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Price-management of traffic congestion: Hong Kong's Lion Rock Tunnel

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Abstract

Hong Kong drivers face rush-hour traffic congestion at the Lion Rock Tunnel (LRT) which interconnects the Northeast New Territories and the Kowloon Peninsula. The LRT's flat toll is HK\$8 (≈ US\$1.03), much lower than the Tate's Cairn Tunnel's (TCT's) vehicle-differentiated tolls of HK\$13 to HK\$34 per vehicular trip. We develop two proposals to raise the LRT's toll and reduce the TCT's tolls. Using the monthly data available from the Hong Kong Transport Department for the 15-year period of 2000-2014, we estimate a Generalized Leontief demand system to document statistically significant (p-value < 0.05) tunnel usage responses to these toll proposals. As the two tunnels' elasticity estimates vary by traffic direction, a directional toll proposal may further ease the LRT's rush-hour congestion. Hence, Hong Kong can price-manage the LRT's congestion because a decrease in the LRT's total usage likely reduces the LRT's peak usage that occurs during the rush hours.

Keywords: Traffic congestion, transportation demand management, revenue-neutral toll proposals, Lion Rock Tunnel, Hong Kong

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1. Introduction

This paper is a case study of price-management of traffic congestion at the Lion Rock Tunnel (LRT) of Hong Kong, a geographically small (~1,100 km^2) metropolis with ~7.3 million residents. Hong Kong drivers face frequent traffic jams, like those in most major cities (e.g., New York City, London, Paris, Tokyo, Beijing and Shanghai). The LRT's rush hours on working weekdays are: (a) 07:00 – 09:00, due to the heavy southbound traffic from the Northeast New Territories to Kowloon Peninsula; and (b) 18:00 – 20:00, caused by the similarly heavy northbound traffic. Hence, the LRT's rush-hour congestion is both time- and direction-dependent.

The following reasons explain the LRT's congestion. First, Fig.1 shows that the LRT is the shortest route between the Lion Rock's immediate north and south. Second, the government-owned LRT has a flat toll of HK$8 (≈ US$1.03 at the pegged exchange rate of approximately US$1 = HK$7.8) per vehicular trip, much lower than the vehicle-differentiated tolls of HK$13 to HK$34 of the privately-owned Tate's Cairn Tunnel (TCT), located east of the LRT (see Fig.2). Third, the main surface route is the toll-free but long and winding Tai Po Road located west of the LRT, an unattractive alternative for drivers travelling between the Lion Rock's immediate north and south. Equally unattractive is Tai Po Road's close substitute, the Eagle's Nest Tunnel (ENT) that charges a flat toll of HK$8 per vehicular trip between West

Kowloon and the northwest of Lion Rock.

Guided by the theory of transportation demand management (Vickrey, 1967, 1969; Pretty, 1988; Meyer, 1999; May and Milne, 2000), this paper answers the policy question: can Hong Kong price-manage the LRT's rush-hour congestion? An affirmative answer seems plausible in the light of the price elasticity estimates reported in several literature reviews (Oum et al., 1992; Goodwin, 1992; Graham and Glaister, 2004; Litman, 2004, 2013), and three prior studies of Hong Kong tunnel demands (Loo, 2003; Hau et al., 2011; Woo et al., 2015). In particular, Loo (2003) applies a double-log demand specification to a monthly sample for January 1979 to September 2000 to obtain non-directional own-price elasticity estimates of -0.103 (p-value < 0.01) for the LRT and -0.123 (p-value < 0.01) for the TCT.

Our paper is timely and relevant because the privately-owned TCT is operating under a build-operate-transfer scheme that will expire in 2018. Thus, now is an opportune time to explore the effectiveness of alternative toll proposals to better manage the traffic pattern of the LRT and TCT, which critically depend on how individual drivers might respond to the proposed toll changes.

We use a sample of monthly aggregate data, published by the Hong Kong Transport Department (HKTD), for the 15-year period of 2000 to 2014 to estimate tunnel usage regressions based on a Generalized Leontief (GL) system of tunnel usage equations described in Woo et al. (2015). Simultaneously raising the LRT’s toll and lowering the TCT’s tolls, our two toll proposals aim to alleviate the LRT’s rush-hour congestion under the revenue-neutrality condition that the LRT’s projected revenue increase would offset the TCT’s projected revenue decrease. To gauge the two proposals’ effectiveness, we estimate the LRT’s directional usage responses of the three vehicle groups defined by the LRT’s usage data classification: (1) private cars, taxis and motor cycles; (2) single-decked buses, light buses and goods vehicles not more than 5.5 tonnes; and (3) double-decked buses and goods vehicles over 5.5 tonnes.

Price management of the LRT’s traffic congestion requires knowledge of the LRT and TCT usage’s price sensitivity, thus justifying our demand estimation. Traditionally, the demand estimation is done via double log or linear specifications; see Litman (2013) for a comprehensive literature review. However, these approaches are less rigorous and comprehensive than system demand estimation that recognizes the LRT and TCT are imperfect substitutes and likely have low price sensitivity. Hence, we choose the GL system approach, thanks to its proven usefulness in representing Hong Kong’s cross harbor usage patterns (Woo et al., 2015).

Relevant to Hong Kong and China’s other major cities (e.g., Beijing, Shanghai, Guangzhou, and Shenzhen), our key message is that a toll change proposal can moderately ease traffic congestion, even if the toll for using a road, bridge or tunnel is only a small fraction of a driver's total vehicular trip cost. A corollary of this message is that such a proposal is unlikely to be sufficient enough to solve a severe congestion problem, necessitating additional pricing measures such as road pricing, parking fees, illegal parking fines, vehicular fuel taxes, vehicular purchase taxes, and vehicular registration fees.

2. Materials and methods

2.1 Monthly tunnel usage

Our empirical analysis is shaped by the LRT's monthly northbound and southbound tunnel usage data published by the HKTD for the three vehicle groups listed above. Hence, we use the TCT's monthly usage data for the eight vehicle types in Fig.2 to develop comparable usage data under the LRT's vehicle-group classification. Fig.3 portrays the LRT's monthly aggregate usage (= northbound trips + southbound trips) by vehicle group, and shows that group 1 has the highest usage, followed by groups 2 and 3. It also shows seasonal fluctuations in the LRT's monthly aggregate usage. Fig. 4 portrays the TCT's monthly aggregate usage by vehicle group, showing a modest decline during 2005 to 2009 and a gradual increase thereafter.

