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ABSTRACT

As one of the most densely populated metropolises in the world, Hong Kong daily sees severe traffic delays at the Cross-Harbour Tunnel (CHT), though not at the Eastern Harbour Crossing (EHC) and the Western Harbour Crossing (WHC). In 2013, the Hong Kong Special Administrative Region (HKSAR) Government proposed raising the tolls of the publicly-owned CHT and lowering those of the publicly-owned EHC for nine vehicle types: private cars, motorcycles, taxis, three kinds of buses, and three kinds of goods vehicles. The privately-owned WHC's already high tolls, however, would remain unchanged. Using monthly usage and peak-hour usage data for January 2003 through June 2015, we estimate a Generalized Leontief demand system to find that private cars, motorcycles and goods vehicles have price-sensitive tunnel usage patterns that are also time-dependent. The usage patterns of taxis and buses, which are public transportation vehicles, are totally price-insensitive. These findings suggest that the HKSAR Government's proposed toll changes would reduce the CHT's monthly usage by 7.4% to 12.2%, and peak-hour usage 5.0% to 16.8%. These usage reduction estimates suggest that a time-of-use (TOU) toll design can better manage CHT congestion than the current non-TOU design.

Keywords: Congestion Pricing, Transportation demand, Traffic management

LIST OF TABLES AND FIGURES

INTRODUCTION

Efficient rationing of the use of congestible roads, bridges, and tunnels is an important aspect of transportation policy *(1-7)*. Like their counterparts in other Chinese metropolises (e.g., Beijing, Shanghai, Guangzhou and Shenzhen), Hong Kong drivers encounter severe traffic congestion on a daily basis, reflecting that Hong Kong is one of the most densely populated cities in the world. Encompassing an area of ~1100 km^2 (1 mi^2 = 2.59 km^2), Hong Kong has a population of ~7.3 million, resulting in a high population density of ~6636 residents per km^2. It has about 340 licensed vehicles for every km (1 mi = 1.62 km) of road and would become one big parking lot if most of these vehicles were on the road at the same time.

This paper is an econometric analysis of the effectiveness of the Hong Kong Special Administrative Region (HKSAR) Government's 2013 proposal to change the tolls of Hong Kong's three cross-harbor tunnels: the dual 2-lane Cross-Harbour Tunnel (CHT), the dual 2-lane Eastern Harbour Crossing (EHC), and the dual 3-lane Western Harbour Crossing (WHC); see Figure 1. Despite an excellent public transportation system that serves about 12.5 million passenger-trips per day, Hong Kong daily sees severe traffic delays between 07:00 and 21:00 at the CHT. A cross-harbor vehicular trip via the 1.8 km CHT may take up to 30 minutes, thanks to long queues along the roads leading to the CHT's northern end in Kowloon Peninsula and southern end on Hong Kong Island. The same trip, however, can be completed in about six minutes (= 1.8 km distance ÷ vehicle speed of ~20 km per hour) during the uncongested hours (e.g., 02:00 to 06:00).

Figure 2 shows that the CHT's aggregate usage per day is about 120,000 vehicular trips in both directions, far above the design capacity of 78,000 trips under uncongested conditions. In contrast, the EHC's aggregate usage per day is below the design capacity of 78,000 trips and the WHC's is less than one third of the design capacity of 180,000 trips. The CHT's heavy congestion is understandable, thanks to the CHT's central location as shown in Figure 1, and the low monthly average tolls shown in Figure 3.

The proposed toll changes aim to price-manage the tunnel usage patterns of nine vehicle types: private cars, taxis, motorcycles, three kinds of buses, and three kinds of goods vehicles *(9)*. If implemented, the proposal would raise the vehicle-specific tolls of the publicly-owned CHT and lower those of the publicly-owned EHC, while keeping those of the privately owned WHC unchanged. Our econometric evidence is timely and relevant, underscored by the HKSAR Government's initiation in late 2015 of a three-month public consultation on an electronic road-pricing pilot for the highly congested Central district and adjacent areas *(10)*.

Our paper is motivated by a presumption of price-sensitive tunnel usage patterns by vehicle type, which implies that the proposed toll changes would shift some traffic away from the heavily congested CHT to the uncongested EHC and WHC (see Figure 1). While this presumption seems reasonable in light of the extant studies of Hong Kong's cross-harbor tunnel demands (*11-13)*, a critical but unanswered question remains: can the same proposal alter each tunnel's peak-hour usage as measured by the maximum number of vehicular trips in a single hour of a given month? If the answer is "no", the proposal's effectiveness in price-managing the CHT's time-dependent congestion is very much in doubt. Hence, our joint investigation of the three tunnels' monthly peak-hour and total usage patterns sharply differentiates this paper from *(11-13)*.

We answer the above question using the monthly cross-harbor tunnel usage data for the 150-month period of January 2003 to June 2015 from the Hong Kong Transportation Department. We estimate the vehicle-specific disaggregate own- and cross-price elasticities of monthly peak-hour and total usage by tunnel and direction (northbound vs. southbound). These disaggregated elasticity estimates are then used to develop each tunnel's aggregate price elasticity estimates. Finally, we estimate the changes in each tunnel's peak-hour usage by direction, thereby addressing the CHT's time-dependent congestion problem.

