THEMA Working Paper n°2021-09
CY Cergy Paris Université, France

TRAFFIC CONGESTION CONTROL: TRADABLE PERMITS vs ROAD TOLLS

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March 2021

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Key Words: Congestion tolls; permits, departure time, uncertainly, network, second-best
JEL Codes : D62 ; R41 ; R48

Introduction

Traffic congestion is growing in many large cities around the world. In addition to its economic impacts caused by travel delay and higher fuel consumption, traffic congestion increases emissions of toxic pollutants that have significant negative environmental and health impacts. Traffic congestion is at its worst during peak hours, and its repercussions are intensified when road capacities are reduced due to temporary conditions such as bad weather, accidents, road repairs and other supply and demand shocks.

Traffic congestion can be alleviated by restricting vehicle access to certain areas, imposing road tolls, expanding or subsidizing public transportation, and other methods. Here, we focus on congestion pricing and tradable permits. Congestion pricing (CP), which is a specific form of road tolling, has been widely studied as one of the most efficient means of mitigating traffic congestion. Early proposals include [1], [2] and [3]. By charging fees on certain roads, CP encourages individuals to make more socially efficient decisions. CP has been implemented in Singapore, London, Stockholm, Milan, and Gothenburg as a way to discourage driving downtown during peak-hours. It has also been proposed for Lyon, Hong Kong and many other cities, but was rejected due to privacy concerns and lack of public acceptance. CP still remains quite limited in practice.

Tradable permits (TP) are another, quantity-based, demand management tool. A predetermined number of driving permits are distributed among a selected group of travelers, and only travelers with a permit can access specific road links. Permits can be freely traded, thereby allowing the price to be determined in a market. Although TP have been implemented in air transport to manage take-off and landing slots in so-called coordinated airports, they have never been used to control traffic congestion on roads. TP have the

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advantage of being revenue neutral if permits are distributed free. Travelers in aggregate then do not incur a net out-of-pocket cost, which is likely to enhance public acceptability.

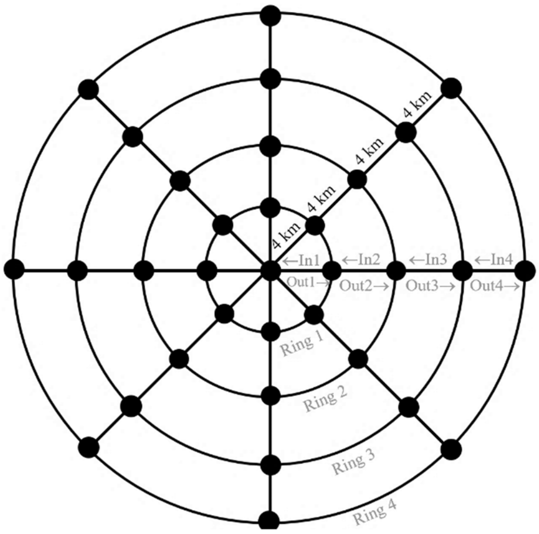
Beginning with the seminal work of Weitzman [4], a number of theoretical papers have studied the choice between price and quantity controls to internalize environmental externalities. The two instruments can be designed so that they are equally efficient under stationary conditions, but not if the benefits and costs are uncertain, and neither prices (e.g., taxes) nor permit quantities can be varied for legal, technical or other reasons. This lack of equivalence also applies when congestion, rather than pollution, is the externality. For instance, [5] and [6] study the performance of the two instruments and show that each instrument can be more or less efficient depending on the benefit and cost fluctuations, and the shape of the cost function.

In this work, we study the performance of CP and TP in controlling traffic congestion during a morning peak travel period on a stylized urban road network. We apply the dynamic traffic network simulator Metropolis in which travelers make mode, departure time and route choice decisions. We investigate the aggregate impacts of the two instruments on traffic flows and welfare as well as the welfare-distributional consequences on individual travelers. Finally, we compare the performance of the two instruments when the regulations are not adaptive to capacity shocks.

The model

We consider the circular city network shown in Figure 1. This network was used in [7], [8] and [9] to study and compare the efficiency of various road-pricing schemes such as flat and time-varying tolls. The network consists of 33 nodes (i.e., intersections) connected by four concentric bidirectional ring roads (Rings 1-4) and eight bidirectional arterial roads.

