simulations relied upon experimentally-determined network-wide relations between vehicle accumulation and average speed. Not surprisingly, these relations were affected by supply-side changes to the network (Daganzo, 2007), and turned out to be different when left-turns were prohibited or permitted.

The two relations were estimated in the following parametric fashion. The network was simulated for a distinct demand level until a steady-state condition was reached and maintained for at least 60 mins. Simulations at the specified demand were repeated several times; and the process was performed for a full range of demands.

The average network accumulations and speeds obtained for each demand level were then plotted on an accumulation vs speed chart. Figure 2 shows the results. Note how turn prohibitions raise average speeds.

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

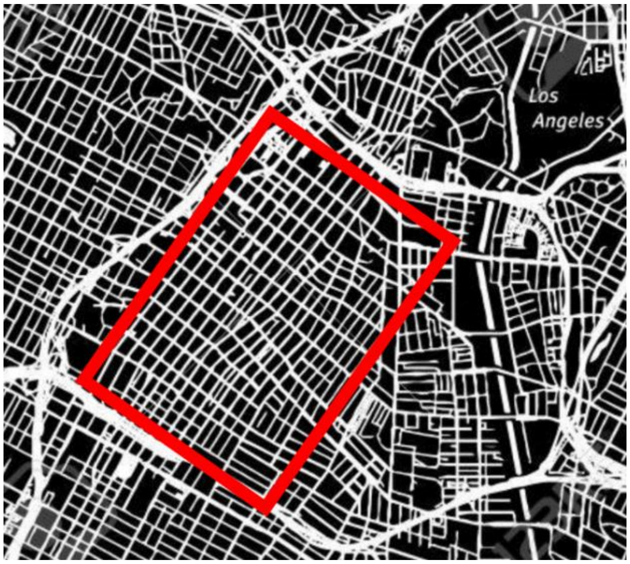

Figure 1. Street map of downtown Los Angeles. Study site is an idealization of area enclosed in box.

Equilibrium Model

The above inputs were simulated using the agent-based, multichannel model in Daganzo and Lehe (2015). 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.

The network's time-varying travel conditions were estimated during each rush by stepping through time in 1-min increments. For each minute, the number of vehicles with entry times that had already occurred, but that still remained on the network (i.e. the accumulation) was determined. This accumulation dictated the network's average speed during that minute, as per the relations in Figure 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 ith commuter, Ci, was then evaluated . It was expressed in units of time. It is the sum of i's time spent traveling on the network, and the penalties incurred, Pi. 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 the cost, Ci, was determined, a small random sample of commuters was assumed to evaluate their Ci 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 with similar traffic performance over many days.

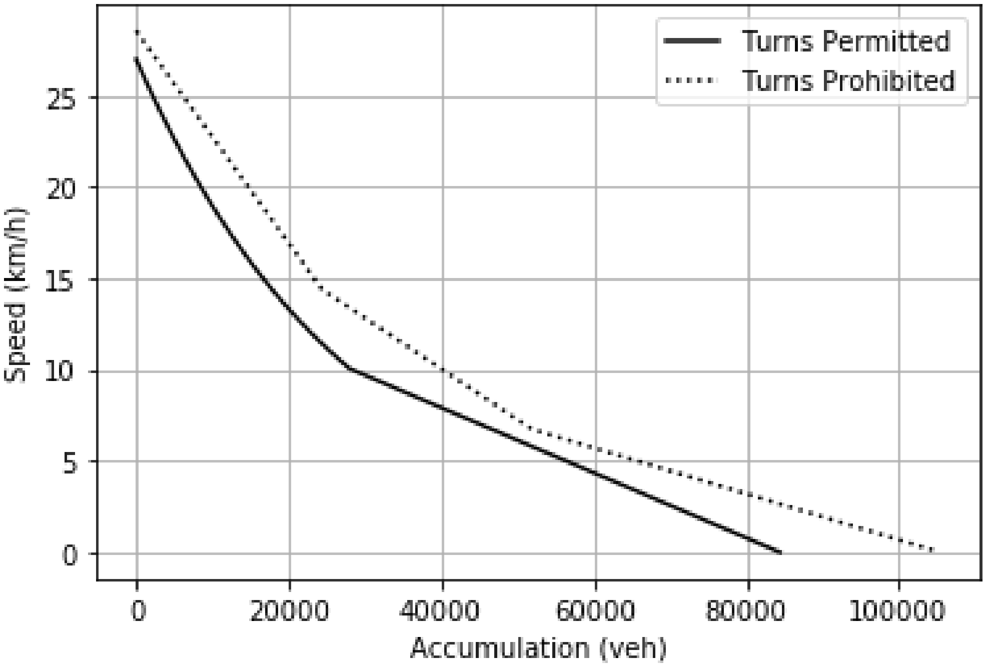

Figure 2. Speed-Accumulation relations for the network with and without left-turn prohibitions

Cost Formulas

Here the formulas for (Ci) are given. The section can be skipped without loss of continuity.