Our paper makes three contributions to Hong Kong's policy debates on cross-harbor tunnel congestion and the broader literature on transportation demand management. First, it presents an approach of system demand estimation that uses publicly available data to dissect a complicated real-world peak-hour congestion problem involving nine vehicle types, three tunnels, and two directions. The approach is useful when survey data collection is costly but aggregate data are readily available *(14)*, yielding results that might complement empirical findings based on route-choice survey data (e.g*., 12, 15-18*). Second, our paper documents that the price-sensitivity of tunnel usage patterns is both time- and direction-dependent. As a result, the HKSAR Government's proposed toll changes represent a first step in price-managing the CHT's severe congestion. A future improvement is directional time-of-use (TOU) tolls *(10)*. Finally, our paper provides detailed price elasticity estimates for monthly peak-hour and total usage patterns by vehicle type and direction, thereby enriching the limited evidence reported in several literature reviews *(19-23)*.

MODEL

Our econometric formulation is shaped by the publicly available data. The challenge is how to best exploit these monthly data to estimate the nine vehicle types' responses to the proposed toll changes.

Usage Data and Variable Definitions

We begin by considering each tunnel's monthly total usage data by direction that corresponds to nine vehicle types, indexed herein by $m = 1$ (private cars), 2 (taxis), 3 (motorcycles), 4 (light buses), 5 (single deck buses), 6 (double deck buses), 7 (goods vehicles not more than 5.5 tonnes), 8 (goods vehicles between 5.5 and 24 tonnes), and 9 (goods vehicles over 24 tonnes). Each tunnel's peak-hour usage data by direction corresponds to three size-differentiated vehicle groups, each of which has three vehicle types. The first group contains private cars, taxis, and motorcycles, the second light buses, single deck buses, and goods vehicles not more than 5.5 tonnes, and the third double deck buses, goods vehicles between 5.5 and 24 tonnes, and goods vehicles over 24 tonnes. We derive the peak-hour usage data at the vehicle type level by allocating each group's peak-hour usage among the group's three constituent vehicle types based on each vehicle type's share of the group's monthly total usage.

Let $t = 1$ for January 2003, …, $T = 150$ for June 2015. For a given t and specific direction (e.g., northbound), we define five usage variables for characterizing the various price elasticities. For notational simplicity, we suppress, for the time being, the subscripts used to index a usage variable's vehicle type and direction.

The first variable is N_{jt} = the vehicle type's monthly total usage of tunnel j. The second variable is M_{jt}, the vehicle type's usage in tunnel j's peak hour in month t. The third variable is P_{jt} = toll of tunnel j in month t. The fourth and fifth variables are Y_t = Hong Kong's monthly real GDP and t = monthly index that captures the time trend's effect on non-toll costs.

Monthly Total Usage and Peak-Hour Usage of a Given Vehicle Type

To analyze the vehicle-specific price responsiveness of N_{jt} and M_{jt}, we follow the Generalized Leontief (GL) specification in *(13, 24*, *25)*. We choose the GL specification because of its global properties as a flexible functional form in characterizing demands with low cross-price responsiveness. The resulting linear usage equations meaningfully link each vehicle type's N_{jt} and

M_{jt}, thereby yielding transparent calculations of aggregate peak-hour and total usage responses by tunnel and direction.

The GL equation for vehicle type's monthly total usage, N_{jt}, in month t is:

$$N_{jt} = \beta_{jj} + \Sigma_{k\neq j}\,\beta_{jk}\,(P_{kt} / P_{jt})^{1/2} + \psi_j\, Y_t + \phi_j\, t, \quad (1)$$

and the vehicle type's peak-hour usage of tunnel j is:

$$M_{jt} = \alpha_{jj} + \Sigma_{k\neq j}\,\alpha_{jk}\,(P_{kt} / P_{jt})^{1/2} + \theta_j\, Y_t + \lambda_j\, t. \quad (2)$$

Equations (1) and (2) state that N_{jt} and M_{jt} linearly depends on $(P_{kt} / P_{jt})^{1/2}$, Y_t, and t. β_{jj} and α_{jj} are constants. $\{\beta_{jk,}\ \alpha_{jk}\}$ for $j\neq k$ are time-invariance coefficients. The effect of GDP on tunnel usage measured by ψ_j and θ_j has two components: (a) rising income that tends to raise car ownership and drivers' trip requirements; and (b) rising income that tends to raise drivers' congestion costs. If (a) dominates (b), rising income tends to raise the tunnel usage.

The effect of the time trend on tunnel usage, measured by ϕ_j and λ_j also has two components: (a) rising operations and maintenance and fuel costs that tend to increase the non-toll costs; and (b) an expanding transportation infrastructure (e.g., new expressways) that tends to reduce drivers' congestion costs. If (a) dominates (b), hourly tunnel usage tends to decline over time, after accounting for the effects of the monthly GDP and tunnel tolls.

Price Elasticities

There are four kinds of price elasticities by direction. Because of the nonlinear nature of the elasticity formulae, we use sample enumeration via a two-step procedure to perform the elasticity calculations *(13)*.

The first kind is a given vehicle type's disaggregate price elasticities for monthly total usage of tunnel j. In step 1, we calculate

$$\eta_{jjt} = \partial\ln N_{jt}/\partial\ln P_{jt} = -1/2\ \Sigma_{k\neq j}\ \beta_{jk}\,(P_{kt} / P_{jt})^{1/2} / N_{jt},$$

the vehicle type's own-price elasticity in month t. In step 2, we calculate $\eta_{jj} = \Sigma_t \eta_{jjt} / T$, the equally-weighted average of η_{jjt} to measure the vehicle-specific monthly total usage's average own-price responsiveness.

Using the same two-step procedure, we first calculate

$$\eta_{jkt} = \partial\ln N_{jt}/\partial\ln P_{kt} = 1/2\ \beta_{jk}\,(P_{kt} / P_{jt})^{1/2} / N_{jt} \text{ for } k\neq j,$$

the vehicle type's cross-price elasticity in month t. We then calculate

$$\eta_{jk} = \Sigma_t \eta_{jkt} / T,$$

the equally-weighted average of η_{jkt} to measure the vehicle-specific monthly total usage's average cross-price responsiveness.

