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Can Hong Kong price-manage its cross-harbor-tunnel congestion?

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ABSTRACT

Hong Kong drivers face daily congestion, especially at the Cross Harbor Tunnel (CHT) whose tolls are substantially lower than those of the drivers' other two tunnel options: the Eastern Harbor Crossing (EHC) and the Western Harbor Crossing (WHC). In 2013, the Hong Kong Special Administrative Region (HKSAR) Government issued a consultation paper, seeking public comments on three toll-change proposals that would raise the CHT's tolls and lower the EHC's tolls. The WHC's tolls would remain unchanged due to its congested connecting roads. Using monthly crossing data available from the HKSAR's Transport Department for 2000–2012, this paper uses a Generalized Leontief demand system to document that the usage patterns of the three tunnels is price-responsive. Hence, we conclude that the proposed toll changes are likely to be effective in transportation demand management, by shifting a portion of the CHT's usage to the EHC and WHC, thereby relieving the CHT's congestion.

1. Introduction

Hong Kong is densely populated, with a geographic size of approximately 1100 km^2 and a population of some 7.2 million. It is prone to severe traffic jams, as is true of most major cities (e.g., Rio de Janeiro, Mexico City, New York City, Los Angeles, London, Paris, Tokyo, Singapore, Beijing, and Shanghai). With 329 licensed vehicles for every km of road,[1] Hong Kong would become one big parking lot if most of these vehicles were on the road, under the assumption that each licensed vehicle's average length is about three meters. Hong Kong drivers experience daily congestion delays, especially at the Cross Harbor Tunnel (CHT), as shown in Fig. 1. In contrast, traffic is relatively light at the Eastern Harbor Crossing (EHC) and the Western Harbor Crossing (WHC).

Each cross-harbor tunnel has nine vehicle-specific tolls,[2] applicable to private cars, taxis, motorcycles, light buses, single-decked buses, double-decked buses, light goods vehicles, medium goods vehicles, and heavy goods vehicles. To reduce the CHT's congestion, the Hong Kong Special Administrative Region (HKSAR) Government has recently issued a consultation paper (Transport and Housing Bureau, 2013) seeking public comments on three toll-change proposals that aim to implement

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[1] See http://www.gov.hk/en/about/abouthk/factsheets/docs/transport.pdf.
[2] See http://www.td.gov.hk/en/transport_in_hong_kong/tunnels_and_bridges/toll_rates_of_road_tunnels_and_lantau_link/index.html.

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Fig. 1. Congestion problem of the Hong Kong Cross Harbor Tunnel, with the red line denoting the queue observed during daily rush hours on the tunnel's connecting roads (Wilbur Smith Associates Limited, 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transportation demand management (Vickrey, 1967, 1969; Pretty, 1988; Meyer, 1999; May and Milne, 2000). The implied premise of the proposed toll changes is that the three tunnels are substitutes with discernible price responsiveness.

There have been two prior studies on the price responsiveness of Hong Kong's three cross-harbor tunnels, the first of which was by Hau et al. (2011). Based on a sample of 426 respondents to a route-choice survey conducted in 1999 (p. 471), their discrete-choice (multinomial logit) analysis yields *disaggregate* price elasticity estimates by vehicle type: (a) private cars' own-price elasticity estimates of −0.30 to −0.43 and cross-price elasticity estimates of 0.10–0.25; (b) taxis' own-price elasticity estimates of −0.55 to −0.82 and cross-price elasticity estimates of 0.18–0.54; (c) light goods vehicles' own-price elasticity estimates of −0.83 to −1.02 and cross-price elasticity estimates of 0.39–0.57; and (d) medium and heavy goods vehicles' own-price elasticity estimates of −0.90 to −1.06 and cross-price elasticity estimates of 0.38–0.56 (Hau et al., 2011, pp. 475–476). These estimates suggest that the tunnel demands by vehicle type are price-inelastic and that the tunnels are substitutes with positive cross-price elasticities.

Hau et al. (2011), however, do not estimate the price responsiveness of motorcycles, light buses, single-decked buses, and double-decked buses. Unless these unstudied vehicles are totally price-insensitive, their study does not provide sufficient information to enable one to assess the potential effectiveness of the HKSAR Government's toll-change proposals. To be sure, the price elasticity estimates for the unstudied vehicles would be unnecessary if their total harbor crossings were close to zero. This, however, is not the case for buses; see Fig. 2.

The second study is due to Loo (2003). Using monthly aggregate data on tunnel usage by all vehicle types, from January 1979 to September 2000, this study estimates six tunnel-specific double-log regressions to examine the monthly tunnel traffic of six major toll tunnels in Hong Kong. The explanatory variables of each cross-harbor tunnel's regression only include the natural-log of the tunnel's own average toll, thus yielding the tunnel's own-price elasticity estimate, while assuming its cross-price elasticities to be zero. These own-price elasticity estimates are *aggregate* estimates that measure the price responsiveness of the total harbor crossings via a given tunnel made by all vehicle types. The own-price elasticity estimate for the CHT is −0.291, and the estimates for the EHC and WHC are positive though statistically insignificant ($p > 0.05$) (Loo, 2003, Table 3). As the study assumes zero cross-price responsiveness for all six tunnels, it lacks the complete information necessary to assess the potential effectiveness of the toll-change proposals for the three cross-harbor tunnels.

Notwithstanding their incomplete information on price responsiveness, these two studies apparently say "yes" to the substantive policy question: Can Hong Kong price-manage its cross-harbor-tunnel congestion? The vast difference in the two studies' elasticity estimates, however, motivates us to seek additional evidence on the price responsiveness of harbor-tunnel crossings. Moreover, both studies are based on data that are over 10 years old, highlighting the need for updated elasticity estimates to answer the policy question posited above.

Our estimates are based on 156 monthly observations during the 13-year period of 2000–2012 on harbor-tunnel crossings described in Appendix A. Using this updated data sample, we estimate *nine* vehicle-specific Generalized Leontief (GL) demand systems to quantify the price responsiveness of monthly harbor crossings made by the *nine* vehicle types. Our

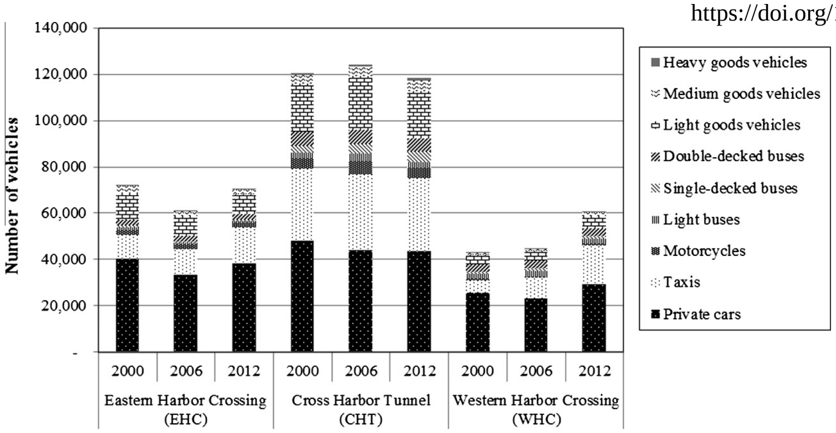

Fig. 2. Average daily tunnel crossings by vehicle type for selected years; CHT's crossings ≈ 120,000 per day > CHT's design capacity = 78,000 per day under uncongested conditions (Wilbur Smith Associates Limited, 2010, p. 1–1).

key findings are as follows. First, our comprehensive set of 27 (= 3 tunnels × 9 vehicle types) disaggregate price elasticity estimates shows that the three tunnels are substitutes and that their usage is price-inelastic, thus corroborating the vehicle-specific own-price elasticity estimates in Hau et al. (2011, pp. 475–476), the CHT's aggregate own-price elasticity estimate in Loo (2003, Table 3), and the lower half of the range in Litman (2013, p. 40). Second, harbor-tunnel crossings by motorcycles are the most price-sensitive, followed by those of private cars and goods vehicles. Crossings by taxis and buses are the least price-sensitive. Finally, we estimate that the toll-change proposals in Transport and Housing Bureau (2013) could reduce the most congested CHT's monthly usage by approximately 19.6%, which in turn could lead to a 16.1% increase in the less congested EHC's daily usage and a 4.4% increase in the least congested WHC's daily usage; see Table 6. These estimated changes imply an estimated reduction of 3.8% in the three tunnels' total monthly usage. Hence, we conclude that Hong Kong can price-manage its cross-harbor-tunnel congestion.

Our paper makes substantive contributions to both the Hong Kong tolling-policy debate and the transportation literature. First, it presents a new approach to comprehensively analyze the vehicle-specific price responsiveness of Hong Kong's monthly harbor-tunnel crossings. Instead of the double-log or linear demand functions used in prior studies (e.g., Hirschman et al., 1995; Loo, 2003; Su, 2010), we use a GL demand specification (Diewert, 1971) to formally test whether the three tunnels are substitutes in the driver's tunnel-choice decisions.

Second, we present a demand modeling alternative when survey data collection is costly but aggregate data are readily available (Nam, 1997), yielding results that would complement empirical findings based on route-choice survey data (e.g., Burris and Pendyala, 2002; Olszewski and Xie, 2005; Washbrook et al., 2005; Train and Wilson, 2008; Hau et al., 2011). Our alternative can be used to analyze the usage pattern of a city's multiple toll-crossing options (e.g., New York City's toll tunnels and bridges,[3]) so long as suitable aggregate data such as those described in Appendix A are available.