2.2 The LRT's peak usage

A major concern is that our toll proposals might only reduce the LRT's total usage but not rush-hour usage, thus rendering our toll proposals ineffective in managing the LRT's rush-hour congestion. To address this concern, we explore the empirical relationship between the LRT's rush-hour usage and total usage. Our exploration uses the LRT's monthly peak and total usage data available from the HKTD's Monthly Traffic and Transport Digest. The sample period is 2003 to 2014, dictated by the availability of the LRT's monthly peak usage data.

We estimate the following regression with AR(1) error υ_t for a given direction:

$$\Delta \ln U_t = \gamma_0 + \gamma_1 \Delta \ln V_{1t} + \gamma_2 \Delta \ln V_{2t} + \upsilon_t, \tag{1}$$

where $\Delta \ln U_t = \ln U_t - \ln U_{t-1}$ = first difference of the natural log of the LRT's peak usage in month $t = 1$ for February 2003, …, 143 for December 2014; $\Delta \ln V_{1t} = \ln V_{1t} - \ln V_{1t-1}$ = first difference of the natural log of the LRT's total usage in month t; and $\Delta \ln V_{2t} = \ln V_{2t} - \ln V_{2t-1}$ = first difference of the natural log of number of days in month t. We use the first-differenced data because estimating the regression in level form yields regression residuals that follow a random walk. We exclude the TCT's monthly total usage from the above regression because a preliminary estimation reveals this variable's insignificant effect (p-value > 0.10) on the LRT's peak usage.

Since $\Delta \ln V_{1t}$ is an endogenous variable that can cause estimation bias (Davidson and MacKinnon, 1993), we use the iterated three-stage-least-squares (IT3SLS) method in PROC MODEL of SAS (2004) to jointly estimate the northbound and southbound peak usage regressions, yielding consistent estimates for (γ_0, γ_1, γ_2).[1] Table 1 reports the IT3SLS estimation results.[2]

2.3 TCT's average tolls by vehicle group

To construct the price variables for our regression analysis, we compute the TCT's monthly average tolls for the three vehicle groups. For example, the monthly average toll for vehicle group 1 (private cars, taxis and motor cycles) is the TCT's monthly toll revenue, collected from group 1 and divided by the monthly vehicular trips made by group 1. Fig. 4 shows that the TCT's monthly average tolls by vehicle group increasingly exceed the LRT's flat toll in our sample period of 2000-2014.

Based on the TCT's usage and toll data, the TCT's average tolls by vehicle group are endogenous variables that might cause estimation bias in our regression analysis. To construct the TCT's exogenous toll variables, we estimate the following OLS regression for each vehicle group: TCT's monthly average toll = $a_0 + \Sigma_q\, a_q \times$ monthly constituent toll q + regression error, where a_0 = intercept estimate and a_q = coefficient estimate for toll q. All three vehicle-group-specific OLS regressions have adjusted R^2 values of 0.99, suggesting an almost perfect correlation between the

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[1] The list of instruments includes the intercept, $\Delta \ln V_{2t}$, the 11 binary indicators for month t (e.g., the January indicator = 1 if month t is January, 0 otherwise), and the first difference of the natural log of monthly real GDP. In response to a referee's comment, we tried including the first difference of monthly number of public holidays in the list of instruments. The ensuing regression results are virtually identical to those reported herein.

[2] The northbound γ_1 estimate is 0.35 (p-value < 0.0001), smaller than the southbound γ_1 estimate of 0.68 (p-value < 0.0001). This makes sense because the northbound evening going-home trips tend to have a less stringent scheduled arrival than the southbound morning going-to-work trips. Thus, if a toll proposal can reduce the LRT's total usage, it can also reduce the LRT's peak usage, thus easing the LRT's rush-hour congestion.

TCT's average tolls and those predicted by the OLS regressions.

2.4 Tunnel usage model

Here we describe the GL demand model for analyzing the directional usage of the LRT and TCT by the drivers of vehicle group $m = 1, 2, 3$. The publicly available data are: (a) the monthly vehicle-group-specific usage by tunnel (LRT vs. TCT) and direction (northbound vs. southbound); (b) the non-directional tolls for the LRT and TCT; and (c) the monthly GDP of Hong Kong. The modeling challenge is how to best exploit (a) to (c), thereby generating credible estimates of toll elasticities and tunnel usage responses by direction.

Let P_{1t} = LRT's monthly toll for a particular vehicle group; P_{2t} = TCT's monthly toll for the same group; Y_t = observable economic indicator proxied by Hong Kong's monthly real GDP; A_t = binary indicator for the ENT's availability = 1 if month t is after the ENT's March 2008 opening, 0 otherwise; $\boldsymbol{S}_t = (S_{1t}, S_{2t}, S_{3t})$ = vector of quarterly binary indicators (e.g., $S_{st} = 1$ if month t is in quarter $s = 1, 2, 3$ of the year; 0 otherwise); and t = month index which aims to capture the time-trend effect. Based on Diewert (1971), Caves and Christensen (1980) and Woo et al. (2015), the GL equations for tunnel demands N_{jt}^* ($j = 1, 2$) under the constraint of $\beta_{jk} = \beta_{kj}$ for $j = 1, 2$ and $j \neq k$ are:

$$N_{1t}^* = \beta_{11} + \beta_{12}\,(P_{2t}/P_{1t})^{1/2} + \psi_1 Y_t + \phi_1 A_t + \Sigma_s\, \mu_{1s}\, S_{st} + \theta_1\, t; \qquad (2.a)$$

$$N_{2t}^{*} = \beta_{22} + \beta_{12}\,(P_{1t}/P_{2t})^{1/2} + \psi_2 Y_t + \phi_2 A_t + \Sigma_s\, \mu_{2s}\, S_{st} + \theta_2\, t. \qquad (2.b)$$

Equations (2.a) and (2.b) state that the monthly demand N_{jt}^{*} for tunnel j (= 1, 2) by the drivers of a particular vehicle group depends linearly on the observable $(P_{kt}/P_{jt})^{1/2}$ for $k \neq j$, Y_t, A_t, $\boldsymbol{S}_t$, and t. When $\beta_{12} \geq 0$, $\partial N_{jt}^{*}/\partial P_{jt} \leq 0$ and $\partial N_{jt}^{*}/\partial P_{kt} \geq 0$.

An increase in GDP tends to raise the drivers' daily trip requirements. It might also raise vehicle ownership and usage, possibly exacerbating congestion that discourages a tunnel's usage. When the first effect dominates the second, the GDP increase tends to increase N_{jt}^{*}.