The second kind is tunnel j's aggregate price elasticities, each of which is denoted by E_{jk} = percentage change in tunnel j's aggregate usage due to a one-percent change in tunnel k's nine vehicle-specific tolls. Based on *(13)*, $E_{jk} = (\Sigma_t\, \Sigma_m\ \eta_{jkmt}\ W_{jmt}) / T$, where η_{jkmt} = vehicle type m's η_{jkt} value and W_{jmt} = vehicle type m's share of tunnel j's aggregate usage in month t.

The third kind is a particular vehicle type's disaggregate price elasticities for peak-hour usage of tunnel j. The vehicle-specific peak-hour usage's own-price elasticity is

$$\gamma_{jj} = \Sigma_t\ \gamma_{jjt} / T, \text{ where } \gamma_{jjt} = \partial\ln M_{jt}/\partial\ln P_{jt} = -1/2\ \Sigma_{k\neq j}\alpha_{jk}\,(P_{kt} / P_{jt})^{1/2} / M_{jt}.$$

The cross-price elasticities are

$$\gamma_{jk} = \Sigma_t\ \gamma_{jkt} / T, \text{ where } \gamma_{jkt} = \partial\ln M_{jt}/\partial\ln P_{kt} = 1/2\ \alpha_{jk}\,(P_{kt} / P_{jt})^{1/2} / M_{jt} \text{ for } k\neq j.$$

The fourth kind is tunnel j's aggregate peak-hour usage elasticities, each of which is denoted by A_{jk} = percent change in tunnel j's aggregate peak-hour usage due to a one-percent change in tunnel k's nine vehicle-specific tolls. Based on *(13)*, $A_{jk} = (\Sigma_t\, \Sigma_m\ \gamma_{jkmt}\ S_{jmt}) / T$, where γ_{jkmt}

= vehicle type m's γ_{jkt} value and S_{jmt} = vehicle type m's share of tunnel j's aggregate peak-hour usage in month t.

Tunnel Usage Responses

Let P_{jm} denote the current toll paid by the drivers of vehicle type m at tunnel j. Further, let P_{jm}' denote the proposed toll. Based on equation (1), the effect of a proposed change in tolls on vehicle type m's total usage per month of tunnel j for a given direction is:

$$X_{jm} = \Sigma_{k \neq j}\, \beta_{jkm}\, [(P_{km}' / P_{jm}')^{1/2} - (P_{km} / P_{jm})^{1/2}], \quad (3)$$

where β_{jkm} = vehicle type m's β_{jk} coefficient for that direction. Hence, the aggregate usage response per month by all vehicle types for tunnel j for a given direction is:

$$X_j = \Sigma_m X_{jm}. \quad (4)$$

Based on equation (2), the effect of the proposed toll change on vehicle type m's peak-hour usage of tunnel j is:

$$Z_{jm} = \Sigma_{k \neq j}\, \alpha_{jkm}\, [(P_{km}' / P_{jm}')^{1/2} - (P_{km} / P_{jm})^{1/2}], \quad (5)$$

where α_{jkm} = vehicle type m's α_{jk} coefficient for that direction. As there are 730 hours per month (= 8760 hours per year ÷ 12 months per year), the peak-hour response Z_{jm} equals the per hour usage response (X_{jm} / 730) when $\alpha_{jkm} = (\beta_{jkm} / 730)$.

Finally, the aggregate peak-hour usage response by all vehicle types for tunnel j is:

$$Z_j = \Sigma_m Z_{jm}. \quad (6)$$

Testable Hypotheses

To better understand congestion management via directional TOU tolls, we use equations (3) and (5) to develop testable hypotheses based on linear restrictions on the GL system's coefficients associated with the square-rooted price ratios. Rejecting these hypotheses would suggest the new toll design's effectiveness is beyond what could be accomplished by the currently non-directional and time-invariant design.

The first hypothesis is **H1**: vehicle-type m's per hour usage response and peak-hour usage response are equal for a given direction. Under **H1**, we have:

H1A: northbound (β_{jkm} / 730) = northbound α_{jkm} for all $j \neq k$.

H1B: southbound (β_{jkm} / 730) = southbound α_{jkm} for all $j \neq k$.

If **H1A** and **H1B** hold for *both* directions, we have:

H1C: northbound (β_{jkm} / 730) = northbound α_{jkm} *and* southbound (β_{jkm} / 730) = southbound α_{jkm} for all $j \neq k$.

The second hypothesis is **H2**: vehicle-type m's directional monthly total usage responses are identical. Under **H2**, northbound β_{jkm} = southbound β_{jkm} for all $j \neq k$.

The third hypothesis is **H3**: vehicle-type m's directional peak-hour usage responses are identical. Under **H3**, northbound α_{jkm} = southbound α_{jkm} for all $j \neq k$.

The last hypothesis combines **H2** and **H3**, resulting in **H4**: vehicle-type m's monthly total usage *and* peak-hour usage responses do not vary by direction. Under **H4**, northbound β_{jkm} = southbound β_{jkm} *and* northbound α_{jkm} = southbound α_{jkm} for all $j \neq k$.

ESTIMATION STRATEGY

As there are three tunnels and nine vehicle types, each direction has 54 equations (= 27 monthly total usage equations + 27 peak-hour usage equations) to be estimated. Since there are two directions, 108 is the total number of equations to be estimated. Our estimation restricts $\beta_{jkm} = \beta_{kjm} \geq 0$ and $\alpha_{jkm} = \alpha_{kjm} \geq 0$ for all $j \neq k$ and m, thus satisfying the price concavity requirement of a well-behaved cost function.