Third, we provide detailed elasticity estimates by vehicle type for all three tunnels, thus enriching the limited evidence in several literature reviews (e.g., Oum et al., 1992; Goodwin, 1992; Graham and Glaister, 2004; Litman, 2004, 2013).

Fourth, our vehicle-specific elasticity estimates for motorcycles and three bus types complete the price responsiveness information absent in Hau et al. (2011).

Fifth, our aggregate own-price elasticity estimates are negative for all three tunnels, unlike those found by Loo (2003), two of which, the estimates for the EHC and WHC, are positive. Further, our positive aggregate cross-price elasticity estimates complete the critical price-responsiveness information that Loo (2003) lacks.

Finally, we document the potential effectiveness of the HKSAR Government's three toll-change proposals (Transport and Housing Bureau, 2013), affirming the virtue of pricing in transportation demand management.

The paper proceeds as follows. Section 2 provides a contextual background for our research. Section 3 is the model specification. Section 4 contains the empirical results, and Section 5 concludes.

2. Background

Table 1 describes the three cross-harbor tunnels constructed under a 30-year build-operate-transfer contract. Completed in 1972, the CHT was the first cross-harbor tunnel connecting the central business districts on the two sides of the Victoria Harbor. The EHC and WHC opened in 1989 and 1997, respectively, to accommodate the traffic growth driven by rapid economic development in the territory.

As shown in Fig. 1, the CHT is heavily congested, with average daily crossings of around 120,000, far exceeding its design capacity of 78,000 under uncongested conditions (Wilbur Smith Associates Limited, 2010, p. 1–1). Fig. 2 suggests that in

[3] The city's tolls are available at: http://www.panynj.gov/bridges-tunnels/tolls.html.

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Table 1
Characteristics of Hong Kong's three cross-harbor tunnels. *Sources:* http://www.td.gov.hk/en/transport_in_hong_kong/tunnels_and_bridges/index.html, http://www.westernharbourtunnel.com/en/about23.html, http://www.easternharbourtunnel.com.hk/nhktc/eng/e-company/e-introduc.htm.

	Cross Harbor Tunnel (CHT)	Eastern Harbor Crossing (EHC)	Western Harbor Crossing (WHC)
Length (km)	1.8	2.2	2.0
Year of opening	1972	1989	1997
Year of franchise expiration	1999	2016	2023
Design capacity (crossings per day) under uncongested conditions	78,000	78,000	180,000

recent years, harbor-tunnel crossings by private cars and taxis have been rising at the EHC and WHC. At the end of 2012, however, the EHC's daily crossings of around 70,000 were still below its design capacity of 78,000. The WHC's daily crossings were just over 60,000, which is about one third of its design capacity.

The usage pattern among the three tunnels is partly due to the differences among the tolls shown in Table 2. From 2002 to 2012, the CHT's tolls were unchanged, while those of the EHC and the WHC had respectively increased once and five times. Fig. 3 displays (a) the ratio of the EHC's average toll and the CHT's average toll, and (b) the ratio of the WHC's average toll and the CHT's average toll. Here a tunnel's average toll is the weighted average of vehicle-specific tolls, with each vehicle type's weight being the share of the tunnel's total crossings by that vehicle type. This figure shows discernible changes in the tunnel usage pattern following the toll increases at the EHC and the WHC.

To balance the traffic flows among the three tunnels, the HKSAR Government proposes to increase the CHT's tolls and reduce those of the EHC, while keeping the WHC's tolls unchanged, due to the WHC's congested connecting roads (Transport and Housing Bureau, 2013). We now investigate whether these toll-change proposals are likely to be effective in affecting the tunnels' usage pattern.

3. Model

Our investigation uses monthly aggregate data to estimate the GL system of tunnel demands by the drivers of each type of vehicle (e.g., private cars). To derive the GL system based on the concept of a cost function, we begin by discussing the cost basis of the monthly aggregate data, as suggested by two very helpful referees' detailed comments. The discussion makes explicit what we know and what we do not know, thereby explaining the kind of information that can be gleaned from the aggregate data. We then show how we use these data to estimate the price responsiveness of cross-harbor tunnel demands.

3.1. Monthly cost to a driver of a particular type of vehicle

We do not know the monthly cost associated with the tunnel choices made by a driver of a particular type of vehicle. Nonetheless, we can develop the cost basis for our empirical analysis. Recognizing the factors known to affect transport demands (Litman, 2013), our cost focus reflects that harbor crossings are an intermediate output for a driver achieving a final output goal on the other side of the harbor (e.g., going to work, attending a meeting, shopping, or goods delivery).

We assume a cost-minimizing driver who decides which of the three tunnels to use for each cross-harbor trip. When making this assumption, we recognize that drivers of public transportation vehicles (e.g., taxis and buses) do not pay the tunnel tolls, which are already included in these vehicles' fares. Also, they may not have the choice of which tunnel to use. Hence, these drivers may not be cost minimizing. Happily, our empirical results in Section 4 broadly support our maintained assumption of a cost-minimizing driver who can make a tunnel choice.

For expositional ease, and with minimal risk of confusion, we initially suppress a monthly index $t = 1, \ldots T$ to denote the month in question. Each $a \to b$ trip begins at point $a = 1, \ldots, A$ and ends at point $b = 1, \ldots B$. Our $a \to b$ trip representation is general, since a can be one of the driver's many points of origin and b one of the driver's many points of destination.

Each $a \to b$ trip involves one of the three tunnels. Suppose the driver uses tunnel $j = 1(\text{EHC}),\ 2(\text{CHT}),$ and $3(\text{WHC})$. The driver's tunnel-specific cost of a single trip made in hour $h = 1, \ldots, 24$ on day $d = 1, \ldots D$ (= the number of days in the month) is the sum of: (1) P_j = the toll for tunnel j; (2) C_{abjhd} = out-of-pocket costs (e.g., vehicular fuel and operation and maintenance [O&M]) for one $a \to b$ trip via tunnel j in hour h on day d; and (3) D_{abjhd} = other costs (e.g., value of travel time, which depends on the trip's distance and traffic congestion, as well as the possible cost of annoyance caused by slow traffic) for one $a \to b$ trip via tunnel j in hour h on day d. As the driver's tunnel-specific single-trip costs on a given day differ by origin, destination and hour, the three tunnels are presumptively imperfect substitutes in the driver's daily tunnel-choice decisions. Thanks to a referee's insightful comment, a case in point is the cross-harbor trip from the Happy Valley area on Hong Kong Island to the Jordan Mass Transit Railway (MTR) Station on the Kowloon Peninsula.

Suppose the driver's daily harbor-crossing requirement is Q_{abd}, which has scheduled hours of arrival that prevent the driver from making trips only during the commonly known uncongested hours (e.g., 02:00–06:00). The daily requirement

Table 2
Cross-harbor tunnel tolls (HK$/crossing) during 1 January 2000–31 December 2012. *Sources:* Annual Transport Digest, various issues, Transport Department, HKSAR; and http://www.westernharbortunnel.com/en/about4.html.

Toll period dates (dd/mm/yyyy)	Cross Harbor Tunnel (CHT)	Eastern Harbor Crossing (EHC)		Western Harbor Crossing (WHC)					
	01/01/2000–31/12/2012	01/01/2000–30/04/2005	01/05/2005–31/12/2012	01/01/2000–02/12/2000	03/12/2000–15/02/2003	16/02/2003–03/07/2004	04/07/2004–05/01/2008	06/01/2008–31/07/2010	01/08/2010–31/12/2012
Private cars	20	15	25	30	35	37	45	45	50
Taxis	10	15	25	30	35	35	40	40	45
Motorcycles	8	8	13	15	20	20	22	22	23
Light buses	10	23	38	40	45	47	55	55	60
Single-decked buses	10	30	50	40	50	60	80	80	90
Double-decked buses	15	45	75	55	70	85	115	115	128
Light goods vehicles (under 5.5 tonnes)	15	23	38	45	50	50	55	55	60
Medium goods vehicles (between 5.5 and 24 tonnes)	20	30	50	65	70	70	80	80	85
Heavy goods vehicles (over 24 tonnes)	30	45	75	95	100	100	110	110	115

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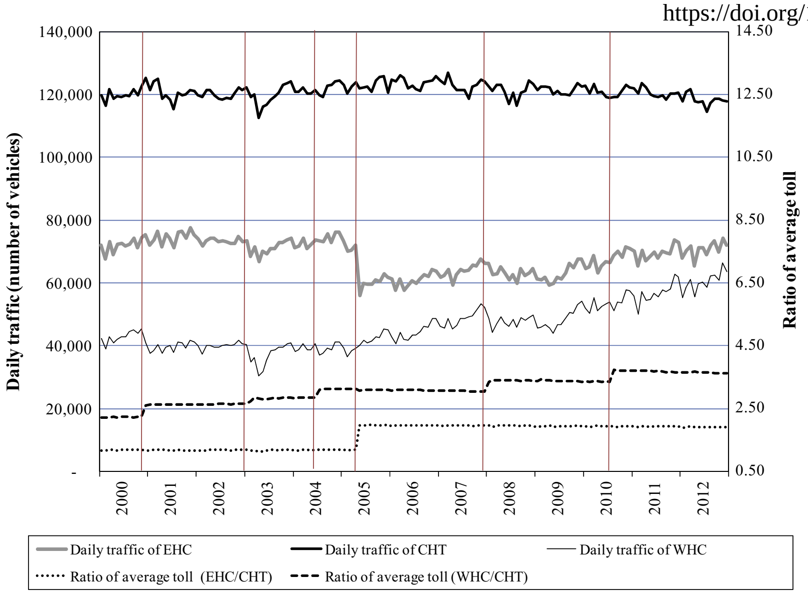

Fig. 3. Daily traffic and toll ratios of the three cross-harbor tunnels.

depends on such factors as the driver's cost budget, which may limit the number of trips per day, employment that may require job-related trips, or other factors such as shopping and social gatherings. Hence, changes in these factors alter the driver's daily harbor-crossing requirements within a month, which are unobservable without data such as those collected through a carefully designed route-choice survey.