The effect of A_t on N_{jt}^{*} is likely negative, reflecting the ENT being a close substitute for Tai Po Road. The effect of $\boldsymbol{S}_t$ on N_{jt}^{*} is not *a priori* known and has to be determined empirically. The time trend's effect on N_{jt}^{*} is likely negative, reflecting the usage-reduction effect of rising non-toll costs (e.g., operations and maintenance and fuel).

2.5 Estimation strategy

Our use of monthly data shapes our estimation strategy that begins with an application of the Phillips-Perron (PP) test (Phillips and Perron, 1988) to each of the time series. The PP test results indicate that the null hypothesis of a data series having a unit root is rejected ($\alpha = 0.05$) for the monthly tunnel usage and real GDP data. The same cannot be said for the monthly square-rooted toll ratio data. The infrequent variations in these ratios, however, obviate the need to remedy the apparent non-stationarity problem because the ratios resemble shift dummies that move tunnel vehicular trips in response to the TCT's toll changes. Hence, we use the monthly data series to estimate our GL demand systems by vehicle group to address concerns of spurious regressions (Davidson and MacKinnon, 1993).

Using the iterated seemingly unrelated regression (ITSUR) technique in PROC MODEL of SAS (2004), we estimate each vehicle group's GL demand system for a given traffic direction (e.g., northbound):

$$\text{LRT: } N_{1t} = \beta_{11} + \beta_{12}\,(P_{2t}/P_{1t})^{1/2} + \psi_1 Y_t + \phi_1 A_t + \Sigma_s\, \mu_{1s}\, S_{st} + \theta_1\, t + \varepsilon_{1t}, \qquad (3.a)$$

$$\text{TCT: } N_{2t} = \beta_{22} + \beta_{12}\,(P_{1t}/P_{2t})^{1/2} + \psi_2 Y_t + \phi_2 A_t + \Sigma_s\, \mu_{2s}\, S_{st} + \theta_2\, t + \varepsilon_{2t}, \qquad (3.b)$$

where N_{1t} and N_{2t} are the group's recorded monthly usage levels. As N_{1t} and N_{2t} differ from $N_{1t}{}^{*}$ and $N_{2t}{}^{*}$, equations (3.a) and (3.b) contain additive errors ε_{1t} and ε_{2t} that follow an AR(4) process based on an initial exploration of an AR(5) process, whose fifth AR parameter estimates are all insignificant at $\alpha = 0.05$.

Since there are two traffic directions (northbound vs. southbound), each GL demand system has four regressions. We jointly estimate the four regressions because the random errors are likely contemporaneously correlated, as the usage of the two tunnels by a vehicle group is the result of the decision making by the drivers of that particular vehicle group.

3. Theory/calculation

3.1 *Elasticity calculation*

Based on equations (2.a) and (2.b), the monthly cross-price elasticity of a given vehicle group for tunnel j (= 1, 2) and k ($j \neq k$) is:

$$\eta_{jkt} = \partial \ln N_{jt}^{*} / \partial \ln P_{kt} = \partial N_{jt}^{*} / \partial P_{kt} * (P_{kt} / N_{jt}^{*}) = 1/2\ \beta_{12}\, (P_{kt} / P_{jt})^{1/2} / N_{jt}^{*}. \qquad (4.a)$$

When $\beta_{12} \geq 0$, $\eta_{jkt} \geq 0$, suggesting that tunnels j and k are substitutes for the drivers of a particular vehicle group.

The monthly own-price elasticity of tunnel j is:

$$\eta_{jjt} = \partial \ln N_{jt}^{*} / \partial \ln P_{jt} = \partial N_{jt}^{*} / \partial P_{jt} * (P_{jt} / N_{jt}^{*}) = -1/2\ \beta_{12}\, (P_{kt} / P_{jt})^{1/2} / N_{jt}^{*}. \qquad (4.b)$$

When $\beta_{12} \geq 0$, $\eta_{jjt} \leq 0$, suggesting that this vehicle group has a downward-sloping demand curve for tunnel j.

Equations (4.a) and (4.b) imply:

$$\eta_{jkt} + \eta_{jjt} = 0, \qquad (4.c)$$

chiefly because a tunnel demand is an input demand (Woo et al., 2015, Section 3) that is homogeneous of degree zero in input prices (Varian, 1992, p.86). Hence, our reporting of the LRT's and TCT's toll-responsiveness in Table 3 only contains the own-price elasticity estimates that are the equally-weighted averages of the monthly η_{jjt} estimates (Woo et al., 2015, p.101).

An aggregate price elasticity estimate summarizes the toll responsiveness of all vehicles using a particular tunnel. The monthly aggregate own-price elasticity is the weighted average of the group *m*'s own-price elasticity, with each weight equal to the vehicle group *m*'s share of the tunnel's monthly total usage. The aggregate own-price elasticity estimates reported in Table 4 are the equally-weighted averages of the monthly estimates (Woo et al., 2015, p.102).

3.2 *Tunnel usage responses to toll changes*

Let P_{jm} denote the current toll paid by drivers of vehicle group *m* at tunnel $j = 1, 2$. Further, let P_{jm}' denote the proposed toll at tunnel *j* for vehicle group *m*. Based on equations (1.a) and (1.b), the effect of a proposed change in tolls on vehicle group *m*'s usage of that tunnel is:

$$X_{jm} \quad = \quad b_{12m}\,[(P_{km}' / P_{jm}')^{1/2} - (P_{km} / P_{jm})^{1/2}], \qquad (5)$$

where $b_{12m} = \beta_{12}$, which is the estimate for vehicle group *m*. We use the standard error of X_{jm}, which is $\mathrm{var}(b_{12m})^{1/2}\,[(P_{km}' / P_{jm}')^{1/2} - (P_{km} / P_{jm})^{1/2}]$, to gauge X_{jm}'s statistical significance.

An estimate for the aggregate usage change for tunnel *j* is:

$$X_j \quad = \quad \Sigma_m X_{jm}, \qquad (6)$$

where the standard error is $[\Sigma_m \mathrm{var}(X_{jm})]^{1/2}$ under the assumption that the usage changes by vehicle group are uncorrelated.

3.3 *Two hypotheses*

We apply a two-tailed *t*-test to the first null hypothesis **H1**: $\beta_{12} = 0$ to determine whether the drivers of a particular vehicle group *m* would respond to a revenue-neutral toll proposal. If **H1** is rejected at $\alpha = 0.05$, the usage response estimates based on equations (2.a) and (2.b) are statistically different from zero, suggesting the proposal's likely effectiveness in mitigating the LRT's congestion.