Let te,i and ta,i be the exit and entry times of commuter i. Then, the commuter's in-vehicle travel time is (te,i – ta,i), and the schedule penalty is max{-ete,i , Lte,i }. Furthermore, if τi denotes the toll paid (in units of in-vehicle time), the commuter's total cost becomes:

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

The toll τi also depends dynamically on te,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 Wi and Vr 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 Wi 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 Figure 2; see Daganzo and Lehe (2015) for further explanation.

Findings

The morning commute was modeled under four control measures: (i) a baseline (no actions taken); (ii) a global left-turn ban; (iii) the tolling scheme just described; and (iv) measures (ii) and (iii) together. Synergies were observed by varying demand parametrically and studying the resulting total travel costs in each scenario. Causal mechanisms are also uncovered by examining the components of total cost under conditions roughly akin to those in downtown Los Angeles.

Parametric Analysis

Total costs of travel measured as added hours of travel are presented for each scenario in Figure 3 as functions of demand. Demand for car-trips varied in increments of 10,000. Each data point was obtained by averaging outcomes across 25 separate equilibrium analyses of the kind previously described. 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 from sole deployment of tolling once demand reached about 50,000 car-trips, an amount that severely congested the network. Not surprisingly perhaps, the light, dotted curve shows that cost savings were greatest when the two measures were implemented jointly.

Further note from Figure 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 Figure 4. Its curves display the percent differences in travel costs 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 vehicles. In that case, the synergistic gain over the sum of separate deployments is 30 percent. This synergy and the turn prohibition were responsible for a 60 percent increase in benefits as compared to tolling alone.