The driver's monthly total use of tunnel j is:

$$Q_j = \sum_d \sum_h \sum_a \sum_b Q_{abjhd}, \tag{1}$$

where Q_{abjhd} = the number of trips made by the driver in hour h on day d via tunnel j to meet the daily harbor-crossing requirement: $\sum_h \sum_j Q_{abjhd} = Q_{abd}$. The value of Q_{abjhd} is likely equal to zero for most hours and equal to unity for a few hours of the day, reflecting the time-dependent discrete choices that a driver makes in selecting the cross-harbor trip routes.

The driver's monthly total cost for using tunnel j is:

$$TC_j = P_j Q_j + K_j, \tag{2}$$

where P_jQ_j = the monthly total toll cost; and $K_j = \sum_d \sum_h \sum_a \sum_b Q_{abjhd}(C_{abjhd} + D_{abjhd})$ = the monthly total non-toll cost.

3.2. Monthly cost to heterogeneous drivers of a particular type of vehicle

The monthly cost TC_j in Eq. (2) applies to a single driver. But Hong Kong has many heterogeneous drivers with diverse attributes (e.g., income, employment, and vehicle size). Suppose there are S categories of drivers, with each s-category ($s = 1, \ldots, S$) containing M_s similar drivers. While we do not know the definition for each category, or the number M_s, we can link these drivers' total costs to their constituent components.

Based on Eq. (1), let Q_{js} be the monthly total use of tunnel j by one driver in the s-category. The monthly aggregate number of harbor crossings via tunnel j for a particular vehicle type is:

$$N_j = \sum_s M_s Q_{js}. \tag{3}$$

Associated with N_j is the monthly aggregate cost for the vehicle type from using tunnel j:

$$F_j = P_j N_j + G_j, \tag{4}$$

where P_jN_j = the monthly aggregate toll cost of using tunnel j; $G_j = \sum_s M_s K_{js}$ = the monthly aggregate non-toll cost of using tunnel j; and K_{js} = the monthly aggregate non-toll cost for one s-category driver, whose calculation is based on the K_j variable in Eq. (2).

Using Eq. (4), the monthly aggregate cost for the vehicle type from using the three tunnels is the sum of the three tunnel-specific costs:

$$F = \sum_j (P_j N_j + G_j). \tag{5}$$

Built from highly disaggregate components, the variable F in Eq. (5) is the monthly cost summary of all tunnel choices made by the drivers of a particular vehicle type.

3.3. The GL demand system for a particular vehicle type

We have monthly aggregate data on P_j and N_j. But we do not know G_j in Eqs. (4) and (5). For empirical implementation, we assume the monthly G_{jt} to be a function of five variables such that $G_{jt} = G_j(Y_t, t, U_{1t}, U_{2t}, U_{3t})$ for month $t = 1,\ldots,T$. The first variable in $G_j(\bullet)$ is an observable economic indicator Y_t, which is proxied by the monthly real GDP. We have considered other aggregate data such as population and monthly employment. We do not use these data because they do not reflect the drivers' incomes, which presumably affect their daily trip requirements. The second variable is the month index t, which aims to capture the time-trend effect (e.g., vehicular fuel and O&M costs) on the monthly non-toll cost. The last three variables are the tunnel utilization factors to account for the congestion effect. Tunnel j's monthly utilization factor U_{jt} is the tunnel's monthly total private-car-equivalent (PCE) crossings divided by the tunnel's monthly total capacity (= daily vehicular capacity $*$ number of days in the month). Our computation of U_{jt} assumes the following PCE conversion rates: (a) taxis: 1.0; (b) motorcycles: 0.4; (c) light buses: 1.5; (d) single-decked buses: 3.0; (e) light goods vehicles: 1.5; (f) medium goods vehicles: 2.0; and (g) heavy goods vehicles: 2.5 (Wong, 2012).

These utilization factors are endogenous in our tunnel demand estimation presented below. To see this point, consider taxis' demand regressions that use taxis' crossings by tunnel as the left-hand-side (LHS) variables. As taxis' crossings directly contribute to the tunnels' total PCE crossings, rising tunnel usage by taxis increases the utilization factors, which are the regressions' right-hand-side (RHS) variables. Thus, these RHS variables are endogenously dependent on the LHS variables. To remedy the potential bias caused by the endogenous utilization factors, we use the three-stage-least-squares technique, as described in Section 3.7.

Based on Sections 3.1 and 3.2, the effect of GDP on the monthly total usage of tunnel j (i.e., N_j) has two parts. The first part is the output effect, reflecting that rising GDP tends to raise the drivers' daily trip requirements, thus increasing N_j. The second part is the congestion effect. Rising GDP tends to increase vehicle ownership and usage, which may cause or exacerbate congestion due to the fixed capacity of each tunnel. This in turn may discourage drivers from using a given tunnel (e.g., the highly congested CHT). When the first part dominates the second, an increase in GDP will tend to increase N_j. The effect of the time trend on N_j is an empirical issue that will be resolved in our demand estimation. The effect of tunnel j's utilization factor on N_j is expected to be negative because a heavily used tunnel j tends to discourage drivers from using it. The effect of tunnel k's utilization factor on N_j is expected to be positive because a heavily used tunnel $k \neq j$ tends to encourage drivers to switch to tunnel j.

Our aggregate data do not contain the information necessary to disentangle the two parts of the GDP effect. Nonetheless, we can still derive the toll responsiveness of monthly total usage of each tunnel. Specifically, consider the monthly cost function that corresponds to Eq. (5). Due to the assumed dependence of G_j on Y_t, t, and $\{U_{jt}\}$, we introduce index t into the monthly cost function $f(\bullet)$ below:

$$F_t = \sum_j [P_{jt}N_{jt} + G_j(Y_t, t, U_{1t}, U_{2t}, U_{3t})] = f(P_{1t}, P_{2t}, P_{3t}; \{G_j(Y_t, t, U_{1t}, U_{2t}, U_{3t})\}). \tag{6.a}$$

We assume that $f(\bullet)$ in Eq. (6.a) is well-behaved with the following properties: (a) it is homogenous of degree one in $\{P_{jt}\}$ and $\{G_{jt}\}$ so that changing all tolls and non-toll costs by a factor of $\lambda > 0$ will change the monthly total cost by that same factor; and (b) it is continuous, concave, and increasing in $\{P_{jt}\}$ and $\{G_{jt}\}$, implying that the tunnel demands have negative own-price elasticities (Varian, 1992, pp. 72–76).

As we do not know $G_j(Y_t, t, U_{1t}, U_{2t}, U_{3t})$, we rewrite $f(\bullet)$ as $H(\bullet)$ whose arguments are the observable tunnel tolls, the monthly GDP, a time trend, and the utilization factors:

$$F_t = H(P_{1t}, P_{2t}, P_{3t}, Y_t, t, U_{1t}, U_{2t}, U_{3t}). \tag{6.b}$$

We use the GL specification to parsimoniously parameterize $H(\bullet)$ (Diewert, 1971):

$$F_t = \left[\sum_j\sum_k \beta_{jk}P_{jt}^{1/2}P_{kt}^{1/2} + \sum_j \psi_j P_{jt}Y_t + \sum_j \theta_j P_{jt}t + \sum_j\sum_k \gamma_{jk}P_{jt}U_{kt}\right] + R_t, \tag{7}$$

where R_t is the arithmetic difference between the total cost in Eq. (6.a) and the [ ] term on the RHS of Eq. (7). We assume $R_t = R(Y_t, t, U_{1t}, U_{2t}, U_{3t})$, the validity of which is verified following the derivation of the GL demand equations below. Each system's parameters to be estimated are: $\{\beta_{jk}\}$, $\{\psi_j\}$, $\{\theta_t\}$, and $\{\gamma_{jk}\}$.

Since by assumption $f(\bullet)$ is homogeneous of degree one, it immediately follows that so too is the cost function of Eq. (7). Changing each cost component by a factor of $\lambda > 0$ will change the total cost by that same factor:

$$\lambda F_t = \left[\sum_j\sum_k \beta_{jk}(\lambda P_{jt})^{1/2}(\lambda P_{kt})^{1/2} + \sum_j \psi_j \lambda P_{jt}Y_t + \sum_j \theta_j \lambda P_{jt}t + \sum_j\sum_k \lambda\gamma_{jk}P_{jt}U_{kt}\right] + \lambda R_t.$$

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The cost function is continuous, increasing, and concave in $\{P_{jt}\}$ and R_t when $\beta_{jk} = \beta_{kj} \geqslant 0 (j \neq k)$ (Diewert, 1971, p. 497). In short, $H(\bullet)$ is a well-behaved cost function under the constraint of $\beta_{jk} = \beta_{kj} \geqslant 0 (j \neq k)$.