Both the LRT and TCT have non-directional tolls. If the estimated tunnel usage responses vary by direction, directional tolls can be more effective than non-directional tolls in price-managing the LRT's congestion. Hence, we apply the Wald test to the second null hypothesis **H2**: β_{12} does not vary by direction.

3.4 *Derivation of a revenue-neutral toll proposal*

Using equation (4), our derivation of a revenue-neutral toll proposal is an Excel-based goal-seeking procedure entailing the following steps:

1. Assume a fractional increase of *K* in the LRT's toll in 2014 (e.g., $K = 0.25$).
2. Find the LRT's new toll (e.g., HK$10 per vehicular trip at $K = 0.25$).
3. Assume a *D* reduction in the TCT's tolls.
4. Find the TCT's new tolls [= 2014 tolls × $(1 - D)$].
5. Estimate the LRT's new usage levels by vehicle group at the new tolls from Steps 2 and 4. Each new usage level is the group's 2014 average monthly usage less the estimated usage response.

6. Compute the LRT's new total revenue = Sum of the LRT's new usage levels priced at the LRT's new toll by vehicle group.
7. Compute the LRT's revenue increase = Δ_{LRT} = Total revenue at the LRT's new toll – total revenue at the LRT's 2014 toll.
8. Estimate the TCT's new usage levels by vehicle group at the new tolls from Steps 2 and 4. Each new usage level is the group's 2014 average monthly usage less the estimated usage response.
9. Find the TCT's new revenue = Sum of the TCT's new usage levels priced at the TCT's new tolls by vehicle group.
10. Find the TCT's revenue reduction for a given $D = \Delta_{\mathrm{TCT}}(D)$ = Total revenue at the TCT's 2014 tolls – total revenue at the TCT's new tolls.
11. Repeat Steps 3 to 10 until $\Delta_{\mathrm{TCT}}(D^*)$ and Δ_{LRT} converge, where D^* = TCT toll reduction required to achieve revenue-neutrality.

4. Empirical evidence

4.1 ITSUR results

Table 2 summarizes the results for the three vehicle-group-specific GL demand systems, each of which has four tunnel usage regressions (= 2 tunnels × 2 traffic directions).[3] It shows that the 12 regressions have adjusted R^2 values of 0.66 to

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[3] For interested readers, our SAS data file, programs, and detailed output listings are available from the corresponding author upon request by email.

0.92, suggesting a reasonable fit by our GL specification of the tunnel usage data. The AR(4) assumption is empirically reasonable based on each regression's number of significant AR parameter estimates. Further, each regression's sum of the AR parameter estimates is less than 1.0, indicating that the estimated AR(4) process is stationary.

We now turn our attention to the coefficient estimates for the non-intercept RHS variables, finding that these estimates support our GL demand regressions' empirical plausibility. Put simply, the 12 estimates for β_{12} are all positive. Further, their statistical significance leads us to reject **H1**: $\beta_{12} = 0$. Hence, the two tunnels' usage pattern is price-sensitive, supporting our conjecture that price-managing the LRT's congestion might be effective.

The 12 positive estimates for (ψ_1, ψ_2) are all significant, thus confirming the expected GDP effect on tunnel usage. The same GDP effect, however, tends to exacerbate the LRT's congestion.

Eleven of the 12 coefficient estimates for the binary indicator A_t are insignificant, in line with our expectation that the ENT's availability does not materially impact the LRT's and TCT's usage pattern.

The coefficient estimates for the binary indicators (S_{1t}, S_{2t}, S_{3t}) suggest seasonality in the LRT's and TCT's usage pattern. These estimates' signs and significance, however, vary by vehicle group and direction.

All estimates for θ_1 and θ_2 are negative and significant, indicating declining tunnel usage over time after controlling for the effects of the tunnel tolls, real GDP, and seasonality.

Finally, the *p*-value of the Wald statistic for testing **H2**: β_{12} does not vary by direction is: (a) 0.0020 for vehicle group 1, (b) 0.0195 for vehicle group 2, and (c) 0.1030 for vehicle group 3. As **H2** is rejected for vehicle groups 1 and 2, a proposal of directional tolls may further ease the LRT's congestion.

4.2 Price elasticity estimates

Table 3 reports the negative own-price estimates by vehicle group, showing that the two tunnels' vehicular trips are price-inelastic. For the LRT, the northbound estimates are between -0.21 and -0.34, while the southbound estimate are between -0.17 and -0.25. For the TCT, the northbound estimates are between -0.14 and -0.22, while the southbound estimates are between -0.11 and -0.19. Thus, the northbound estimates are moderately larger than the southbound estimates. This makes sense because the northbound traffic is mainly related to work-to-home trips with a more flexible schedule than southbound traffic mainly caused by home-to-work trips.

Table 4 reports the LRT's aggregate own-price elasticity estimates of -0.25 for the northbound usage and -0.21 for the southbound usage. The corresponding estimates for the TCT are -0.21 and -0.18. Our elasticity estimates are larger in size than the LRT estimate of -0.103 and the TCT estimate of -0.123 in Loo (2003, Table 3). We attribute the numerical differences between our and Loo's estimates to the differences in data (our 2000-2014 monthly directional data vs. Loo's 1979-2000 monthly non-directional data) and estimation techniques (our GL demand estimation vs. Loo's double-log regressions).

4.3 Usage responses to a revenue-neutral proposal of non-directional tolls

Panel A of Table 5 reports the tunnel usage response estimates for the revenue-neutral toll proposal of a 25% increase in the LRT's toll from HK$8 to HK$10 and an offsetting 14.9% reduction in the TCT's tolls. The usage response estimates are all significant and non-trivial, underscored by the LRT's estimates of -7.6% to -13.1% and the TCT's estimates of 4.2% to 9.5% of their respective average monthly usage levels in 2014.

Panel B reports the tunnel usage response estimates for a revenue-neutral toll proposal of a 50% increase in the LRT's toll from HK$8 to HK$12 and an offsetting 27.6% reduction in the TCT's tolls. These response estimates are all significant and about twice those seen in Panel A.

4.4 Discussion

Our case study makes several contributions to Hong Kong's tunnel congestion management and the transportation literature. First, it presents an approach based on a GL demand estimation to analyze the toll responsiveness of the directional usage pattern of the LRT and TCT. It illustrates the approach's usefulness when survey data collection is costly but aggregate data are readily available (Nam, 1997), yielding results that complement the literature on route-choice behavior modeling (e.g., Yildirim and Hearn, 2005; Stewart, 2007; Chung et al., 2012; Bao et al., 2015; Rambha and Boyles, 2016) and empirical findings based on route-choice survey data (e.g., Burris and Pendyala, 2002; Olszewski and Xie, 2005; Washbrook et al., 2006; Train and Wilson, 2008; Hau et al., 2011).