Figure 1 Circular City Network



Ring roads are spaced 4 km apart, and arterial roads are uniformly oriented around the compass. The links of the arterial roads are labeled as shown in Figure 1. All arterial links are 4 km long; hence ring roads are multiples of 8π km in length. The number of lanes, the flow capacity of each lane (vehicles per lane per hour), and the free-flow speed (kilometers per hour) of the links are listed in Table 1.

Table 1 Road Link Characteristics

	No. of Lanes	**Flow Capacity (Veh. per Lane/hr)**	**Free-flow Speed (km/hr)**
In1, Out 1	1	3,000	50
In 2-4, Out 2-4	2	2,000	70
Ring Roads	1	2,000	50

Trip origins (homes) and destinations (workplaces) are located at zones connected to the nodes by congestion-free connecting links. Each of the 33 zones is the origin for 8,000 travelers, for a total of 264,000 travelers. The number of trips between each pair of zones is an exponentially decreasing function of the free-flow auto travel time between the zones.

Public transit operates congestion-free on a dedicated right of way at a constant speed of 40 km/h. Road links are subject to traffic congestion which takes the form of vertical queuing at a bottleneck at the downstream end of a link. If the arrival rate of vehicles at the bottleneck exceeds the link's flow capacity, vehicles accumulate in a queue without extending "horizontally" upstream on the link so that congestion does not spill back and block upstream nodes. Travelers encounter a delay equal to the number of vehicles in the queue when they arrive, divided by the link's capacity. If the arrival rate of the vehicles is below capacity, no queue develops, and vehicles travel at the free-flow speed.

In Metropolis, travelers differ in their desired arrival times, as well as their idiosyncratic preferences for mode and departure time. Individual daily travel decisions are described by a nested logit model. Travelers first make a binary choice of mode between driving and taking public transit. Those who choose to drive then decide on their departure time according to a continuous logit model, and then a route that minimizes their expected travel time. Depending on information that may become available, travelers may revise their choice of route when they reach an intersection.

Each traveler is described by a set of parameters:

- t^*: desired time of arrival
- δ: on-time window, the permissible amount of deviation from t^* without a penalty
- α: value of time spent driving
- β: penalty incurred per unit of time for early arrival
- γ: penalty incurred per unit of time for late arrival
- α^{PT}: value of time spent in public transit
- P^{PT}: fixed penalty associated with public transit

The cost of riding public transit for an origin-destination pair (o, d) is

$$C^{PT}(o,d) = \alpha^{PT} \cdot tt^{PT}(o,d) + P^{PT},$$

where $tt^{PT}(o,d)$ is the in-vehicle travel time. The cost of an auto trip when the driver departs at time t is

$$C(t) = \alpha \cdot tt(t) + \beta \cdot \left[\left(t^* - \frac{\delta}{2}\right) - \left(t + tt(t)\right)\right]^+ + \gamma \cdot \left[\left(t + tt(t)\right) - \left(t^* + \frac{\delta}{2}\right)\right]^+ + q,$$

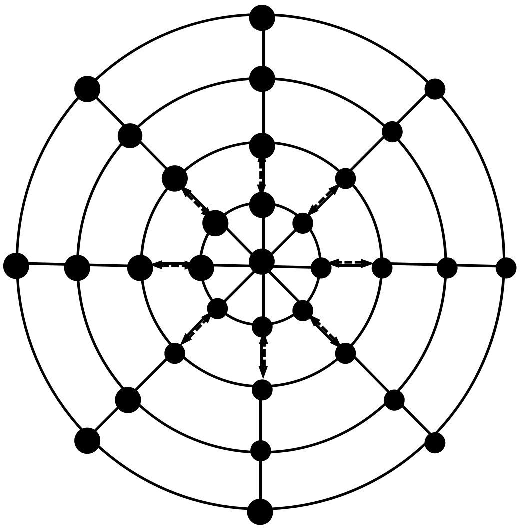
where $[]^+$is the positive part function, and q is the cost of traversing regulated road links. If CP is implemented, q is the toll. If TP are implemented, q is either the cost of buying a permit or the profit from selling a permit (in which case, $q < 0$). Parameter values are listed in Table 2.