Applying Shephard's Lemma (Diewert, 1971, p. 495) to Eq. (7), we derive the following estimable demand equations that obey the constraint of $\beta_{jk} = \beta_{kj} \geqslant 0 (j \neq k)$:

$$\partial F_t/\partial P_{1t} = N_{1t} = \beta_{11} + \beta_{12}(P_{2t}/P_{1t})^{1/2} + \beta_{13}(P_{3t}/P_{1t})^{1/2} + \psi_1 Y_t + \theta_1 t + \sum_k \gamma_{1k} U_{kt} \tag{8.a}$$

$$\partial F_t/\partial P_{2t} = N_{2t} = \beta_{22} + \beta_{12}(P_{1t}/P_{2t})^{1/2} + \beta_{23}(P_{3t}/P_{2t})^{1/2} + \psi_2 Y_t + \theta_2 t + \sum_k \gamma_{2k} U_{kt} \tag{8.b}$$

$$\partial F_t/\partial P_{3t} = N_{3t} = \beta_{33} + \beta_{13}(P_{1t}/P_{3t})^{1/2} + \beta_{23}(P_{2t}/P_{3t})^{1/2} + \psi_3 Y_t + \theta_3 t + \sum_k \gamma_{3k} U_{kt} \tag{8.c}$$

Eqs. (8.a)–(8.c) imply that the total toll cost is $\sum_j P_{jt} N_{jt} = \sum_j \sum_k \beta_{jk} P_{jt}^{1/2} P_{kt}^{1/2} + \sum_j \psi_j P_{jt} Y_t + \sum_j \theta_j P_{jt} t + \sum_j \sum_k \gamma_{jk} P_{jt} U_{kt}$. Using Eq. (6.a), we verify $R_t = \sum_j G_j(Y_t, t, U_{1t}, U_{2t}, U_{3t})$, which is the total non-toll cost that is independent of the tolls.

Eqs. (8.a)–(8.c) state that the monthly demand for tunnel j, or N_{jt}, by the drivers of a particular type of vehicle depends linearly on the observable variables $\{P_{kt}/P_{jt}\}$, Y_t, t, and $\{U_{jt}\}$. They allow each tunnel's vehicle-specific monthly crossings to vary with these variables. This is in contrast to a discrete-choice analysis that typically splits a *fixed* volume of harbor crossings among the three tunnels (e.g., Hau et al., 2011). To see this point, consider a vehicle type whose tunnel-specific usage share is (N_j/N), where $N = \sum_j N_j$ = total usage of all three tunnels by the vehicle type. As $\ln(N_j/N) = \ln N_j - \ln N$, the usage share's elasticity based on $\ln(N_j/N)$ is the same as the usage level's elasticity based on $\ln N_j$ when there is no change in the total usage N. In other words, absent a noticeable change in the vehicle type's total tunnel usage, the usage share's elasticity estimate should be close to the usage level's elasticity estimate when *both* estimates come from one single data file. This may not be true, however, when the usage share's elasticity estimate is based on route-choice survey data collected in a given year, as in Hau et al. (2011), while the usage level's elasticity estimate is based on the aggregate monthly data as in the present study.

When $\beta_{jk} = \beta_{kj} \geqslant 0$, $\partial N_{jt}/\partial P_{jt} \leqslant 0$ and $N_{jt}/P_{kt} \geqslant 0$. We postulate $\psi_j \geqslant 0$, implying that an increase in Y_t tends to increase N_{jt}. We have no expectations as to the sign of θ_j, which is to be determined in our demand estimation. Finally, we postulate $\gamma_{jj} \leqslant 0$ to reflect that a heavily used tunnel j tends to discourage drivers from using tunnel j, and $\gamma_{jk} \geqslant 0$ for $j \neq k$ to reflect that a heavily used tunnel k tends to encourage drivers to switch to tunnel j.

3.4. Elasticity calculation

3.4.1. Disaggregate elasticity of a vehicle type

Based on Eqs. (8.a)–(8.c), the monthly cross-price elasticity of a given vehicle type for tunnels j and k $(j \neq k)$ is:

$$\eta_{jkt} = \partial \ln N_{jt}/\partial \ln P_{kt} = 1/2\beta_{jk}(P_{kt}/P_{jt})^{1/2}/N_{jt}. \tag{9.a}$$

When $\beta_{jk} \geqslant 0,\ \eta_{jkt} \geqslant 0$, suggesting that tunnels j and k are substitutes for the drivers of a particular vehicle type.

The monthly own-price elasticity of tunnel j is:

$$\eta_{jjt} = \partial \ln N_{jt}/\partial \ln P_{jt} = -1/2\left[\sum_{k \neq j} \beta_{jk}(P_{kt}/P_{jt})^{1/2}\right] \Big/ N_{jt}. \tag{9.b}$$

When $\beta_{jk} \geqslant 0,\ \eta_{jjt} \leqslant 0$, suggesting that this vehicle type has a downward-sloping demand curve for tunnel j.

Because of the nonlinear and monthly nature of the elasticity formulae given by Eqs. (9.a) and (9.b), our disaggregate elasticity estimates are computed via a two-step procedure. First, we use Eqs. (9.a) and (9.b) to compute the elasticity estimates for each month in the sample. Then, we compute the equally-weighted average of the monthly values for a given elasticity (e.g., η_{11} = own-price elasticity for EHC crossings), which is the number shown in Fig. 5 in Section 4.

3.4.2. Aggregate elasticity of all vehicle types

An aggregate price elasticity estimate summarizes the price responsiveness of all vehicles using a particular tunnel. To compute an aggregate elasticity, we first use the index m to denote a vehicle type. As each tunnel has nine vehicle-specific tolls, m = 1 (private cars), 2 (taxis), 3 (motorcycles), 4 (light buses), 5 (single-decked buses), 6 (double-decked buses), 7 (light goods vehicles under 5.5 tonnes), 8 (medium goods vehicles between 5.5 and 24 tonnes), and 9 (heavy goods vehicles over 24 tonnes).

Suppose the total use of tunnel j by all vehicle types in month t is Z_{jt}, which is the sum of its nine components, $Z_{1jt}, \ldots, Z_{mjt}, \ldots, Z_{9jt}$, where $Z_{mjt} = N_{jt}$ for vehicle type m in Eqs. Eqs. (8.a)–(8.c). The monthly aggregate own-price elasticity of Z_{jt} is the percent change in the total usage of tunnel j resulting from a one-percent change in that tunnel's nine tolls:

$$E_{jjt} = E_{1jjt} W_{1jt} + \cdots + E_{9jjt} W_{9jt}, \tag{10.a}$$

where $E_{mjjt} = \eta_{jjt}$ for vehicle type m based on Eq. (9.b), and $W_{mjt} = (Z_{mjt}/Z_{jt})$ = vehicle type m's share of the monthly total usage of tunnel j. To derive Eq. (10.a), we first recognize that the change in tunnel j's total usage is $dZ_{jt} = (\partial Z_{1jt}/\partial P_{1jt})dP_{1jt} + \cdots + (\partial Z_{9jt}/\partial P_{9jt})dP_{9jt}$. Evaluated at $dP_{mjt}/P_{mjt} = 1$ for all $m = 1, \ldots, 9$, the percent change in Z_{jt} is $(dZ_{jt}/Z_{jt}) = (\partial Z_{1jt}/\partial P_{1jt})(P_{1jt}/Z_{1jt})(Z_{1jt}/Z_{jt}) + \cdots + (\partial Z_{9jt}/\partial P_{9jt})(P_{9jt}/Z_{9jt})(Z_{9jt}/Z_{jt}) = E_{1jjt}W_{1jt} + \cdots + E_{9jjt}W_{9jt} = E_{jjt}$.

Our aggregate own-price elasticity is computed via a two-step procedure. First, we use Eq. (10.a) to compute the E_{jjt} estimate as a weighted average of the vehicle-specific estimates based on Eq. (9.b) for each month in the sample. Then, we compute the equally-weighted average of the monthly values to find the aggregate own-price elasticity estimate of E_{jj} reported in Table 4.

The calculation of the aggregate cross-price elasticity $E_{jk} (j \neq k)$ is analogous to the one for E_{jj}, except that we now use:

$$E_{jkt} = E_{1jkt}W_{1jt} + \cdots + E_{9jkt}W_{9jt}, \tag{10.b}$$

where $E_{mjkt} = \eta_{jkt}$ for vehicle type m, based on Eq. (9.a).

3.5. The hypothesis

To determine whether the drivers of a particular vehicle type consider the three tunnels to be substitutes, we apply the Wald test (Davidson and MacKinnon, 1993, Chapter 13) to the null hypothesis:

$$H_0: \ \beta_{jk} = 0 \quad \text{for all } j \neq k.$$

If the data do not reject $H_0 (\alpha = 0.01)$, the elasticity estimates based on Eqs. (9.a) and (9.b) are not statistically different from zero, suggesting that a toll-change proposal is unlikely to be effective in altering tunnel usage.