Our key findings suggest that Hong Kong can moderately price-manage its LRT's rush-hour congestion. Our first finding comprises: (a) 12 (= 2 tunnels × 3 vehicle groups × 2 traffic directions) disaggregate own-price elasticity estimates of -0.11 to -0.34; and (b) four (= 2 tunnels × 2 traffic directions) aggregate own-price elasticity estimates of -0.18 to -0.25. Thus, the usage pattern of the LRT and TCT is price-inelastic, corroborating the own-price elasticity estimates in Loo (2003, Table 3) and the lower half of the range in Litman (2013, p. 40).

Our results also show that that a 25% (50%) increase in the LRT's flat toll would trigger an offsetting 14.9% (27.6%) reduction in the TCT's tolls. These toll changes would cause: (a) a 9.9% (17.2%) reduction in the LRT's northbound usage;

(b) an 8.1% (14.1%) reduction in the LRT's southbound usage; (c) a 7.7% (15.9%) increase in the TCT's northbound usage; and (d) a 6.6% (13.8%) increase in the TCT's southbound usage. All statistically significant (p-value < 0.01), these response estimates support price-management of the two tunnels' usage pattern.

Second, our study documents that the toll-sensitivity of tunnel usage is direction-dependent. Our finding is that a 1% change in the LRT's monthly northbound (southbound) total usage likely causes a 0.35% (0.68%) change in the LRT's northbound (southbound) peak usage during the LRT's rush hours. As the LRT's northbound total usage reduction is 9.9% to 17.2%, the estimated reduction in the LRT's northbound peak usage is 3.5% (= 0.35 × 9.9%) to 6.0% (= 0.35 × 17.2%). The estimated reduction in the LRT's southbound peak usage is 5.5% (= 0.68 × 8.1%) to 9.6% (= 0.68 × 14.1%), reflecting the LRT's southbound total usage reduction of 8.1% to 14.1%.

As a result, a non-directional toll proposal may be seen as the first step towards price-managing the LRT's congestion. After this proposal being in place for a couple of years, an assessment may occur to determine the need for further toll changes, including: (a) adjusting the non-directional tolls, (b) replacing the non-directional tolls with directional tolls, or (c) adopting a directional design with time-varying tolls.

Third, our study provides detailed price elasticity estimates by vehicle group and direction for the LRT and TCT, thus enriching the limited evidence in several literature reviews (Oum et al., 1992; Goodwin, 1992; Graham and Glaister, 2004; Litman, 2004, 2013). Furthermore, our aggregate own-price elasticity estimates corroborate those of Loo (2003), reinforcing the usefulness of price-management in mitigating tunnel congestion in Hong Kong. Based on such elasticity estimates, we show how to develop two revenue-neutral toll proposals and document each proposal's likely effectiveness in relieving the LRT's rush-hour congestion, thus affirming the virtue of pricing in transportation demand management.

5. Conclusion

Using the publicly available monthly usage data by vehicle group and direction for the 15-year period of 2000 – 2014, we find that the LRT's directional usage has discernible toll responsiveness. Further, implementing a revenue-neutral proposal is estimated to modestly reduce the LRT's total directional usage and increase the TCT's total directional usage.

We also find that the GL system yields empirically plausible price sensitivity estimates, thus enabling our assessment of a revenue-neutral toll change proposal. The peak usage analysis is particularly useful because it directly addresses the LRT's time- and direction-dependent congestion during the morning and afternoon rush hours. To the best of our knowledge, we are unaware of similar studies carried out for Hong Kong or other cities based on publicly available data. Hence, the case study serves to accentuate the merit of price-management of a congested facility.

The policy implications and lessons for other cities are that price-management of traffic congestion can be effective. However, limited price responsiveness implies that a toll change proposal is only part of an overall solution. Demand management of severe congestion may require additional pricing measures, including road pricing, parking fees, illegal parking fines, vehicular fuel taxes, vehicular purchase taxes, and vehicular registration fees. For this reason, we recommend cities with severe traffic congestion adopt an integrated approach that entails both the above-listed demand-side alternatives and supply-side alternatives (e.g., road widening and route additions).

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References

Bao, Y., Gao, Z., Xu, M., Sun, H., Yang, H., 2015. Travel mental budgeting under road toll: An investigation based on user equilibrium. Transportation Research Part A: Policy and Practice 73, 1-17.

Burris, M.W., Pendyala, R.M., 2002. Discrete choice models of traveler participation in differential time of day pricing programs. Transport Policy 9, 241-251.

Caves, D.W., Christensen, L.R., 1980. Global properties of flexible functional forms. American Economic Review 70, 422-432.

Chung, B.D., Yao, T., Friesz, T.L., Liu, H., 2012. Dynamic congestion pricing with demand uncertainty: a robust optimization approach. Transportation Research Part B: Methodological 46(10), 1504-1518.

Davidson, R., MacKinnon, J.G., 1993. Estimation and Inference in Econometrics. Oxford University Press, Oxford.

Diewert, W.E., 1971. An application of the Shephard duality theorem: A Generalized Leontief production function. Journal of Political Economy 79, 481-507.

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

Graham, D.J., Glaister, S., 2004. Road traffic demand elasticity estimates: A review. Transport Reviews 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. The Singapore Economic Review 56, 467–488.

Litman, T., 2004. Transit price elasticities and cross-elasticities. Journal of Public Transportation 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. Environment and Planning A 35, 249-276.

May, A.D., Milne, D.S., 2000. Effects of alternative road pricing systems on network performance. Transportation Research Part A: Policy and Practice 34, 407-436.

Meyer, M.D., 1999. Demand management as an element of transportation policy: Using carrots and sticks to influence travel behavior. Transportation Research Part A: Policy and Practice 33, 575-599.

Nam, K.C., 1997. A study on the estimation and aggregation of disaggregate models of mode choice for freight transport. Transportation Research Part E: Logistics and Transportation Review 33, 223-231.

Olszewski, P., Xie, L., 2005. Modelling the effects of road pricing on traffic in Singapore. Transportation Research Part A: Policy and Practice 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. Journal of Transport Economics and Policy 26,139-154.

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? Transportation Research Part A: General 22, 319-327.

Rambha, T., Boyles, S.D., 2016. Dynamic pricing in discrete time stochastic day-to-day route choice models. Transportation Research Part B: Methodological 92, 104-118.