Our initial exploration reveals that we cannot jointly estimate the 108 usage equations due to the problem of non-convergence. As a result, we separately estimate each of the nine vehicle-specific GL systems to obtain its α_{jkm} and β_{jkm} estimates. Each vehicle-specific system has 12 regressions: (a) three northbound monthly total usage regressions; (b) three southbound monthly total usage regressions; (c) three northbound peak-hour usage regressions; and (d) three southbound peak-hour usage regressions. To ascertain that our regression results are not spurious, we first examine if our sample's monthly data series have a unit root and are therefore non-stationary.

Based on the Phillips-Perron (PP) test *(26)*, real GDP is found to be trend-stationary and the monthly total usage and peak-hour usage are either stationary or trend-stationary at the 5% significance level used throughout the rest of this paper. The monthly square-rooted toll ratios are non-stationary. These ratios' infrequent variations, however, obviate the need to remedy the apparent non-stationarity problem because they are akin to shift dummies that move tunnel usage in response to toll changes. Hence, we directly use the monthly data series to estimate the tunnel usage equations. The nine estimation samples by vehicle type are available from the corresponding author upon request.

We apply the iterative seemingly unrelated regression (ITSUR) method in *(27)* to estimate vehicle type m's monthly total usage and peak-hour usage equations differentiated by tunnel and direction:

Monthly total usage: $N_{jmt} = \beta_{jjm} + \Sigma_{k \neq j}\, \beta_{jkm}\, (P_{kmt} / P_{jmt})^{1/2} + \psi_{jm}\, Y_t + \phi_{jm}\, t + \upsilon_{jmt},$ (7.a)

Peak-hour usage: $M_{jmt} = \alpha_{jjm} + \Sigma_{k \neq j}\, \alpha_{jkm}\, (P_{kmt} / P_{jmt})^{1/2} + \theta_{jm} Y_t + \lambda_{jm}\, t + \mu_{jmt}.$ (7.b)

The estimated N_{jmt} and M_{jmt} should be positive, as required by a well-behaved cost function. This requirement is met when the coefficient estimates in equations (7.a) and (7.b) are all positive.

The random errors υ_{jmt} and μ_{jmt} on the right-hand-side (RHS) of equations (7.a) and (7.b) are assumed to be contemporaneously correlated and follow an AR(3) process. The errors are contemporaneously correlated because vehicle type m's usage pattern of the three tunnels is the result of the decision making by drivers of that vehicle type (e.g., private cars, motorcycles, or goods vehicles) or passengers of that vehicle type (e.g., taxis or buses). The AR(3) assumption is based on an exploration of an AR(4) process, finding that over 90% of the fourth AR parameter estimates are insignificant. These results are available upon request.

RESULTS

ITSUR Regressions

The GL systems for taxis and buses have α_{jkm} and β_{jkm} ($j \neq k$) estimates that are restricted to zero. Hence, these public transportation vehicles have price-insensitive monthly total and peak-hour usage patterns, reflecting that their drivers do not have route choices and do not pay the tunnel tolls. This finding also suggests that passengers' route choices do not translate into empirically detectable price-sensitivity of tunnel usage patterns of taxis and buses.

The rest of this subsection focuses on the results of the 30 monthly total usage and 30 peak-hour usage regressions for private cars, motorcycles, and goods vehicles. Table 1 summarizes the voluminous coefficient estimates. Panel A indicates that some intercept estimates are significantly negative. Thus, we use the estimated regressions to calculate the within-sample predictions of the peak-hour and monthly total usage. These predictions are strictly positive for all observations, as required by a well-behaved cost function.

Panel B reports the estimates for α_{jkm} and β_{jkm} ($j \neq k$). Ten of the 30 α_{jkm} estimates are significantly positive for the peak-hour usage regressions. Twenty-two of the 30 β_{jkm} estimates are significantly positive for the monthly total usage regressions. While there are negative α_{jkm} and β_{jkm} coefficient estimates, they are all insignificant and therefore restricted to zero. Hence, Panel B suggests the empirical plausibility of the peak-hour and monthly total usage regressions for private cars, motorcycles and goods vehicles.

The significant coefficient estimates for monthly GDP in Panel C suggest that rising GDP tends to raise monthly total usage, though less so for peak-hour usage. The time trend's coefficient estimates in Panel D have mixed significance levels and signs. Hence, they do not tell a uniform story of how the monthly total usage and peak-hour usage may move over time, after accounting for the effects of the tunnel tolls and monthly GDP.

Hypothesis Testing

The second to fourth columns of Table 2 report the p-values of the Wald statistics for testing **H1A** to **H1C**, suggesting that the peak-hour usage and per hour usage of private cars, motorcycles, and goods vehicles have different price sensitivities. The p-values for testing **H2** indicate that the price sensitivity of private cars' and goods vehicles' monthly total usage varies by direction. The p-values for testing **H3**, however, suggest that the peak-hour usage's price sensitivity is largely non-directional. The p-values for testing **H4** indicate directionally differentiated responses by private cars and goods vehicles. When taken together, these findings suggest the potential usefulness of directional TOU tolls to ease the CHT's congestion.

Price Elasticity Estimates

When calculating the price elasticities reported here and the tunnel usage responses in the next section, we conservatively set the insignificant α_{jkm} and β_{jkm} ($j \neq k$) estimates to zero for two reasons. First, using the unadjusted α_{jkm} estimates leads to implausibly large peak-hour elasticity estimates. Second, the response estimates given by equations (4) and (6) are insignificant when the α_{jkm} and β_{jkm} ($j \neq k$) estimates are insignificant. Setting the insignificant α_{jkm} and β_{jkm} estimates to zero pre-empts allegations of an imprudent use of large but insignificant response estimates to substantiate price-management's effectiveness in easing CHT congestion.