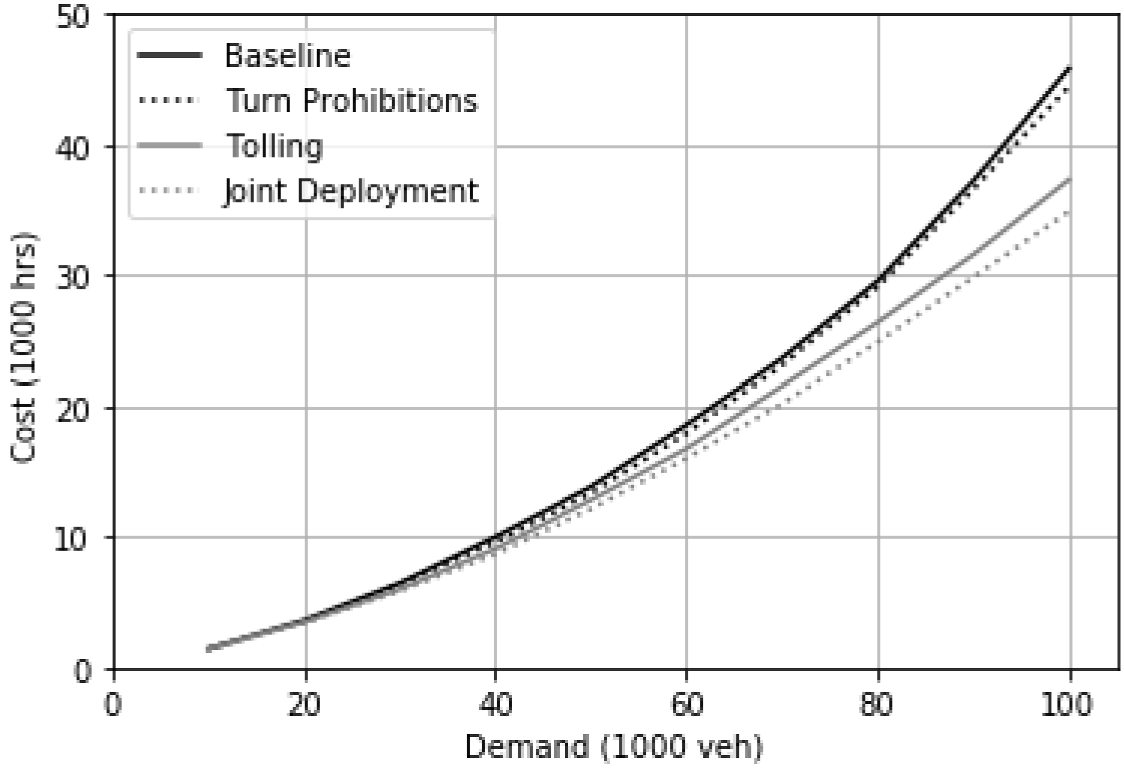

Figure 3. Total travel costs as functions of demand

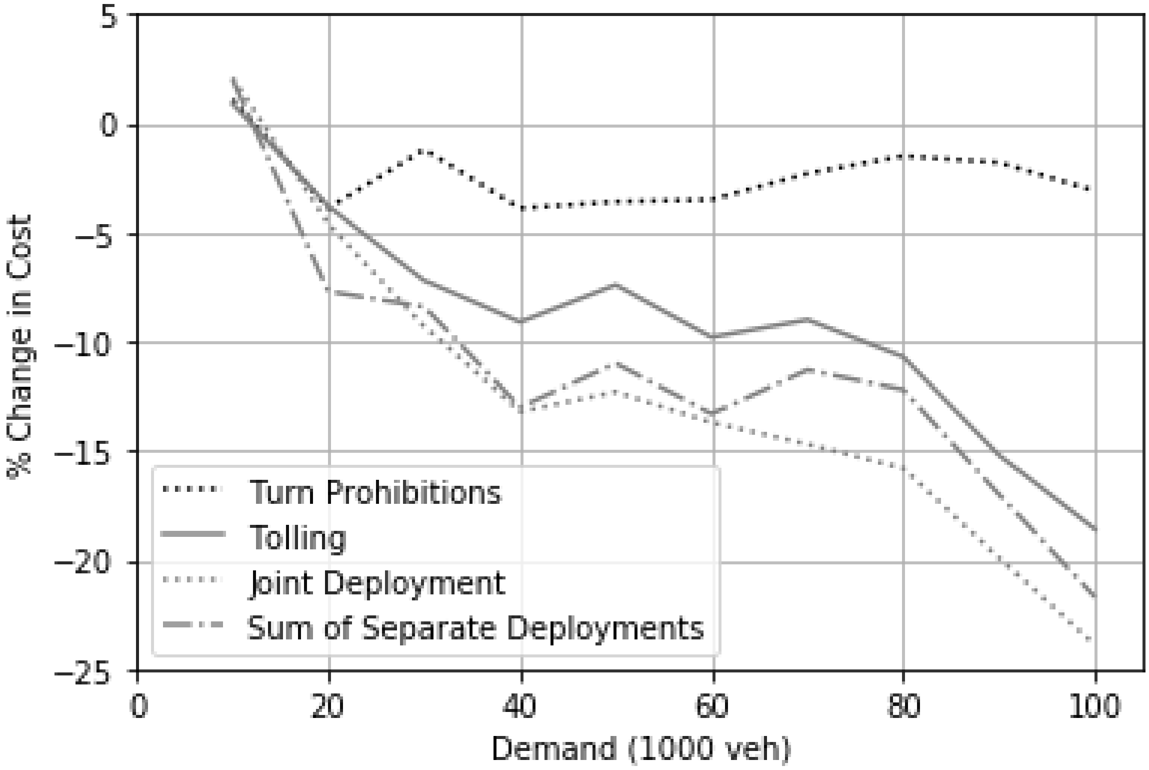

Figure 4. Costs saved relative to baseline

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.[2] This produced congestion that persisted on the network for nearly 2 hours, which is roughly commensurate with what occurs each weekday morning in downtown Los Angeles (Burger and Kaffine, 2009).

The bar graph in Figure 5 presents cost components for: the baseline, do-nothing case; separate deployments of each measure; and joint deployment of both. 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 hours for turn prohibitions alone; 8,510 hours for pricing alone; and 10,955 hours for the deployment of both measures combined. The rest of this section examines how the various components of generalized cost varied across strategies.

The 1,410-hour reduction in baseline total cost due to turn prohibitions alone was relatively small, a drop of just 3 percent. This was due in small part to modest savings (about 200 hours) in delay brought by higher speeds; see again Figure 2. The benefit was partially offset by longer trip distances, however.[3] The higher speeds, moreover, 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 hours from the baseline.