Table 2 Travelers' Parameter Values

	Parameter	*Description*	*Value*
Mode Choice	μ_m	Logit Scale	\$5
Auto	μ_d	Departure Time Logit Scale	\$2
	t^*	Desired Arrival Time	Uniformly Distributed (Mean = 8:00 AM, SD = 20 mins)
	δ	Width of on-time Window	10 mins
	β	Unit Cost of Early Arrival	\$6 /hr
	γ	Unit Cost of Late Arrival	\$25 /hr
	α	Unit Cost of Travel Time by Auto	\$10 /hr
Public Transit	α^{PT}	Unit Cost of Travel Time by PT	\$15 /hr
	P^{PT}	Fixed Penalty for Taking PT	\$10 /hr

Tolls or permit requirements are imposed on the In2 links extending from Ring 2 to Ring 1, shown with dashed lines in Figure 2, which yield the highest welfare gain in [8]. Since the network is invariant to 45-degree rotations, we assume that toll levels and permit requirements are the same for all In2 links. In addition, we assume that the permits market is competitive so that all permits trade at the same price. We focus on user equilibrium in which no traveler can reduce her travel cost by modifying her decisions.

Figure 2 Regulated Links



Variability in travel conditions is assumed to be caused by capacity shocks. Capacity shocks can be either perfectly correlated or independent. Perfect correlation is descriptive of conditions such as bad weather in which all road links are similarly affected. Independence is descriptive of accidents, construction or other temporary conditions that affect road links individually. In either case, each link experiences one of two states each day: A *Good day* or a *Bad day*. On Good days, which happen with probability p, the road link operates at its design capacity. On Bad days, which happen with probability 1-p, the link's capacity is reduced by x%. For the simulations, we set p=0.75 and x=20.

As noted above, toll levels and permit quantities are constrained to be the same each day, and thus cannot be conditioned on the state of the network. Instead, they are based on p and x. However, individuals are assumed to learn the state of each link before they make their travel decisions. (In practice, such information can be obtained from traffic websites, mobile phones and other sources.) The sequence of events and decisions for tolls are as follows:

Tolls:

1. The regulator imposes a common and state-independent toll on each of the eight In2 links.
2. The state (i.e., type of day) on each link is realized.
3. Travelers decide whether to drive or take public transit.
4. Travelers who choose to drive select a departure time and make a provisional choice of route that may be revised en route if travelers experience travel times that differ from what they expected.

In the case of permits, two types of decisions are made. First, the regulator decides on the number of permits to distribute and the number of permits required to traverse each type of link. Second, travelers decide on a mode, departure time and route. The sequence of events and decisions for permits are as follows:

Permits:

1. The regulator imposes a common permit requirement on each of the eight In2 links.
2. The regulator allocates the permits to travelers. We assume that permit quantities are normalized so that traversing each In2 link requires one permit.
3. The state (i.e., type of day) on each link is realized.
4. Travelers buy or sell their permits in a free market while they plan their trips. The price of permits is determined endogenously in the market. All trades are made at the same price.
5. Travelers decide whether to drive or take public transit.
6. Travelers who choose to drive select a departure time and make a provisional choice of route that may be revised en route.

METROPOLIS employs a day-to-day adjustment process with learning by individuals. Several dozen iterations are required to approach a stationary state, and because travelers review their mode and departure-time choices on an ongoing basis, travel conditions continue to oscillate. Hence, with either tolls or permits, an equilibrium in which no traveler can modify her decisions to strictly lower her cost is never quite reached.

Results

Perfectly correlated capacity shocks

Using Metropolis simulations, we find the optimal (i.e., social-surplus maximizing) toll level and permit quantity for Good days and Bad days, and the corresponding welfare gain relative to no regulation. We also investigate the welfare-distributional effects on the travelers based on their origins and destinations. Then we find the state-independent toll level and permit quantity, and their corresponding welfare gains, and compare the efficiency of the two instruments.