Table 3 reports the own- and cross-price elasticity estimates for the monthly total usage of private cars, motorcycles, and goods vehicles, showing that these vehicle types have price-inelastic total usage patterns. Table 4 reports the own- and cross-price elasticity estimates for the peak-hour usage patterns of private cars, motorcycles, and goods vehicles. These peak-hour elasticity estimates are generally smaller in size than those in Table 3. This makes sense because the peak-hour estimates correspond to the maximal tunnel demands of the drivers of these vehicle types.

Panels A and B of Table 5 report the aggregate own- and cross-price elasticity estimates for each tunnel's total usage, showing that all three tunnels exhibit price-inelastic usage patterns. Panels C and D report the aggregate own- and cross-price elasticity estimates for each tunnel's peak-hour usage. These peak-hour elasticity estimates are generally smaller in size than those in Panels A and B.

AGGREGATE RESPONSES TO THE PROPOSED TOLL CHANGES

Panel A of Table 6 presents the HKSAR Government's three options for the CHT's and EHC's toll changes *(9)*. Some of the relative toll changes are large, as evidenced by Option A's 25% (= HK$5/HK$20) increase for the CHT's toll for private cars and 87% (= HK$26/HK$30) increase for the CHT's toll for goods vehicles over 24 tonnes.

Based on equation (4), Panel B of Table 6 summarizes each option's estimated effects on each tunnel's monthly total usage by direction. It shows that Option A is estimated to reduce the CHT's total usage by between 11.3% and 12.0% and increase the EHC's by between 14.9% and 15.1%. Its estimated effect on the WHC is negligible. The estimated effects of the other options are smaller than, but qualitatively similar to, those of Option A.

Based on equation (6), Panel C of Table 6 summarizes each option's estimated effects on each tunnel's monthly peak-hour usage by direction. It shows that Option A is estimated to reduce the CHT's peak-hour usage by about 9.6% to 16.8% and increase the EHC's by 7.2% to 12.9%. Its estimated effect on the WHC is negligible. The other options' estimated effects are smaller than Option A's.

CONCLUSION

Using the January 2003 – June 2015 monthly peak-hour and total usage data for nine vehicle types, we document that Hong Kong can price-manage its CHT's congestion because the three cross-harbor tunnels' aggregate usage patterns are found to have discernible price responsiveness. The three tunnels' disaggregate price elasticity estimates, however, suggest price-inelastic monthly total usage patterns by vehicle type. The most price-sensitive total usage pattern belongs to motorcycles, followed by private cars and goods vehicles. Taxis and buses, which are public transportation vehicles, do not have price-sensitive monthly total usage patterns. Further, the aggregate elasticity estimates indicate that the three tunnels' monthly total usage patterns are price-inelastic, implying that the proposed toll changes can only modestly shift Hong Kong's cross-harbor tunnel traffic. Finally, the monthly peak-hour usage patterns' disaggregate and aggregate price elasticity estimates are generally smaller in size than those of the monthly total usage patterns. Hence, the effectiveness of price-managing the CHT's peak-hour congestion may be improved by implementing directional TOU tolls as part of the HKSAR Government's pilot of electronic road pricing.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: CK Woo, KH Cao, YS Cheng; data collection: YS Cheng, KH Cao; analysis and interpretation of results: CK Woo, KH Cao, R Li; draft manuscript preparation: CK Woo, A Shiu. All authors reviewed the results and approved the final version of the manuscript.

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TABLE 1 Summary of the ITSUR/AR(3) Northbound (NB) and Southbound (SB) Regressions' Coefficient Estimates by Vehicle Type (m = 1, 3, 7, 8, 9) and Tunnel (j = 1, 2, 3).

Coefficient	1. Private cars		3. Motorcycles		7. Goods vehicles not more than 5.5 tonnes		8. Goods vehicles between 5.5 and 24 tonnes		9. Goods vehicles over 24 tonnes	
	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Panel A. Intercepts: α_{jj} for peak-hour usage (M_{jt}) based on equation (2) and β_{jj} for monthly total usage (N_{jt}) based on equation (1)										
α_{11}	△	▽	▼	▼	▽	△	▽	▲	▽	▲
α_{22}	▲	▲	▼	△	△	▽	▽	△	▽	▽
α_{33}	▲	△	▽	▽	▽	△	▽	▽	▽	▼
β_{11}	△	△	▼	▼	▼	▼	▼	▼	▽	▽
β_{22}	▽	▽	▼	▼	▼	▼	▼	▼	▼	▼
β_{33}	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼
Panel B. Square-rooted toll ratios: α_{jk} for peak-hour usage (M_{jt}) based on equation (2) and β_{jk} for monthly total usage (N_{jt}) based on equation (1)										
α_{12}	△	▲	▲	▲	▲	▲	△	△	○	○
α_{13}	△	△	△	▲	△	△	△	○	△	○
α_{23}	△	○	○	○	△	△	▲	▲	▲	▲
β_{12}	▲	▲	▲	▲	▲	▲	▲	▲	△	△
β_{13}	▲	▲	▲	▲	○	▲	○	▲	△	△
β_{23}	▲	▲	△	△	▲	▲	▲	▲	▲	▲
Panel C. Monthly GDP: θ_j for peak-hour usage (M_{jt}) based on equation (2) and ψ_j for monthly total usage (N_{jt}) based on equation (1)										
θ_1	△	▽	▲	▲	▼	▽	▼	▽	▽	△
θ_2	▽	▽	▲	▲	△	△	▲	▲	△	▲
θ_3	△	▽	▲	▲	▲	▲	▲	▲	△	△
ψ_1	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
ψ_2	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
ψ_3	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Panel D. Time trend: λ_j for peak-hour usage (M_{jt}) based on equation (2) and ϕ_j for monthly total usage (N_{jt}) based on equation (1)										
λ_1	▽	▽	▼	▼	△	▽	△	▽	▲	△
λ_2	▽	▼	▼	▼	▼	▲	▼	▼	△	△
λ_3	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
ϕ_1	▼	▼	▼	▼	▼	▼	▼	▼	▽	▽
ϕ_2	▼	▼	▼	▼	▼	▼	▼	▼	▽	▽
ϕ_3	▲	△	△	△	△	△	△	△	▲	▲