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

Stewart, K., 2007. Tolling traffic links under stochastic assignment: Modelling the relationship between the number and price level of tolled links and optimal traffic flows. Transportation Research Part A: Policy and Practice 41(7), 644-654.

Train, K., Wilson, W.W., 2008. Estimation on stated-preference experiments constructed from revealed-preference choices. Transportation Research Part B:

Methodological 42, 191–203.

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

Vickrey, W.S., 1967. Optimization of traffic and facilities. Journal of Transport Economics and Policy 1, 123-136.

Vickrey, W.S., 1969. Congestion theory and transport investment. American Economic Review 59(2), 251-260.

Washbrook, K., Haider, W., Jaccard, M., 2006. Estimating commuter mode choice: A discrete choice analysis of the impact of road pricing and parking charges. Transportation 33, 621–639.

Woo, C.K., Cheng, Y.S., Li, R., Shiu, A., Ho, S.T., Horowitz, I., 2015. Can Hong Kong price-manage its cross-harbor-tunnel congestion? Transportation Research Part A: Policy and Practice 82, 94-109.

Yildirim, M.B., Hearn, D. W., 2005. A first best toll pricing framework for variable demand traffic assignment problems. Transportation Research Part B: Methodological 39(8), 659-678.

Table 1. IT3SLS regression results for $\Delta\ln U_t$, the first difference of the natural log of the Lion Rock Tunnel's (LRT's) monthly peak usage; sample period = 2003 – 2014

Variable [coefficient]	Northbound			Southbound		
	Estimate	Standard error	*p*-value	Estimate	Standard error	*p*-value
Adjusted R^2	0.2093			0.1783		
AR(1) parameter	-0.4585	0.1970	0.0214	-0.1845	0.2035	0.3662
Intercept [γ_0]	-0.0006	0.0009	0.5445	-0.0003	0.0016	0.8627
$\Delta\ln V_{1t}$ = First difference of ln(LRT's monthly total usage in month t) [γ_1]	0.3467	0.0856	<.0001	0.6753	0.1280	<.0001
$\Delta\ln V_{2t}$ = ln(Number of days in month t) [γ_2]	-0.3295	0.0956	0.0008	-0.8172	0.1398	<.0001

Note: The list of instruments includes the intercept, $\ln V_{2t}$, the 11 binary indicators for month t (e.g., the January indicator = 1 if month t is January, 0 otherwise), and the first difference of the natural log of monthly real GDP.

Table 2. Summary of ITSUR/AR(4) estimation results based on the monthly data for the 15-year period of 2000 – 2014 for the three vehicle-group-specific GL demand systems for the Lion Rock Tunnel (LRT; $j = 1$) and Tate's Cairn Tunnel (TCT; $j = 2$)

Variable [coefficient for tunnel $j = 1, 2$]	Vehicle group 1				Vehicle group 2				Vehicle group 3			
	Northbound		Southbound		Northbound		Southbound		Northbound		Southbound	
	LRT	TCT	LRT	TCT	LRT	TCT	LRT	TCT	LRT	TCT	LRT	TCT
Adjusted R^2	0.7976	0.8818	0.7777	0.8843	0.6634	0.8644	0.7044	0.8707	0.9169	0.7141	0.9149	0.6758
Number of significant ($\alpha = 0.05$) AR parameter estimates	4	4	4	4	3	3	4	4	3	3	3	3
Sum of AR estimates	0.8367	0.9447	0.8596	0.9453	0.9503	0.8440	0.8991	0.8467	0.9587	0.9192	0.9623	0.9204
Intercept [β_{jj}]	▲	▲	▲	▲	▼	▽	▼	▽	▽	▼	▽	▼
$(P_{kt} / P_{jt})^{1/2}$ [$\beta_{jk} = \beta_{kj}$ for $j \neq k$, or β_{12}]	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
Y_t [ψ_j]	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
A_t [ϕ_j]	▼	▽	▽	▽	△	△	△	△	△	△	△	△
S_{1t} [μ_{j1}]	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
S_{2t} [μ_{j2}]	△	△	△	▲	▲	▲	▲	▲	▲	▲	▲	▲
S_{3t} [μ_{j3}]	▼	△	▼	▼	▲	▲	▲	▲	△	▲	△	▲
t [θ_j]	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼	▼

Notes: (1) Each vehicle-group-specific demand system has two northbound usage regressions for the LRT and TCT and two southbound usage regressions for the LRT and TCT; vehicle group 1 = private cars, taxis and motor cycles; 2 = single-decked buses, light buses and goods vehicles not more than 5.5 tonnes; and 3 = double-decked buses and goods vehicles over 5.5 tonnes.

(2) The non-intercept variables are: (a) $(P_{2t} / P_{1t})^{1/2}$ = monthly (TCT toll / LRT toll)$^{1/2}$; (b) $(P_{1t} / P_{2t})^{1/2}$ = monthly (LRT toll / TCT toll)$^{1/2}$; (c) Y_t = monthly real GDP; (d) $A_t = 1$ if month t is after the ENT's March 2008 opening, 0 otherwise; (e) $S_{st} = 1$ if month t in quarter s (= 1, 2, 3) of the year, 0 otherwise; (f) t = time trend.

(3) At $\alpha = 0.05$ for a two-tailed t-test, "▲" = "positive and significant"; "▼" = "negative and significant"; "△" = "positive and insignificant"; "▽" = "negative and insignificant".

(4) The p-value of the Wald statistic for testing **H2**: β_{12} does not vary by direction is 0.0020 for vehicle group 1, 0.0195 for vehicle group 2, and 0.1030 for vehicle group 3.

Table 3. Disaggregate own-price elasticity estimates by vehicle group, tunnel and travel direction

Vehicle group	Lion Rock Tunnel		Tate's Cairn Tunnel	
	Northbound	Southbound	Northbound	Southbound
1 = Private cars, taxis and motor cycles	-0.24	-0.21	-0.22	-0.19
2 = Single-decked buses, light buses and goods vehicles not more than 5.5 tonnes	-0.34	-0.25	-0.22	-0.18
3 = Double-decked buses and goods vehicles over 5.5 tonnes	-0.21	-0.17	-0.14	-0.11

Note: This table does not report the cross-price elasticity because (cross-price elasticity + own-price elasticity) = 0, see equation (3.c).

Table 4. Aggregate own-price elasticity estimates by tunnel and travel direction

Lion Rock Tunnel		Tate's Cairn Tunnel	
Northbound	Southbound	Northbound	Southbound
-0.25	-0.21	-0.21	-0.18

Note: This table does not report the cross-price elasticity because (cross-price elasticity + own-price elasticity) = 0, see equation (3.c).