Tolling alone reduced baseline total cost by a more substantial 8,510 hours. This came throuh a reduction in delay of 49.5 percent (10,740 hours), coupled with a partially offsetting rise in unpunctuality cost (of 1,480 hours) and the initiation of tolls (collectively equivalent to 750 hours). All this is because tolling brought about the pattern of trip scheduling shown by the dark-shaded data in Figure 6. These collectively denote each commuter's toll-induced equilibrium values of workplace arrival time and trip distance in a single rush. Note how long-distance trips occurred further from the assumed work start time than did short-distance trips.

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

This synergy was manifest as a reduction in baseline delay. It fell by approximately 12,400 hours (56.4 percent). The value exceeds the sum of the delay reductions separately achieved from each measure (200 hours + 10,800 hours) by 1,400 hours. This extra savings was partially offset by tolling and unpunctuality costs associated with joint deployment.

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[2] Average cost per user can be obtained by dividing total costs in Figure 5 by the demand (100,000 car trips).

[3] These grew by 16 percent on average. Added trip times created by these longer trip distances are accounted for in the delays shown in Figure 5.

Inspection of the two right-most bars in Figure 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 20h) when accompanied by turn prohibitions. The rise is so small as to be barely visible in the figure, and tolls still only comprise about 3 percent 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 Figure 6 and compare its lightly-shaded data (for joint deployment) with the dark-shaded data (for tolling alone). On the upside, Figure 5 reveals that delay under joint deployment diminished by 1,600h relative to tolling alone, a reduction of more than 14%. Unpunctuality fell by 900 hours, a reduction of just over 6 percent. 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 Figure 6.

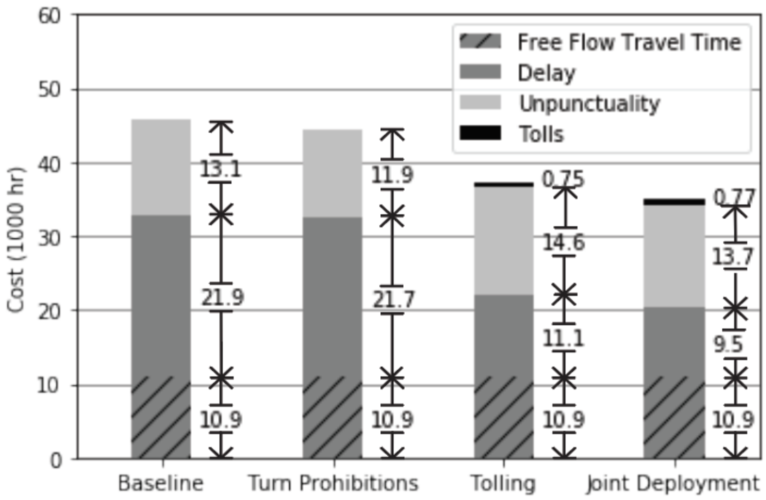

Figure 5. Cost breakdowns under four scenarios

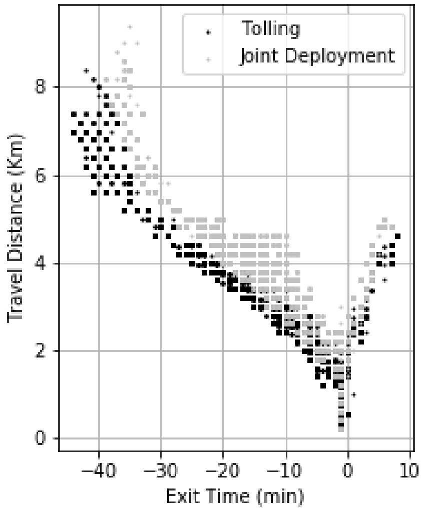

Figure 6. Workplace arrival and trip distances

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 one minute in duration, and likely too small to be noticed by most commuters.

Conclusions

Idealizations of the street network in downtown Los Angeles were used to explore the impacts of using 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 Figure 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 created an incentive for commuters to adjust their travel schedules in ways that diminished the total number of vehicles on the network during the heart of the rush.

By applying both measures together, savings increased as shown in Figures 3, 4 and 5. This is not surprising, because the supply-side measure favorably changed the shape of a network-wide traffic relation; 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 percent.

Despite these overall improvements, both measures impact some commuter metrics unfavorably. Turn prohibitions can add to trip distances, and thus increase overall network VMT. But the effect was small in this instance. 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 might engender public opposition to tolling, despite its effectiveness in curbing congestion.[4]

This is one of the reasons why the synergies found in this study could be important. That effect accounted for as much as 30 percent savings in travel cost. 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. These idealizations regarding driver behavior and network structure may, however, actually diminish the actual 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. Our preliminary studies find that synergies also arise in this case.

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

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