To compute the optimal toll in each state, we increment the toll in steps of \$0.20 from \$3 to \$7.80, and find the user equilibria at each toll level. Then we fit a second-order polynomial curve to the set of (toll, welfare gain) trial points, and find the maximum of the curve. On Good days, when road links operate at their design capacities, the optimal toll level is \$4.71 and the welfare gain is \$62,656 (see Figure 3). The maximum relative margin of error for all the welfare gains reported throughout this paper is 1.68%. On Bad days, when road link capacities drop by 20%, the optimal toll level is \$6.23 and the welfare gain is \$57,309 (see Figure 4). The maximum number of individuals that can travel without congestion increases with capacity. Since road link capacities drop on Bad days while travel demand remains unchanged, congestion begins to emerge at a lower value of usage than on Good days and boosts the optimal toll on Bad days above the toll on Good days.

Figure 3 Welfare Gain vs Toll on Good Days

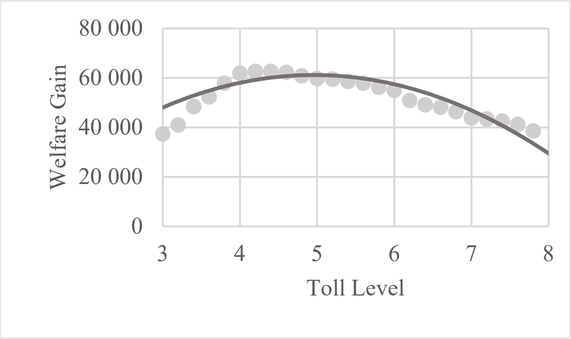
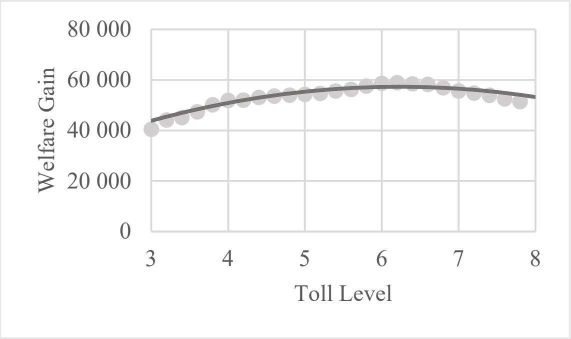


Figure 4 Welfare Gain vs Toll on Bad days



We follow a similar procedure to compute the optimal permit quantity. The number of permits issued is incremented in steps of 550 from 27,050 to 40,250, and user equilibria are found at each level. A second-order polynomial is then fitted to the set of equilibria. On Good days, the optimal permit quantity is 37,016 and the welfare gain is \$62,463 (see Figure 5). On Bad days, the optimal permit quantity is 28,752 and the welfare gain is \$57,127 (see Figure 6).

For each state, we record the properties of the no-regulation equilibrium and the user equilibrium when the optimal regulation is employed. Table 3 presents summary statistics in each state for the toll regulations. Since tolls and permits both support optimal usage under stationary conditions, the statistics for permits are the same and hence omitted.

When either of the regulations is imposed, the percentage of trips made by automobile, the length of the peak period, the congestion index, the average auto travel time and the schedule delay cost (i.e., the cost of arriving early or late) decrease. In addition, the average driving speed and more importantly the social surplus increase. Therefore, regulations alleviate overall traffic congestion and improve social welfare. Nevertheless, the average driving distance of auto trips, the average free-flow travel cost and the late arrivals increase as some travelers choose to take longer trips to avoid the regulated links.