Notes: (1) All SAS data files, programs, output listings and logs are available from the corresponding author by email. (2) The restrictions are $\beta_{jk} = \beta_{kj} \geq 0$ and $\alpha_{jk} = \alpha_{kj} \geq 0$ for all $j \neq k$. (3) At the 5% significance level for a two-tailed *t*-test, "▲" = "positive and significant"; "▼" = "negative and significant"; "△" = "positive and insignificant"; "▽" = "negative and insignificant"; and "○" = "negative, insignificant and restricted to zero".

TABLE 2 Summary of the *P*-values of the Wald Statistics for Testing H1A to H4; *P*-values ≤ 0.05 in Bold.

Vehicle type	H1A: northbound (β_{jk} / 730) = northbound α_{jk} for all $j \neq k$.	H1B: southbound (β_{jk} / 730) = southbound α_{jk} for all $j \neq k$.	H1C: H1A plus H1B	H2: northbound β_{jk} = southbound β_{jk} for all $j \neq k$.	H3: northbound α_{jk} = southbound α_{jk} for all $j \neq k$.	H4: H2 plus H3
1. Private cars	0.7343	**<.0001**	**<.0001**	**0.0006**	0.6377	**0.0045**
3. Motorcycles	**0.0015**	0.0514	**0.0057**	0.0963	unavailable	unavailable
7. Goods vehicles not more than 5.5 tonnes	0.0933	0.2084	0.0972	**0.0048**	0.3416	**0.0075**
8. Goods vehicles between 5.5 and 24 tonnes	0.0757	**0.0340**	**0.0144**	**0.0289**	0.4025	0.0623
9. Goods vehicles over 24 tonnes	0.1102	**0.0267**	0.0503	0.9412	0.4953	0.7761

Note: PROC MODEL of SAS (2010) does not provide the *p*-values for **H3** and **H4** when motorcycles' northbound and southbound α_{23} estimates are restricted to zero in the ITSUR/AR(3) estimation.

TABLE 3 Disaggregate Elasticity (η_{jk}) Estimates Based on Significant β_{jk} Estimates for Monthly Total Usage (N_{jt}) by Direction and Vehicle Type.

Vehicle type	η_{11}	η_{12}	η_{13}	η_{21}	η_{22}	η_{23}	η_{31}	η_{32}	η_{33}
Panel A: Northbound									
1. Private cars	-0.31	0.08	0.23	0.08	-0.32	0.24	0.17	0.18	-0.35
3. Motorcycles	-0.67	0.41	0.26	0.60	-0.60	0.00	0.88	0.00	-0.88
7. Goods vehicles not more than 5.5 tonnes	-0.32	0.32	0.00	0.32	-0.49	0.17	0.00	0.21	-0.21
8. Goods vehicles between 5.5 and 24 tonnes	-0.30	0.30	0.00	0.22	-0.41	0.19	0.00	0.28	-0.28
9. Goods vehicles over 24 tonnes	0.00	0.00	0.00	0.00	-0.53	0.53	0.00	0.88	-0.88
Panel B: Southbound									
1. Private cars	-0.35	0.10	0.24	0.11	-0.32	0.20	0.20	0.15	-0.35
3. Motorcycles	-0.63	0.39	0.24	0.60	-0.60	0.00	0.91	0.00	-0.91
7. Goods vehicles not more than 5.5 tonnes	-0.35	0.31	0.04	0.32	-0.47	0.15	0.05	0.18	-0.23
8. Goods vehicles between 5.5 and 24 tonnes	-0.32	0.27	0.05	0.21	-0.40	0.19	0.05	0.24	-0.29
9. Goods vehicles over 24 tonnes	0.00	0.00	0.00	0.00	-0.52	0.52	0.00	0.67	-0.67

Note: The elasticity estimates for taxis and buses are all equal to zero because their β_{jk} estimates ($j \neq k$) have been restricted to zero. Further, the insignificant β_{jk} estimates for the vehicle types in this table are conservatively set to zero.

TABLE 4 Disaggregate Elasticity (γ_{jk}) Estimates Based on Significant α_{jk} Estimates for Peak-Hour Usage (M_{jt}) by Direction and Vehicle Type.