3.6. Change in tunnel usage in response to changes in the tolls

Let P_{jm} denote the current toll paid by drivers of vehicle type m at tunnel j. Further, let P'_{jm} denote the proposed toll at tunnel j for vehicle type m. Based on Eqs. Eqs. (8.a)–(8.c), the effect of a proposed change in tolls on vehicle type m's usage of that tunnel is:

$$X_{jm} = \sum_{k \neq j} b_{jkm}[(P'_{km}/P'_{jm})^{1/2} - (P_{km}/P_{jm})^{1/2}], \tag{11}$$

where b_{jkm} is the estimate of $\beta_{j \neq k}$ for vehicle type m. An estimate for the aggregate usage change for tunnel j is therefore equal to:

$$X_j = \sum_m X_{jm}. \tag{12}$$

3.7. Estimation strategy

3.7.1. Unit root tests

Our use of monthly data shapes our estimation strategy because of the potential problem of non-stationary data. To examine the stationarity property of our monthly time series, we apply the Augmented Dickey–Fuller (ADF) test (Dickey and Fuller, 1979) and the Phillips–Perron (PP) test (Phillips and Perron, 1988) to each of the time series. For brevity, we do not report the detailed unit-root results, which are available from the corresponding author upon request.

The unit-root results are mixed. While both tests conclude that real GDP is trend-stationary in level, they do not reach a unified conclusion as to the stationarity property of the tunnel-crossing series. But both tests decisively reject ($\alpha = 0.01$) the null hypothesis of a unit root for the first-differenced tunnel-crossing data, regardless of the specification of the deterministic components in the tests. The unit-root tests also indicate that the toll-ratio series are non-stationary. The infrequent variations in the toll ratios in Fig. 3, however, obviate the need to remedy the apparent non-stationarity problem, because the toll ratios resemble shift dummies that move tunnel crossings in response to a toll change at a given tunnel. Finally, the PP test indicates that the utilization factor series are either stationary or trend-stationary in levels while the ADF test finds them stationary only when first-differenced.

Since real GDP and the utilization factors are trend-stationary, they cannot be cointegrated with tunnel crossings in our demand equations because a meaningful cointegration relationship requires both the dependent and explanatory variables to be non-stationary. But direct estimation of Eqs. Eqs. (8.a)–(8.c) can be problematic because we cannot entirely rule out the possibility that some of the tunnel-crossing series are only difference-stationary.

3.7.2. Estimation of each GL demand system

To ensure that all variables enter the regression without a stochastic trend component, we apply PROC MODEL of SAS (2004) to estimate each GL system for a particular vehicle type in first-differenced form. We cannot jointly estimate the nine GL systems due to the problem of non-convergence.

Our use of the first-differenced data leads to the GL demand system for a given vehicle type described by Eq. (13), which has an intercept θ_j that reflects the presence of a time trend in Eqs. Eqs. (8.a)–(8.c):

$$\Delta N_{jt} = \theta_j + \sum_{k \neq j} \beta_{jk} \Delta (P_{kt}/P_{jt})^{1/2} + \psi_j \Delta Y_t + \sum_k \gamma_{jk} \Delta U_{kt} + \mu_{jt}, \quad (13)$$

where μ_{jt} is a random-error term with zero mean and finite variance. Our system estimation recognizes that μ_{jt} and $\mu_{kt} (j \neq k)$ may be contemporaneously correlated, since the usage pattern of the three tunnels by a vehicle type is the result of the decision making by the drivers of that particular vehicle type.

Since the first-differenced series are found to be stationary, the estimates of $\{\beta_{jk}\}$, $\{\psi_j\}$, $\{\theta_j\}$, and $\{\gamma_{jk}\}$ are not susceptible to spurious interpretation. Our first-differencing approach has two drawbacks if the monthly series are actually stationary (Murray, 2006, Chapter 18). First, differenced time series often vary less than un-differenced ones. As a result, the precision of the coefficient estimates may decrease. This, however, is not a major concern, since Section 4 reports that most of our coefficient estimates are statistically significant ($\alpha = 0.01$).

Second, differencing a monthly data series can exacerbate serial correlation. As a remedy, we assume that μ_{jt} follows an AR(2) error process because monthly data tend to follow an AR(1) process. Thus, our estimates for the changes in tunnel usage and the elasticities in Section 4 are based on the coefficient estimates found under the maintained assumption of contemporaneously correlated AR(2) errors. While some systems are found to have small and insignificant AR(2) parameter estimates at the $\alpha = 0.01$ level, we maintain the AR(2) assumption throughout the rest of the paper for expositional ease. Moreover, our re-estimation of those systems under the AR(1) assumption yields comparable parameter estimates.

Paying due obeisance to (Diewert, 1971), we impose, where necessary, the non-negative constraints of $\beta_{jk} \geqslant 0$. These restrictions turn out to be unnecessary for six of the nine vehicle types. As reported in the next section, our chosen specification yields the result that the GL system for taxis has one negative coefficient estimate, as do those for light buses and heavy goods vehicles. But only the estimate for taxis is statistically significant ($\alpha = 0.01$).

Finally, when applying PROC MODEL, we recognize that the first-differenced utilization factors ΔU_{kt} are based on the vehicle-specific tunnel crossing N_{jt} and may therefore be endogenous. To remedy the potential problem of endogeneity bias, we use the iterated three-stage least squares (IT3SLS) method in PROC MODEL. The instruments are the first-differenced square-root of toll ratios given by $\{\Delta(P_{kt}/P_{jt})^{1/2}\}$, the first-differenced GDP given by ΔY_t, the binary indicators for the month of each observation (e.g., $D_{Jan} = 1$ if January and 0 otherwise), and the binary indicators for the year of each observation (e.g., $D_{2000} = 1$ if year 2000 and 0 otherwise). As an additional check, we use the iterated seemingly unrelated regressions (ITSUR) method to re-estimate the nine GL demand systems. This method assumes ΔU_{kt} to be exogenous, thus obviating the need for instruments.

3.7.3. Over-specification

Both estimation methods described in the last subsection produce many coefficient estimates that are statistically insignificant ($\alpha = 0.01$). Hence, we consider whether the three first-differenced utilization factors are the possible cause for over-specification that leads to imprecise coefficient estimates with large standard errors. We focus on the utilization factors for two reasons. First, the GDP effect contains the output and congestion effects, and the utilization factors aim to capture the congestion effect. Second, our initial data exploration suggests that the GDP effect estimates are mostly significant ($\alpha = 0.01$).

Since there are nine γ_{jk} estimates in each GL demand system, we have a total of 81 γ_{jk} estimates (= 9 γ_{jk} estimates per system $\times$ 9 systems) to consider. When the IT3SLS method is used, we find 50 (62%) of the 81 estimates are statistically insignificant, and 44 (54%) have signs that are inconsistent with our expectation of $\gamma_{jj} \leqslant 0$ and $\gamma_{jk} \geqslant 0$ for $j \neq k$. When the ITSUR method is used, we find 47 (58%) of the 81 estimates are statistically insignificant, and 46 (57%) have the wrong sign.

The above findings lead us to conclude that Eq. (13) is over-specified. Hence, we impose the restrictions of $\gamma_{jk} = 0$ for all j and k in Eq. (13), yielding the following specification used to produce the empirical evidence reported in the next section:

$$\Delta N_{jt} = \theta_j + \sum_{k \neq j} \beta_{jk} \Delta (P_{kt}/P_{jt})^{1/2} + \psi_j \Delta Y_t + \mu_{jt}. \quad (14)$$

As all the RHS variables are exogenous, the ITSUR method is appropriate for estimating the GL demand system given by Eq. (14).

4. Empirical evidence

4.1. ITSUR results

Fig. 4 portrays the adjusted R^2s of the 27 regressions that are based on the specification given by Eq. (14). Twenty-two of the 27 adjusted R^2 values are above 0.5, suggesting a reasonable fit by our GL specification of the noisy first-differenced data described in Appendix A.

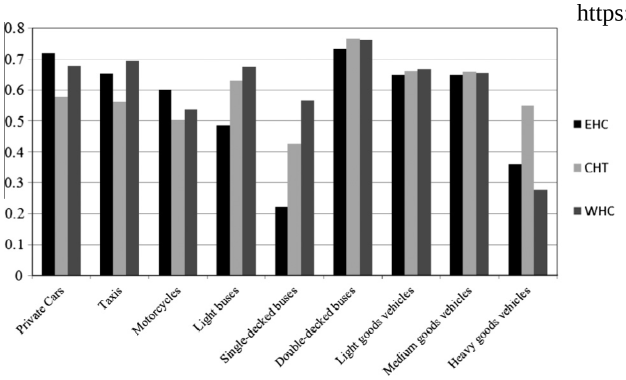

Fig. 4. Adjusted R^2 of nine GL demand systems for harbor crossings.

Table 3
Summary of the SUR regression results for the GL demand systems by vehicle type.