Figure 5 Welfare Gain vs Permit Quantity on Good Days

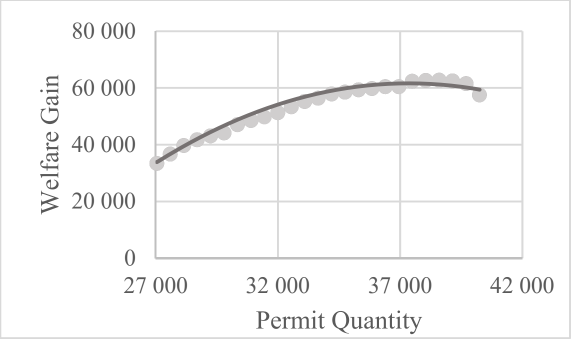


Figure 6 Welfare Gain vs Permit Quantity on Bad Days

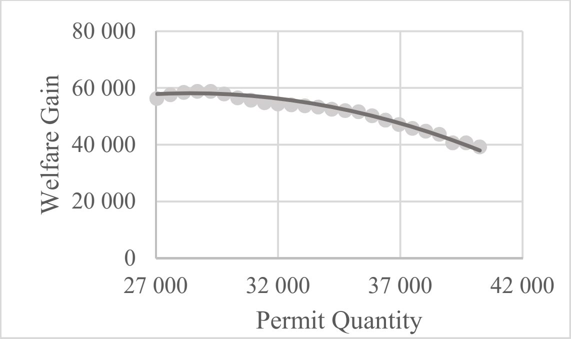


Table 3 Summary Statistics for No-regulation and Optimal Regulation Equilibria

	Good Day		*Bad Day (20% Capacity Reduction)*	
Statistic	*No Regulation*	*Optimal Regulation*	*No Regulation*	*Optimal Regulation*
Auto share	69.8%	66.2%	66.6%	62.0%
Free-flow travel cost	$2.63	$2.71	$2.70	$2.80
Peak period length	1.34 h	1.23 h	1.4 h	1.3 h
Congestion index	35.4%	20.7%	52.3%	33.3%
Avg. auto mileage	14.9 km	15.0 km	15.1km	15.4 km
Avg. auto speed	41.7 km/h	45.9 km/h	36.8 km/h	41.2 km/h
Avg. travel time	21.4 min	19.6 min	24.6 min	22.3 min
Travel cost	$5.04	$5.58	$5.71	$6.22
Consumer's surplus	$-4.38	$-4.80	$-4.76	$-5.21
Early arrivals	59.6%	57.6%	59.8%	57.7%
On-time arrivals	29.3%	30.5%	28.7%	29.7%
Late arrivals	11.1%	11.9%	11.5%	12.6%
Schedule delay cost	$1.47	$1.32	$1.60	$1.41
Welfare gain	—	$62,631	—	$57,891

Auto share: percentage of trips made by auto
Free-flow travel cost: average auto free-flow travel time cost
Peak period length: duration of peak period, starting when 10% of drivers have reached their destination, and ending when 90% have reached their destination
Congestion index: congestion delay as percentage of free-flow travel time on same route
Average auto mileage: average kilometers per auto trip
Average auto speed: average auto travel speed
Average travel time: average auto travel time
Travel cost: average travel cost for auto including the price of regulations
Consumer’s surplus: average user surplus
Early arrivals: Percentage of drivers arriving early
On-time arrivals: Percentage of drivers arriving within their desired arrival-time window
Late arrivals: Percentage of drivers arriving late
Schedule delay cost: Mean cost of arriving by auto early or late
Welfare gain: the increase in social surplus when a regulation is imposed

In aggregate, TP leave travelers better off if they receive permits free of charge. Such is not the case with the toll since average consumer’s surplus drops. However, the regulator can offset the loss by rebating toll revenues. If a rebate is distributed in the form of a uniform lump sum to each traveler, the net welfare effect on each person is the same as for TP if permits are also allocated uniformly to each person. Nevertheless, every person does not necessarily end up better off because the effects of regulation vary by origin, destination, individual preferences and whether the person needs a permit to traverse one of the In2 links. Table 4 and Table 5 show the net average welfare effects on individual travelers by origin and destination. A positive value indicates that a group is better off, and a negative value that it is worse off. All but six groups end up better off. Those that lose start their trips on or outside Ring 2, and end their trips inside it. This is not surprising since these groups cannot avoid paying the toll or using a permit if they choose to drive. All the welfare effects are larger in magnitude for Bad days than Good days.