Vehicle type	γ_{11}	γ_{12}	γ_{13}	γ_{21}	γ_{22}	γ_{23}	γ_{31}	γ_{32}	γ_{33}
Panel A: Northbound									
1. Private cars	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3. Motorcycles	-0.41	0.41	0.00	0.43	-0.43	0.00	0.00	0.00	0.00
7. Goods vehicles not more than 5.5 tonnes	-1.06	1.06	0.00	0.24	-0.24	0.00	0.00	0.00	0.00
8. Goods vehicles between 5.5 and 24 tonnes	0.00	0.00	0.00	0.00	-0.23	0.23	0.00	0.32	-0.32
9. Goods vehicles over 24 tonnes	0.00	0.00	0.00	0.00	-0.56	0.56	0.00	0.91	-0.91
Panel B: Southbound									
1. Private cars	-0.21	0.21	0.00	0.13	-0.13	0.00	0.00	0.00	0.00
3. Motorcycles	-0.78	0.43	0.34	0.39	-0.39	0.00	0.71	0.00	-0.71
7. Goods vehicles not more than 5.5 tonnes	-1.16	1.16	0.00	0.37	-0.37	0.00	0.00	0.00	0.00
8. Goods vehicles between 5.5 and 24 tonnes	0.00	0.00	0.00	0.00	-0.20	0.20	0.00	0.24	-0.24
9. Goods vehicles over 24 tonnes	0.00	0.00	0.00	0.00	-0.52	0.52	0.00	0.63	-0.63

Note: The elasticity estimates for taxis and buses are all equal to zero because their α_{jk} estimates ($j \neq k$) have been restricted to zero. Further, the insignificant α_{jk} estimates for the vehicle types in this table are conservatively set to zero.

TABLE 5 Aggregate Elasticity (E_{jk}) Estimates for Monthly Total Usage and Peak-Hour Usage.

Tunnel ID	1. Cross-Harbour Tunnel (CHT)	2. Eastern Harbour Crossing (EHC)	3. Western Harbour Crossing (WHC)
Panel A: Total Northbound Usage			
1. Cross-Harbour Tunnel (CHT)	-0.2065	0.1113	0.0951
2. Eastern Harbour Crossing (EHC)	0.1120	-0.2749	0.1629
3. Western Harbour Crossing (WHC)	0.1002	0.1179	-0.2182
Panel B: Total Southbound Usage			
1. Cross-Harbour Tunnel (CHT)	-0.2276	0.1183	0.1093
2. Eastern Harbour Crossing (EHC)	0.1313	-0.2716	0.1403
3. Western Harbour Crossing (WHC)	0.1152	0.1002	-0.2154
Panel C: Peak-Hour Northbound Usage			
1. Cross-Harbour Tunnel (CHT)	-0.1056	0.1056	0.0000
2. Eastern Harbour Crossing (EHC)	0.0503	-0.0595	0.0092
3. Western Harbour Crossing (WHC)	0.0000	0.0060	-0.0057
Panel D: Peak-Hour Southbound Usage			
1. Cross-Harbour Tunnel (CHT)	-0.2342	0.2189	0.0153
2. Eastern Harbour Crossing (EHC)	0.1313	-0.1422	0.0109
3. Western Harbour Crossing (WHC)	0.0063	0.0070	-0.0137

TABLE 6 Aggregate Responses to the Toll Changes Proposed by the HKSAR Government.

Vehicle type/Direction	Option A			Option B			Option C		
	CHT	EHC	WHC	CHT	EHC	WHC	CHT	EHC	WHC
Panel A: Proposed Tolls (HK$/vehicle trip) in Hong Kong Transport and Housing Bureau (2013, p.13), with Changes from the January 2016 Tolls in ( )									
1. Private cars	25 (+5)	20 (-5)	60 (0)	25 (+5)	20 (-5)	60 (0)	30 (+10)	20(-5)	60 (0)
2. Taxis	19 (+9)	15 (-10)	55 (0)	13 (+3)	20 (-5)	55 (0)	10 (0)	15(-10)	55 (0)
3. Motorcycles	12 (+4)	9 (-4)	25 (0)	10 (+2)	10 (-3)	25 (0)	12 (+4)	9(-4)	25 (0)
4. Light buses	25 (+15)	20 (-18)	70 (0)	13 (+3)	30 (-8)	70 (0)	10 (0)	38 (0)	70 (0)
5. Single deck buses	31 (+21)	25 (-25)	110 (0)	13 (+3)	40 (-10)	110 (0)	10 (0)	50 (0)	110 (0)
6. Double deck buses	47 (+32)	38 (-37)	155 (0)	19 (+4)	60 (-15)	155 (0)	15 (0)	75 (0)	155 (0)
7. Goods vehicles not more than 5.5 tonnes	28 (+13)	23 (-15)	70 (0)	19 (+4)	30 (-8)	70 (0)	19 (+4)	23 (-15)	70 (0)
8. Goods vehicles between 5.5 and 24 tonnes	38 (+18)	30 (-20)	95 (0)	25 (+5)	40 (-10)	95 (0)	25 (+5)	30 (-20)	95 (0)
9. Goods vehicles over 24 tonnes	56 (+26)	45 (-30)	125 (0)	38 (+8)	60 (-15)	125 (0)	38 (+8)	45 (-30)	125 (0)
Panel B: Change in Average Monthly Total Usage (= Annual Sum of Monthly Total Usage ÷ 12 Months) of All Vehicle Types; Percentage Change from the July 2014 – June 2015 Value in ( )									
Northbound	-195746	171227	-4855	-129164	102324	-2015	-199055	149623	7643
	(-11.3%)	(14.9%)	(-0.5%)	(-7.4%)	(8.9%)	(-0.2%)	(-11.5%)	(13.0%)	(0.8%)
Southbound	-211428	167448	2268	-142047	102169	2878	-215854	151277	14022
	(-12.0%)	(15.1%)	(0.2%)	(-8.1%)	(9.2%)	(0.3%)	(-12.2%)	(13.6%)	(1.5%)
Panel C: Change in Average Peak-Hour Usage (= Annual Sum of Peak-Hour Usage ÷ 12 Months) of All Vehicle Types; Percentage Change from the July 2014 – June 2015 Value in ( )									
Northbound	-290	228	-7	-150	90	-3	-220	158	-7
	(-9.6%)	(7.2%)	(-0.2%)	(-5.0%)	(2.9%)	(-0.1%)	(-7.3%)	(5.0%)	(-0.2%)
Southbound	-521	414	-2	-322	229	0	-462	369	-2
	(-16.8%)	(12.9%)	(-0.1%)	(-10.3%)	(7.1%)	(-0.0%)	(-14.9%)	(11.5%)	(-0.1%)