Table 5. Average monthly tunnel usage responses by vehicle group, tunnel and travel direction; value in [ ] = usage response as a percent of the average monthly usage in 2014; values in ( ) = *p*-value for a two-tailed *t*-test of H_0: tunnel usage response = 0

Panel A: LRT's toll increase = 25%; TCT's toll reduction = 14.9% to offset the LRT's toll increase

Vehicle group	Lion Rock Tunnel (LRT)				Tate's Cairn Tunnel (TCT)			
	Northbound		Southbound		Northbound		Southbound	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
1 = Private cars, taxis and motor cycles	-90793 [-8.9%]	10649.7 (< 0.0001)	-74179 [-7.6%]	11565.6 (< 0.0001)	52148 [7.7%]	6116.8 (< 0.0001)	42605 [6.9%]	6642.8 (< 0.0001)
2 = Single-decked buses, light buses and goods vehicles not more than 5.5 tonnes	-29228 [-13.1%]	6585.6 (< 0.0001)	-21165 [-9.2%]	6605.2 (< 0.0001)	11395 [9.5%]	2567.5 (< 0.0001)	8251 [7.6%]	2575.1 (< 0.0001)
3 = Double-decked buses and goods vehicles over 5.5 tonnes	-17712 [-11.3%]	4296.3 (< 0.0001)	-14378 [-9.1%]	4423.1 (< 0.0001)	5490 [5.2%]	1331.7 (< 0.0001)	4456 [4.2%]	1370.9 (< 0.0001)
Total	-137733 [-9.9%]	13238.0 (< 0.0001)	-109721 [-8.1%]	14034.1 (< 0.0001)	69032 [7.7%]	6766.1 (< 0.0001)	55313 [6.6%]	7255.2 (< 0.0001)

Panel B: LRT’s toll increase = 50%; TCT’s toll reduction = 27.6% to offset the LRT’s toll increase

Vehicle group	Lion Rock Tunnel (LRT)				Tate’s Cairn Tunnel (TCT)			
	Northbound		Southbound		Northbound		Southbound	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
1 = Private cars, taxis and motor cycles	-158681	18612.7	-129643	20213.4	108284	12701.4	88469	13793.7
	[-15.6%]	(< 0.0001)	[-13.3%]	(< 0.0001)	[16.0%]	(< 0.0001)	[14.3%]	(< 0.0001)
2 = Single-decked buses, light buses and goods vehicles not more than 5.5 tonnes	-51081	11509.7	-36991	11544.1	23661	5331.3	17134	5347.2
	[-22.9%]	(< 0.0001)	[-16.0%]	(< 0.0001)	[19.7%]	(< 0.0001)	[15.7%]	(< 0.0001)
3 = Double-decked buses and goods vehicles over 5.5 tonnes	-30955	7508.8	-25128	7730.3	11399	2765.1	9253	2846.7
	[-19.7%]	(< 0.0001)	[-15.9%]	(< 0.0001)	[10.9%]	(< 0.0001)	[8.7%]	(< 0.0001)
Total	-240717	23136.3	-191762	24527.7	143345	14049.7	114856	15065.3
	[-17.2%]	(0.00)	[-14.1%]	(0.00)	[15.9%]	(0.00)	[13.8%]	(0.00)

Fig. 1. Map of the Lion Rock Tunnel (LRT), the Tate's Cairn Tunnel (TCT), Tai Po Road, and the Eagle's Nest Tunnel (ENT) that connects to the Sha Tin Heights Tunnel (STHT), and the Route 8 expressway that links Cheung Sha Wan in West Kowloon and the Tsing Yi Island

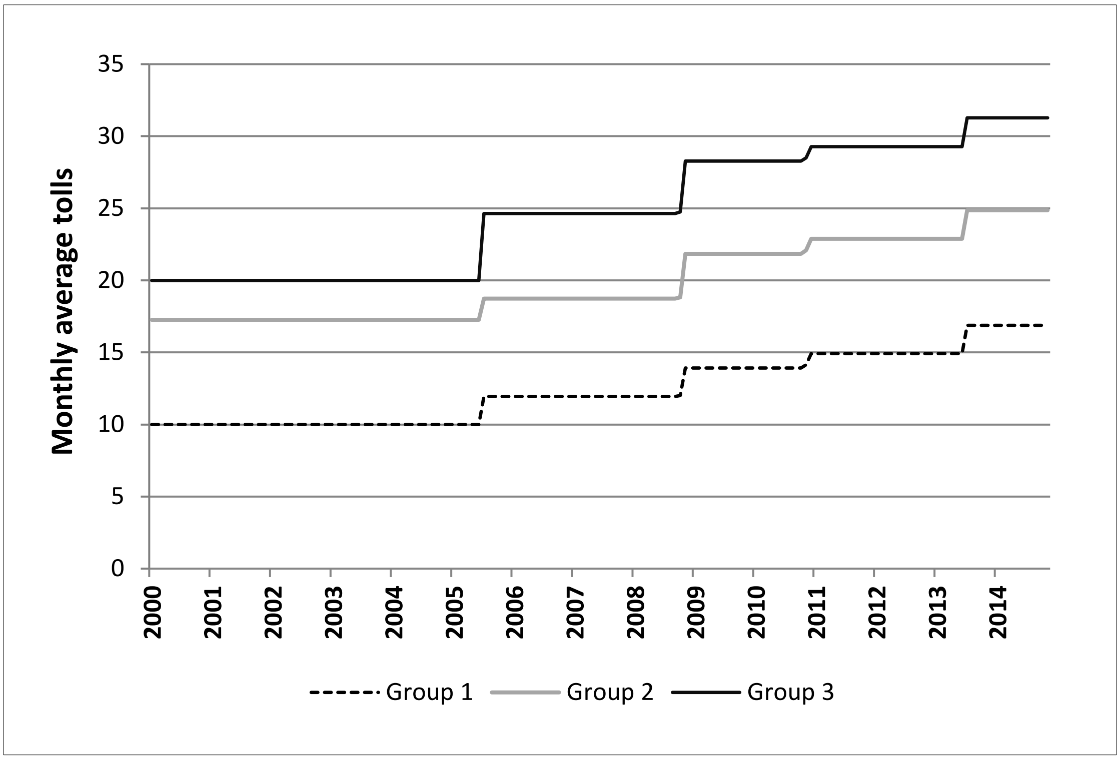

Fig. 2. Tate's Cairn Tunnel's monthly average tolls by vehicle group that increasingly exceed the Lion Rock Tunnel's HK$8 per vehicular trip in 2000-2014, with Group 1 = private cars, taxis and motor cycles; Group 2 = single-decked buses, light buses and goods vehicles not more than 5.5 tonnes; and Group 3 = double-decked buses and goods vehicles over 5.5 tonnes.