Table 4 Average welfare effects on Good days by origin and destination when toll revenue is redistributed

Destination Origin	CBD	Ring 1	Ring 2	Ring 3	Ring 4
CBD		0.74	0.76	0.76	0.75
Ring 1	1.45	1.34	1.19	1.17	1.13
Ring 2	-1.30	-1.47	0.17	0.31	0.31
Ring 3	-1.08	-1.25	0.43	0.37	0.45
Ring 4	-0.98	-1.14	0.47	0.49	0.53

Table 5 Average welfare effects on Bad days by origin and destination when toll revenue is redistributed

Destination / Origin	CBD	Ring 1	Ring 2	Ring 3	Ring 4
CBD		0.74	0.77	0.80	0.80
Ring 1	1.58	1.37	1.28	1.29	1.24
Ring 2	-1.75	-1.93	0.32	0.47	0.47
Ring 3	-1.46	-1.60	0.59	0.50	0.57
Ring 4	-1.30	-1.43	0.64	0.60	0.60

Next, we study state-independent regulations when the probability of a Bad day is 0.25. The optimal state-independent toll level is \$4.82. It yields a social welfare gain of \$62,593 on Good days and \$54,742 on Bad days, for an expected gain of \$60,630. The optimal state-independent permit quantity is 36,233, which yields a social welfare gain of \$62,075 on Good days and \$48,710 on Bad days, for an expected gain of \$58,734. Permits trade at a price of \$4.94 on Good days, and \$3.72 on Bad days. The price is lower on Bad days because the cost of driving is higher, and travelers have a lower willingness to pay for a permit.

In summary, when road link capacities are perfectly correlated, and regulations are non-adaptive, tolls yield an expected welfare gain about 3% higher than permits. Tolls also outperform permits in each state. Note, however, that in general one instrument could outperform the other on average, but do worse in particular states.

Independent capacity shocks

In the independent capacity scenario, each link is independently susceptible to a 20% capacity drop with probability 0.25. Using this distribution, we draw 25 random samples for each of the 128 unidirectional links on the Circular City network. As before, to compute the optimal state-independent toll level for each sample draw, we increment the toll in steps of \$0.20 from \$3 to \$7.80, and find the user equilibria for each toll level. Then we fit a second-order polynomial curve to the (toll, welfare gain) pairs to find the optimal toll level and the corresponding expected welfare gain. The curve is shown in Figure 7. The optimal state-independent toll is \$4.88, which increases social welfare by \$59,328 relative to no regulation.

Similarly, to compute the optimal state-independent permit quantity, for each sample draw we increment the number of permits in steps of 550 and record the welfare gain. Then we fit a second-order polynomial curve to the (quantity, welfare gain) pairs to find the optimal quantity and the corresponding expected welfare gain. The curve is shown in Figure 8. The optimal state-independent permit quantity is 35,936, which increases social welfare by \$59,647.

Figure 7 Welfare Gain vs Toll for i.i.d. Capacity Shocks

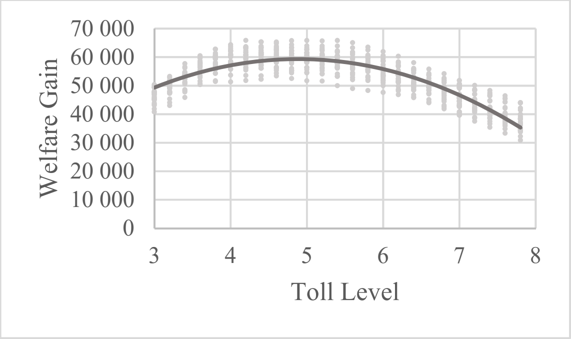
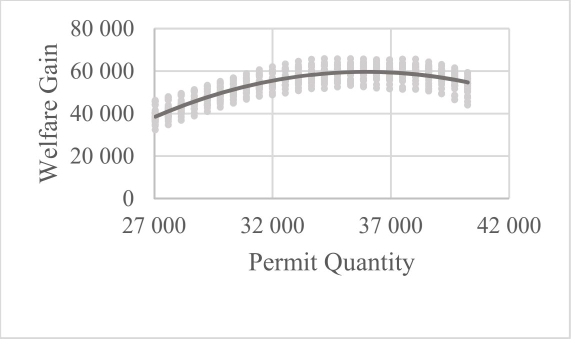