Parameter or question	Private cars	Taxis	Motorcycles	Light buses	Single-decked buses	Double-decked buses	Light goods vehicles	Medium goods vehicles	Heavy goods vehicles
θ_1	▽	△	▽	▽	▽	▽	▽	▽	▽
θ_2	▼	▽	▽	▽	▽	▽	▽	▽	▽
θ_3	▽	▲	▽	▽	▽	▽	▽	△	△
β_{12}	◒	⬤	●	◓	◒	◒	●	●	◒
β_{13}	●	●	●	◒	◒	◒	●	●	◒
β_{23}	●	◒	●	●	◒	◒	◒	◒	◓
ψ_1	●	●	●	●	●	●	●	●	●
ψ_2	●	●	●	●	●	●	●	●	●
ψ_3	●	●	●	●	●	●	●	●	●
$\beta_{j \neq k} = 0$ for all j and k?	No	No	No	No	Yes	No	No	No	No
Number of significant AR parameter estimates for the EHC	2	2	1	1	2	1	2	2	1
Number of significant AR parameter estimates for the CHT	2	2	1	2	2	1	2	2	1
Number of significant AR parameter estimates for the WHC	2	2	1	1	2	1	2	2	1

Notes: (1) Each GL demand system is vehicle-specific and based on Eq. (13) in the main text.
(2) For the intercepts $\{\theta_j\}$, we define: "▲" = "positive and significant at $\alpha = 0.01$"; "△" = "positive but insignificant at $\alpha = 0.01$"; "▼" = "negative and significant at $\alpha = 0.01$"; "▽" = "negative but insignificant at $\alpha = 0.01$".
(3) For the slope coefficients $\{\beta_{jk}\}$ and $\{\psi_j\}$, we define: "●" = "positive and significant at $\alpha = 0.01$"; "◒" = "positive but insignificant at $\alpha = 0.01$"; "◓" = "restricted to zero when the unconstrained estimate is negative but insignificant at $\alpha = 0.01$"; "⬤" = "restricted to zero when the unconstrained estimate is negative and significant at $\alpha = 0.01$".
(4) The answer for the $\beta_{j \neq k} = 0$ question is "No", when the Wald statistic for testing H_0: $\beta_{j \neq k} = 0$ is significant at $\alpha = 0.01$; it is "Yes", otherwise.
(5) The last three rows report the number of statistically significant AR parameter estimates at $\alpha = 0.01$.

For conciseness and easy understanding, we use Table 3 to summarize the voluminous regression results. For the interested readers, our SAS data file, programs, and detailed output listings are available from the corresponding author upon request by email. Table 3 yields the following findings, based on the statistical significance criterion of $\alpha = 0.01$:

- Of the 27 estimates of the intercepts $(\theta_1, \theta_2, \theta_3)$ of the GL demand systems, 23 are negative, thus hinting at negative time-trend effects. This inference, however, is weak, as only one of the 23 negative estimates is statistically significant. Hence, we have also estimated Eq. (14) without the intercepts. As expected, the resulting elasticity estimates are very similar to those reported below. We retain the intercept estimates in reporting the results, in compliance with a referee's suggestion.
- Fifty-one of the 54 estimates of the GL demand system's slope coefficients $(\beta_{12}, \beta_{13}, \beta_{23}, \psi_1, \psi_2, \psi_3)$ are positive. Moreover, 38 of the 51 positive estimates are statistically significant, a finding that remains unchanged after our removal of the intercepts from the GL demand systems described by Eq. (14).
- There are three negative coefficient estimates: (a) the β_{12} estimates for taxis and light buses, and (b) the β_{23} estimate for heavy goods vehicles. Only the β_{12} estimate for taxis is statistically significant. Thanks to a referee's insightful comment, this seemingly anomalous finding may be explained by a taxi's possible "chained" trips via different tunnels (e.g., Kow-

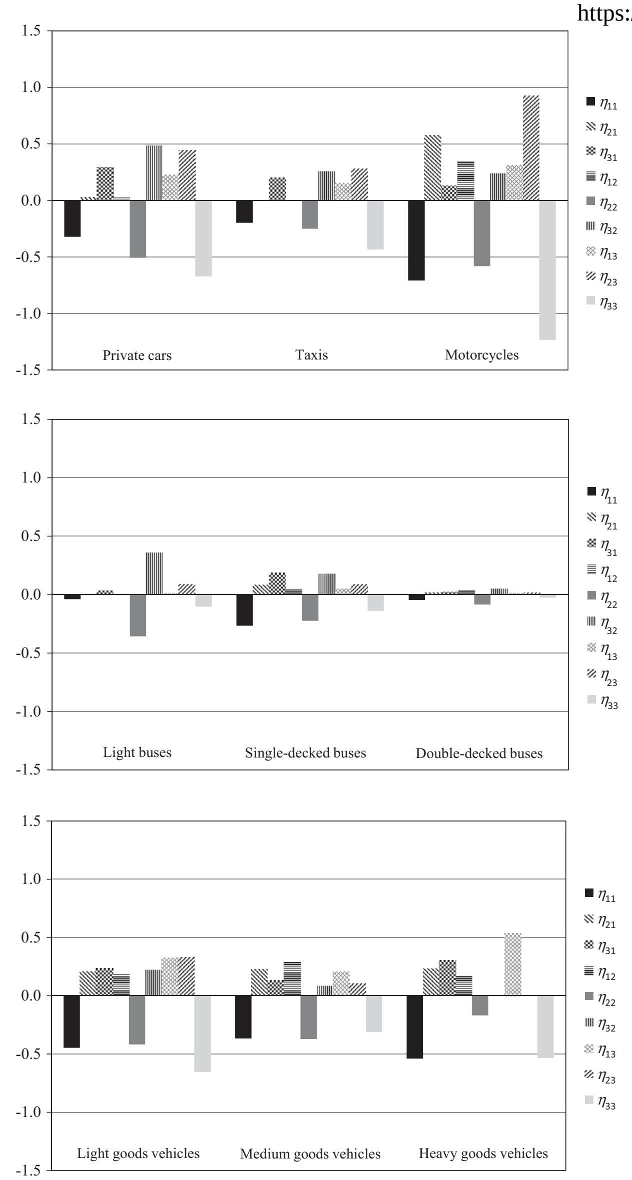

Fig. 5. Elasticity estimates by vehicle type based on Section 3.4.1: $\eta_{jk} = \partial \ln N_j / \partial \ln P_k$ = elasticity of tunnel j's usage of a particular vehicle type with respect to tunnel k's applicable toll for all j, k = 1 (EHC), 2 (CHT), 3 (WHC).

Table 4
Estimates of E_{jk} = aggregate price elasticity = percent change in tunnel j's total usage due to one percent change in tunnel k's tolls.

Cross-harbor tunnel ID	1. Eastern Harbor Crossing (EHC)	2. Cross Harbor Tunnel (CHT)	3. Western Harbor Crossing (WHC)
1. Eastern Harbor Crossing (EHC)	−0.318	0.075	0.242
2. Cross Harbor Tunnel (CHT)	0.072	−0.385	0.314
3. Western Harbor Crossing (WHC)	0.189	0.337	−0.526

Notes: (1) The monthly aggregate elasticity estimates are based on Section 3.4.2 in the main text.
(2) The E_{12} estimate is 0.072 and the E_{21} estimate is 0.075. Their small size is mainly due to the β_{12} estimate being constrained to zero in the taxis' GL system (see Table 3), implying taxis' cross-price elasticity $\eta_{12} = 0$ and $\eta_{21} = 0$; this is notwithstanding that taxis are a large component of Hong Kong's total harbor crossings (see Fig. 2).

loon to Hong Kong Island via the EHC (i.e., tunnel 1) and Hong Kong Island to Kowloon via the CHT (i.e., tunnel 2)). An increase in the EHC's toll may cause the taxi not to make any cross-harbor trip, resulting in the EHC and CHT being seen as complements, rather than substitutes, in taxis' tunnel usage pattern. Consistent with the assumptions underlying our GL approach (Diewert, 1971), however, we impose the constraint $\beta_{12} = 0$, which does not materially change either the other parameter estimates or our inferences.

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Table 5
Proposed tolls (HK$/crossing) in Transport and Housing Bureau (2013, p. 13), with changes from the January 2013 tolls in ().

Vehicle type	Option A			Option B			Option C		
	CHT	EHC	WHC	CHT	EHC	WHC	CHT	EHC	WHC
Private cars	25(+5)	20(−5)	55	25(+5)	20(−5)	55	30(+10)	20(−5)	55
Taxis	19(+9)	15(−10)	50	13(+3)	20(−5)	50	10	15(−10)	50
Motorcycles	12(+4)	9(−4)	25	10(+2)	10(−3)	25	12(+4)	9(−4)	25
Light buses	25(+15)	20(−18)	65	13(+3)	30(−8)	65	10	38	65
Single-decked buses	31(+21)	25(−25)	100	13(+3)	40(−10)	100	10	50	100
Double-decked buses	47(+32)	38(−37)	140	19(+4)	60(−15)	140	15	75	140
Light goods vehicles	28(+13)	23(−15)	65	19(+4)	30(−8)	65	19(+4)	23(−15)	65
Medium goods vehicles	38(+18)	30(−20)	90	25(+5)	40(−10)	90	25(+5)	30(−20)	90
Heavy goods vehicles	56(+26)	45(−30)	120	38(+8)	60(−15)	120	38(+8)	45(−30)	120

Table 6
Estimated effects of the proposed toll changes (HK$/crossing) in Transport and Housing Bureau (2013, p. 13) on average monthly tunnel usage.

Tunnel ID	Option A		Option B		Option C	
	Crossings	Percent	Crossings	Percent	Crossings	Percent
EHC	346,445	16.1	197,935	9.2	294,807	13.7
CHT	−705,382	−19.6	−415,574	−11.5	−502,718	−13.9
WHC	80,354	4.4	43,040	2.3	67,749	3.7

Notes: (1) These estimated effects are based on Eq. (12) in the main text.
(2) Each percent estimate is the estimated effect divided by the average monthly tunnel usage in 2012.