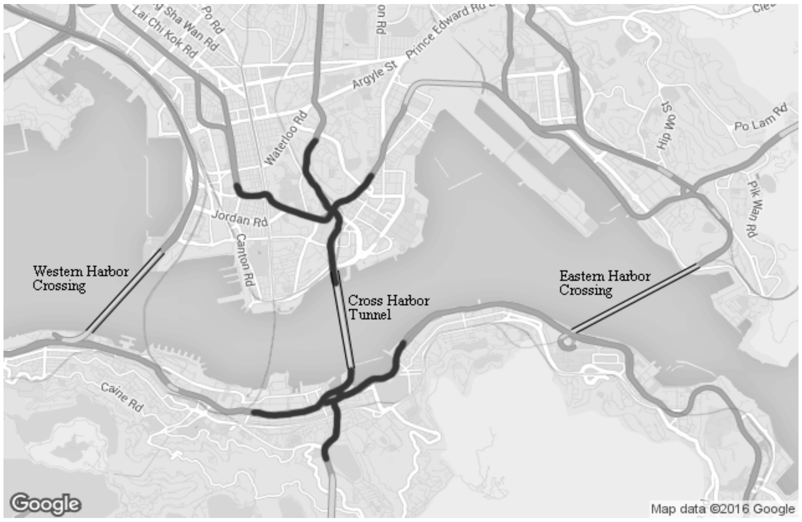

FIGURE 1 Severe congestion at Hong Kong's Cross-Harbour Tunnel (CHT), with the darkened line denoting the daily queues observed during rush hours along the roads leading to the CHT's northern end in Kowloon Peninsula and southern end on Hong Kong Island *(8)*.

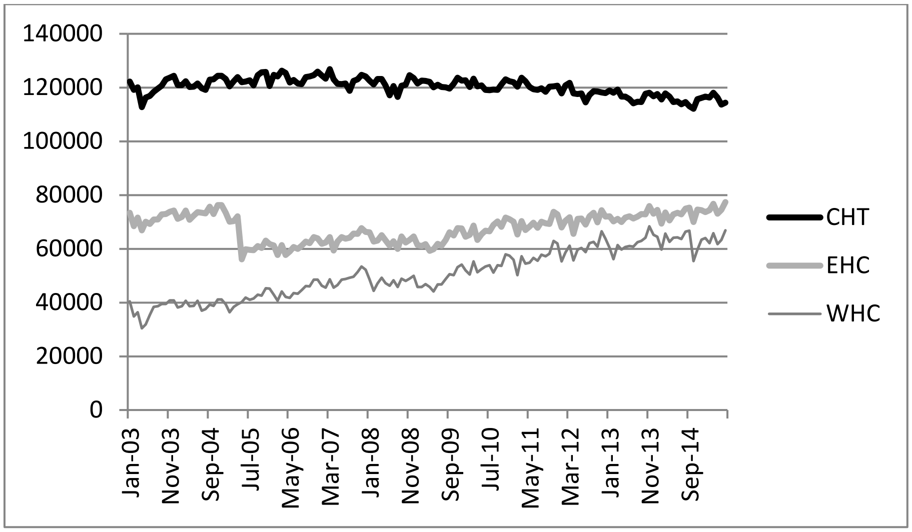

FIGURE 2 Monthly usage of the Cross-Harbour Tunnel (CHT), Eastern Harbour Crossing (EHC), and Western Harbour Crossing (WHC) for January 2003 – June 2015.

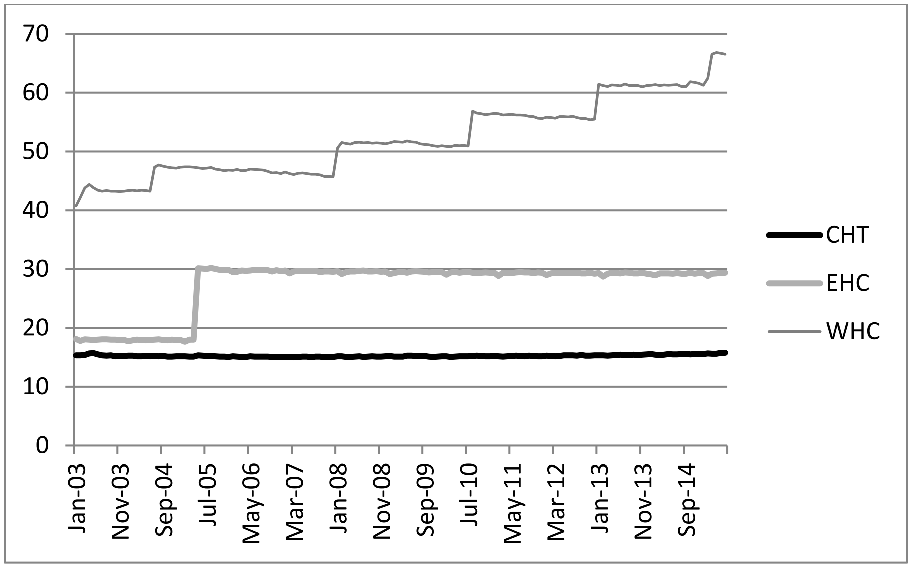

FIGURE 3 Monthly average tolls in HK$ (US$1 ≈ HK$7.8) of the Cross-Harbour Tunnel (CHT), Eastern Harbour Crossing (EHC) and Western Harbour Crossing (WHC) for January 2003 – June 2015.