Figure 8 Welfare Gain vs Permit Quantity for i.i.d. Capacity Shocks



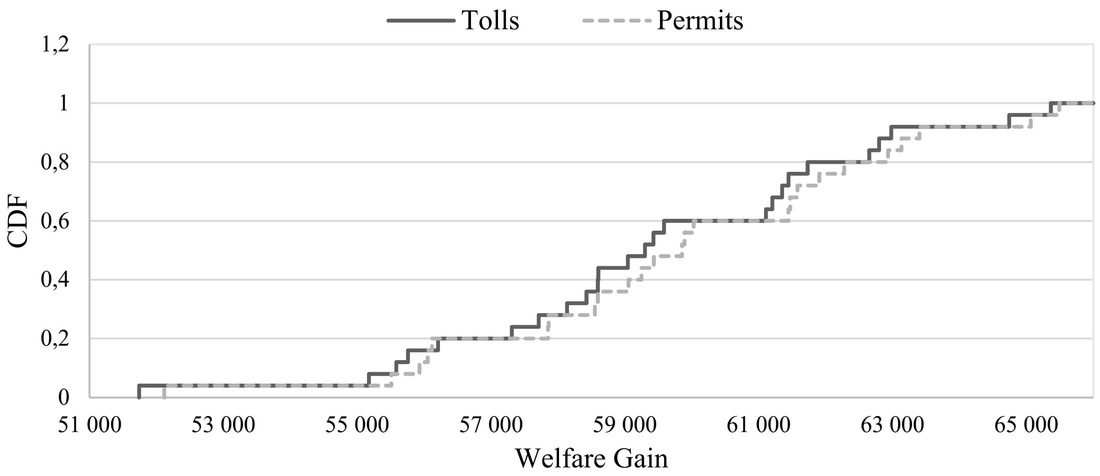
Unlike for the case of correlated capacities, with independent capacities the permit yields an expected welfare gain that is about 0.5% higher than for the toll. To compare the frequency distribution of gains of the two instruments for the 25 random draws, we apply first- and second-order stochastic dominance. An instrument A has first-order stochastic dominance (FOSD) over another instrument B if, for any welfare gain value w, A has a higher probability than B of achieving at least w. FOSD can be assessed by comparing the cumulative distribution functions (CDFs) of the two instruments. A has FOSD over B if $F_A(w) \leq F_B(w)$ for all values of w. As shown in Figure 9, the CDF for the toll lies mostly above the CDF for the permits. However, the two CDFs cross at a welfare gain of about \$56,000. There is one random draw for which the toll yields a higher welfare gain than the permit, and neither instrument outperforms the other as far as FOSD.

Hence, we turn attention to second-order stochastic dominance (SOSD). Instrument A has SOSD over instrument B if, for any welfare gain value w,

$$\int_{-\infty}^{w} [F_A(\omega) - F_B(\omega)]\, d\omega \leq 0,$$

with strict inequality for some w. If this condition is satisfied, a risk-averse regulator will prefer instrument A as it involves less risk. As shown in Figure 9, permits have SOSD over tolls because the integral under the CDF for the toll exceeds the integral under the CDF for the permit.

Figure 9 CDFs for Tolls and Permits



Conclusions

Using the dynamic traffic network simulator Metropolis, we have studied the absolute and relative performance of congestion pricing (CP) and tradable permits (TP) in controlling traffic congestion. For stationary travel conditions we established that the two instruments reduce overall traffic congestion and increase social welfare, although some travelers end up worse off depending on their origin and destination. We have also studied the performance of the two instruments when road link capacities experience fluctuations. When these fluctuations are perfectly correlated, the simulation results indicate that CP outperforms TP. This is consistent with the analytical results for cost shocks in [6]. When capacity fluctuations are independent, TP yield higher welfare gains than CP in all but one state, and outperform CP in terms of second-order stochastic dominance. This could be because route-choice decisions are more volatile when link capacities vary independently, and TP are more effective than tolls at internalizing congestion externalities in these circumstances. Further research is needed to investigate this.

Acknowledgements

Financial support from the Social Sciences and Humanities Research Council of Canada (Grant 435-2014-2050) and CY Cergy Paris Université (ANR-11-LBX-0023-01 and ANR-16-IDEX-0008) is gratefully acknowledged.

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