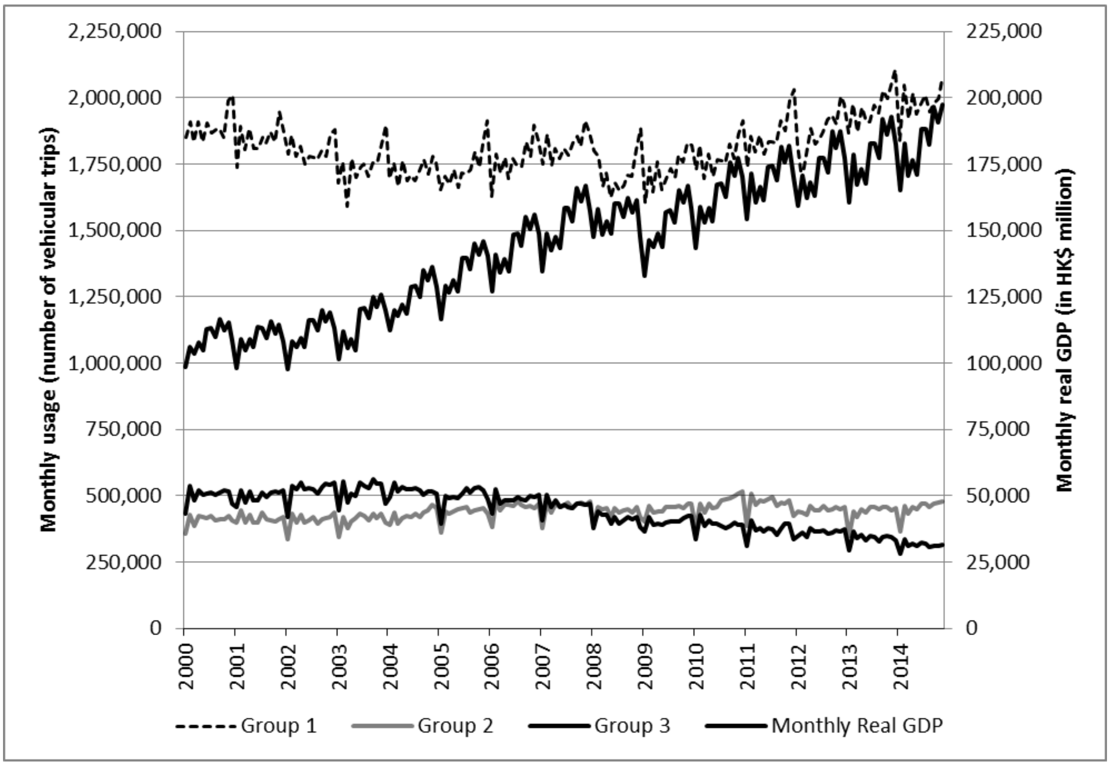

Fig. 3. Lion Rock Tunnel's monthly aggregate usage (= north-bound trips + south-bound trips) by vehicle group and monthly GDP in 2000-2014, with Group 1 = private cars, taxis and motor cycles; Group 2 = single-decked buses, light buses and goods vehicles not more than 5.5 tonnes; and Group 3 = double-decked buses and goods vehicles over 5.5 tonnes.

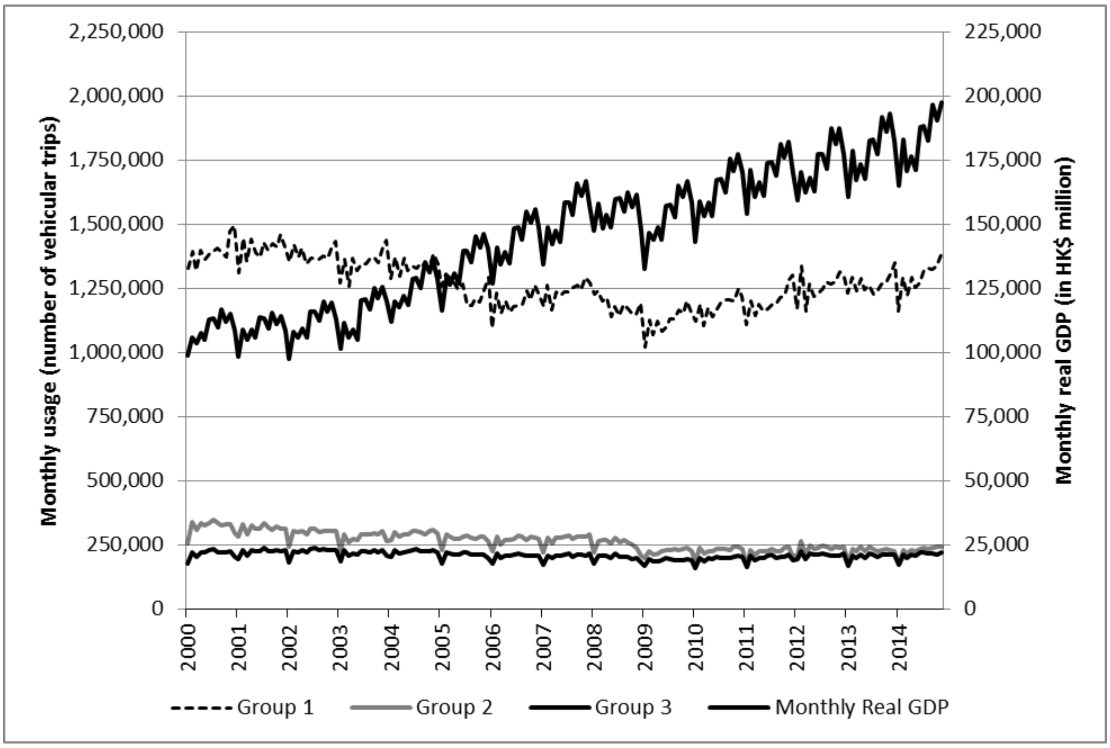

Fig. 4. Tate's Cairn Tunnel's monthly aggregate usage (= north-bound trips + south-bound trips) by vehicle group and monthly GDP in 2000-2014, with Group 1 = private cars, taxis and motor cycles; Group 2 = single-decked buses, light buses and goods vehicles not more than 5.5 tonnes; and Group 3 = double-decked buses and goods vehicles over 5.5 tonnes.