- The Wald statistics lead us to reject $H_0: \ \beta_{jk} = 0$ for all $j \neq k$ for eight of the nine vehicle types. The only exception is the case for single-decked buses.
- Five of the nine systems have statistically-significant AR(2) parameter estimates and the remaining systems only have statistically-significant AR(1) parameter estimates. We have considered AR(3) errors, but the parameter estimate for μ_{jt-3} is statistically insignificant even at the $\alpha = 0.1$ level of statistical significance for every vehicle type.

In addition to justifying our GL specification given by Eq. (14) as empirically plausible, the aforementioned findings suggest that harbor-tunnel crossings are responsive to toll changes.

4.2. Price elasticity estimates

4.2.1. Disaggregate price elasticity estimates

Fig. 5 reports the negative own-price and positive cross-price elasticity estimates by vehicle type. It shows that all tunnel crossings by vehicle type are price-inelastic. Motorcycles' crossings are the most price-sensitive, followed by those of private cars and goods vehicles. This is unsurprising, since the drivers (or owners) of these vehicles are likely to pay some, if not all, of the toll charges. Taxis and buses that provide public transportation are the least price-sensitive, since they can pass on the tunnel tolls to their passengers as part of their total fares.

The finding that taxis and buses do exhibit some, albeit small, price responsiveness is plausible because their passengers respond to the toll-included fares, which in turn influence the volume of harbor crossings by these vehicles. For example, Hong Kong taxi drivers often offer route choices to their passenger(s), asking: "Which tunnel would you like me to use?" Similarly, a bus passenger may choose which bus to ride because bus fares vary by their tunnel-specific routes.

Comparing our elasticity estimates to those of Hau et al. (2011, pp. 475–476): (a) our estimates for private cars are moderately larger in size than theirs; (b) our estimates for taxis are about half as large as theirs; and (c) our estimates for goods vehicles are about two-thirds the size of theirs. We attribute the numerical differences between our and the Hau et al. (2011) estimates to the differences in data (our aggregate monthly data for 2000–2012 vs. Hau et al.'s survey data collected in 1999) and estimation techniques (our GL demand estimation vs. Hau et al.'s discrete-choice analysis). We cannot compare the elasticity estimates for motorcycles, light buses, single-decked buses, and double-decked buses, because Hau et al. (2011) do not provide such estimates.

4.2.2. Aggregate price elasticity estimates

Table 4 reports our aggregate elasticity estimates. It shows: (a) our CHT's aggregate own-price elasticity estimate is −0.385, or 1.32 times the −0.291 estimate in Loo (2003, Table 3); and (b) our aggregate own-price elasticity estimates for the EHC and WHC are −0.318 and −0.526, respectively, unlike the positive though insignificant ($\rho > 0.05$) estimates in Loo (2003, Table 3). We attribute the numerical differences between our and the Loo (2003) estimates to the differences in data (our 2000–2012 monthly data vs. Loo's 1979–2000 monthly data) and estimation techniques (our GL demand estimation vs. Loo's double-log regressions). Further, Table 4 reports that all tunnel demands have positive cross-price elasticity estimates, which are not provided by Loo (2003). In summary, Table 4 indicates that all three tunnels have price-inelastic demands and that they are imperfect substitutes.

4.3. Effects of the toll changes proposed by Transport and Housing Bureau (2013)

Keeping the WHC's tolls unchanged, the HKSAR Government's public consultation paper (Transport Department, 2013) derives the proposed changes as follows:

- Option A: (1) reduce the EHC private car toll by $5 and those of other types of vehicles correspondingly, such that the tolls would be closer to the CHT tolls after adjustment; and (2) increase the CHT private car toll by $5 and increase tolls of other vehicle types to reflect the road space occupied as well as the wear and tear caused on the road surface by these vehicles.
- Option B: (1) reduce the EHC private car toll by HK$5; and (2) increase the CHT private car toll by HK$5. The remaining EHC (CHT) toll changes are found by first computing the percent change of EHC (CHT) car toll and then applying the same percent change to the remaining EHC (CHT) tolls.
- Option C: (1) for the EHC, change the non-bus tolls as Option A, and freeze the bus tolls; and (2) for the CHT, increase the private car toll by HK$10, increase the motorcycle toll by HK$4, freeze the tolls for taxis and buses, and adopt the goods vehicles tolls in Option B.

Some of the relative toll changes in Table 5 are large, as evidenced by the 25% (= $5/$20) increase for the CHT's car toll, and the 90% (= $9/$10) increase for the CHT's taxi toll, with Option A.

Using Eq. (12), Table 6 estimates the effects of each option. Option A is estimated to (a) reduce the CHT's monthly crossings in 2012 by about 19.6%, (b) increase the EHC's monthly crossings by about 16.1%, and (c) increase the WHC's monthly crossings by about 4.4%. The total estimated effect of (a)–(c) is an approximate 3.8% reduction in total usage of all three tunnels by all vehicle types. The estimated effects of the other options are smaller than, but qualitatively similar to, those of Option A.

5. Conclusion

Based on the 2000–2012 monthly tunnel crossings by nine vehicle types, we show that Hong Kong can price-manage its cross-harbor-tunnel congestion, since the three tunnels are found to be substitutes with discernible price responsiveness. The toll changes proposed by the Transport and Housing Bureau (2013) are estimated to reduce crossings via the CHT by as much as 19.6%. Taken together, these findings imply that the HKSAR Government can implement a pricing policy for effective transportation demand management of Hong Kong's three cross-harbor tunnels.

Table A.1
Variable definitions and data sources.

Variable	Definition	Source
N_{1t}	Monthly vehicle-specific crossings: Eastern Harbour Crossing (EHC)	Monthly Traffic and Transport Digest, various issues, Transport Department, HKSAR
N_{2t}	Monthly vehicle-specific crossings: Cross Harbour Tunnel (CHT)	Same as above
N_{3t}	Monthly vehicle-specific crossings: Western Harbour Crossing (WHC)	Same as above
P_{1t}	Monthly vehicle-specific tolls (HK$/crossing): Eastern Harbour Crossing (EHC)	Annual Transport Digest, various issues, Transport Department, HKSAR; and http://www.westernharbourtunnel.com/en/about4.html When a toll changes in the midst of a month, the monthly toll is the average of the daily tolls
P_{2t}	Monthly vehicle-specific tolls (HK$/crossing): Cross Harbour Tunnel (CHT)	Same as above
P_{3t}	Monthly vehicle-specific tolls (HK$/crossing): Western Harbour Crossing (WHC)	Same as above
Y_t	Monthly real GDP (2011 HK$M)	Hong Kong Monthly Digest of Statistics, Census and Statistics Department, Hong Kong SAR. Since the HKSAR Government only publishes quarterly real GDP and quarter-end employment, we first derive the monthly employment figures by linear extrapolation. Then, we estimate the monthly GDP as (a) quarterly GDP times (b) monthly share of the quarterly total employment-days = monthly employment $*$ monthly number of calendar days

Table A.2
Mean, standard deviation (SD), maximum (Max) and minimum (Min) of the nine estimation samples by vehicle type.

Panel A: First-differenced data for real GDP (2011 HK$M) and tunnel utilization factors used in all estimation samples

Variable	Mean	SD	Min	Max
ΔY_t	502	7640	−15,139	16,204
ΔU_{1t}	−0.00027	0.00781	−0.02038	0.02209
ΔU_{2t}	0.00018	0.01107	−0.02771	0.02510
ΔU_{3t}	−0.00031	0.00570	−0.02009	0.02266

Panel B: First-differenced data for private cars, taxis and motorcycles

Variable	Private cars				Taxis				Motorcycles			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
ΔN_{1t}	−169	65,023	−22,2037	15,0846	1072	21,399	−67,507	62,242	19	7869	−34,373	18,781
ΔN_{2t}	−799	63,712	−202,154	136,404	245	50,835	−154,601	122,791	20	15,296	−36,506	43,013
ΔN_{3t}	1238	55,477	−173,989	160,237	2472	24,040	−69,098	105,099	−3	1880	−5259	5686
$\Delta\,(P_{1t}/P_{2t})^{1/2}$	0.0016	0.0202	0.0000	0.2520	0.0023	0.0286	0.0000	0.3564	0.0018	0.0221	0.0000	0.2748
$\Delta\,(P_{2t}/P_{1t})^{1/2}$	−0.0017	0.0209	−0.2603	0.0000	−0.0012	0.0148	−0.1840	0.0000	−0.0014	0.0173	−0.2155	0.0000
$\Delta\,(P_{1t}/P_{3t})^{1/2}$	0.0000	0.0157	−0.0494	0.1782	0.0002	0.0167	−0.0494	0.1905	0.0001	0.0155	−0.0927	0.1657
$\Delta\,(P_{3t}/P_{1t})^{1/2}$	0.0000	0.0323	−0.3681	0.1063	−0.0005	0.0302	−0.3443	0.1063	−0.0003	0.0335	−0.3574	0.1991
$\Delta\,(P_{2t}/P_{3t})^{1/2}$	−0.0012	0.0064	−0.0571	0.0000	−0.0007	0.0046	−0.0404	0.0000	−0.0009	0.0078	−0.0927	0.0000
$\Delta\,(P_{3t}/P_{2t})^{1/2}$	0.0023	0.0121	0.0000	0.0921	0.0025	0.0167	0.0000	0.1302	0.0021	0.0171	0.0000	0.1991

Panel C: First-differenced data for light buses, single-decked buses and double-decked buses

Variable	Light buses				Single-decked buses				Double-decked buses			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
ΔN_{1t}	−124	1988	−4682	5149	34	2368	−5109	6745	−73	3598	−8711	8761
ΔN_{2t}	14	5193	−13,622	11,304	369	15,029	−61,986	28,960	−89	8400	−19,452	20,204
ΔN_{3t}	−47	4149	−11,370	9756	81	3173	−10,067	9272	35	4930	−12,409	12,984
$\Delta\,(P_{1t}/P_{2t})^{1/2}$	0.0028	0.0348	0.0000	0.4328	0.0033	0.0405	0.0000	0.5040	0.0033	0.0405	0.0000	0.5040
$\Delta\,(P_{2t}/P_{1t})^{1/2}$	−0.0009	0.0118	−0.1464	0.0000	−0.0008	0.0105	−0.1301	0.0000	−0.0008	0.0105	−0.1301	0.0000
$\Delta\,(P_{1t}/P_{3t})^{1/2}$	0.0002	0.0165	−0.0408	0.1935	−0.0008	0.0184	−0.0863	0.1905	−0.0009	0.0193	−0.0971	0.1952
$\Delta\,(P_{3t}/P_{1t})^{1/2}$	−0.0004	0.0279	−0.3273	0.0750	0.0012	0.0326	−0.3443	0.1279	0.0013	0.0321	−0.3360	0.1330
$\Delta\,(P_{2t}/P_{3t})^{1/2}$	−0.0006	0.0032	−0.0269	0.0000	−0.0011	0.0055	−0.0499	0.0000	−0.0012	0.0060	−0.0561	0.0000
$\Delta\,(P_{3t}/P_{2t})^{1/2}$	0.0029	0.0153	0.0000	0.1138	0.0065	0.0312	0.0000	0.2215	0.0065	0.0314	0.0000	0.2304

Panel D: First-differenced data for light goods vehicles (under 5.5 tonnes), medium goods vehicles (between 5.5 and 24 tonnes) and heavy goods vehicles (over 24 tonnes)

Variable	Light goods vehicles				Medium goods vehicles				Heavy goods vehicles			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
ΔN_{1t}	−697	35,611	−107,299	107,523	−78	9524	−26,649	31,428	−21	2282	−7727	8666
ΔN_{2t}	−229	61,571	−183,574	190,163	104	13,413	−41,763	45,912	16	3542	−11,722	12,635
ΔN_{3t}	298	14,583	−54,204	51,079	142	3145	−12,631	12,995	49	1080	−6889	5065
$\Delta\,(P_{1t}/P_{2t})^{1/2}$	0.0023	0.0284	0.0000	0.3534	0.0023	0.0286	0.0000	0.3564	0.0023	0.0286	0.0000	0.3564
$\Delta\,(P_{2t}/P_{1t})^{1/2}$	−0.0012	0.0144	−0.1793	0.0000	−0.0012	0.0148	−0.1840	0.0000	−0.0012	0.0148	−0.1840	0.0000
$\Delta\,(P_{1t}/P_{3t})^{1/2}$	0.0005	0.0156	−0.0354	0.1845	0.0006	0.0149	−0.0373	0.1782	0.0008	0.0153	−0.0274	0.1861
$\Delta\,(P_{3t}/P_{1t})^{1/2}$	−0.0009	0.0290	−0.3433	0.0709	−0.0011	0.0310	−0.3681	0.0922	−0.0014	0.0291	−0.3524	0.0636
$\Delta\,(P_{2t}/P_{3t})^{1/2}$	−0.0005	0.0034	−0.0279	0.0000	−0.0004	0.0031	−0.0304	0.0000	−0.0003	0.0023	−0.0224	0.0000
$\Delta\,(P_{3t}/P_{2t})^{1/2}$	0.0017	0.0116	0.0000	0.0878	0.0017	0.0115	0.0000	0.1130	0.0012	0.0079	0.0000	0.0779

6. Uncited reference

Elliott et al. (1996).

Appendix A. Data sources and descriptive statistics

Table A.1 details the variable definitions and sources of our monthly data series for the 13-year period of 2000–2012. Table A.2 reports the descriptive statistics of the estimation samples.

References

Burris, M.W., Pendyala, R.M., 2002. Discrete choice models of traveler participation in differential time of day pricing programs. Transp. Policy 9, 241–251.
Davidson, R., MacKinnon, J.G., 1993. Estimation and Inference in Econometrics. Oxford University Press, Oxford.
Dickey, D.A., Fuller, W.A., 1979. Distribution of the estimators for autoregressive time series with a unit root. J. Am. Stat. Assoc. 74, 427–431.
Diewert, W.E., 1971. An application of the Shephard duality theorem: a generalized Leontief production function. J. Polit. Econ. 79, 481–507.

Elliott, G., Rothenberg, T.J., Stock, J.H., 1996. Efficient tests for an autoregressive unit root. Econometrica 64, 813–836.

Goodwin, P.B., 1992. A review of new demand elasticities with special reference to short and long run effects of price changes. J. Transport Econ. Policy 26, 155–169.

Graham, D.J., Glaister, S., 2004. Road traffic demand elasticity estimates: a review. Transport Rev. 24, 261–274.

Hau, T.D., Loo, B.P.Y., Wong, K.I., Wong, S.C., 2011. An estimation of efficient time-varying tolls for cross harbor tunnels in Hong Kong. Singapore Econ. Rev. 56, 467–488.

Hirschman, I., McKnight, C., Pucher, J., Paaswell, R.E., Berechman, J., 1995. Bridge and tunnel toll elasticities in New York: some recent evidence. Transportation 22, 97–113.

Litman, T., 2004. Transit price elasticities and cross-elasticities. J. Publ. Transport. 7, 37–58.

Litman, T., 2013. Understanding Transport Demands and Elasticities: How Prices and Other Factors Affect Travel Behavior. Victoria Transport Policy Institute <http://www.vtpi.org/elasticities.pdf> (accessed on 20 June, 2013).

Loo, B.P.Y., 2003. Tunnel traffic and toll elasticities in Hong Kong: some recent evidence for international comparisons. Environ. Plan. A 35, 249–276.

May, A.D., Milne, D.S., 2000. Effects of alternative road pricing systems on network performance. Transport. Res. Part A: Policy Pract. 34, 407–436.

Meyer, Michael D., 1999. Demand management as an element of transportation policy: using carrots and sticks to influence travel behavior. Transp. Res. Part A 33, 575–599.

Murray, M.P., 2006. Econometrics: A Modern Introduction. Pearson Addison Wesley, Reading, MA.

Nam, K.C., 1997. A study on the estimation and aggregation of disaggregate models of mode choice for freight transport. Transport. Res. Part E: Logist. Transport. Rev. 33, 223–231.

Olszewski, P., Xie, L., 2005. Modelling the effects of road pricing on traffic in Singapore. Transport. Res. Part A: Policy Pract. 39, 755–772.

Oum, T.H., Waters, W.G., Yong, J.S., 1992. Concepts of price elasticities of transport demand and recent empirical estimates: an interpretative survey. J. Transport Econ. Policy 26, 135–154.

Phillips, P.C.B., Perron, P., 1988. Testing for a unit root in time series regression. Biometrika 75, 335–346.

Pretty, R.L., 1988. Road pricing: a solution for Hong Kong? Transport. Res. Part A: General 22, 319–327.

SAS, 2004. SAS/ETS 9.1 User's Guide. SAS Institute Inc., Cary, NC.

Su, Q., 2010. Travel demand in the US urban areas: a system dynamic panel data approach. Transport. Res. Part A: Policy Pract. 44, 110–117.

Train, K., Wilson, W.W., 2008. Estimation on stated-preference experiments constructed from revealed-preference choices. Transport. Res. Part B: Meth. 42, 191–203.

Transport and Housing Bureau, 2013. Proposed Measures to Improve the Traffic Distribution among the Road Harbour Crossings – Public Consultation. The Government of the Hong Kong Special Administrative Region <http://www.thb.gov.hk/eng/policy/transport/policy/consultation/RHC_consultation_2013_eng.pdf> (accessed on 25 June, 2013).

Varian, H., 1992. Microeconomics Analysis. Norton, New York.

Vickrey, W.S., 1967. Optimization of traffic and facilities. J. Transport Econ. Policy 1, 123–136.

Vickrey, W.S., 1969. Congestion theory and transport investment. Am. Econ. Rev. (Pap. Proc.) 59, 251–260.

Washbrook, K., Haider, W., Jaccard, M., 2005. Estimating commuter mode choice: a discrete choice analysis of the impact of road pricing and parking charges. Transportation 33, 621–639.

Wilbur Smith Associates Limited, 2010. Consultancy Services for Providing Expert Advice on Rationalizing the Utilization of Road Habour Crossings. Transport and Housing Bureau, The Government of the Hong Kong Special Administrative Region <http://www.thb.gov.hk/eng/policy/transport/policy/consultation/RHC_Final_Report_Sep2010.pdf> (accessed on 25 June, 2013).

Wong, C.K.L., 2012. EMFAC-HK, EMFAC-HK April 2012 Training. Environmental Protection Department and Eastern Research Group, Inc. <http://www.epd.gov.hk/epd/english/environmentinhk/air/guide_ref/files/4.HK_Local_data_rev3.pdf> (accessed on 27 March, 2015).

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