Impact of second-best congestion pricing schemes on CO_2 emissions and temporal shift of freight transport

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Abstract: This paper examines freight transport temporal shift and the vehicular pollutants emissions in an urban transport network with congestion pricing schemes, specifically when only freight transportation is tolled in the peak period. The equivalent minimization models of no-toll, first-best, and second-best congestion pricing scenarios are presented with an excess-demand approach based on user equilibrium analysis, in which the different pricing schemes include multiple time periods and mixed traffic. We established proofs for the equivalent conditions and the uniqueness conditions of the models. The findings and policy insights are discussed using simulation and sensitivity analyses of the key parameters.

Keywords: Sustainable transport; Urban freight; Congestion pricing; User equilibrium; Emissions

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The impact of second-best congestion pricing schemes on CO emission and the temporal shift of freight transport

Abstract: This paper examines the freight transport temporal shift and the vehicular pollutants emissions in an urban transport network with congestion pricing schemes, specifically when only freight transportation is tolled in the peak period. The equivalent minimization models of no-toll, first-best, and second-best congestion pricing scenarios are presented with an excess-demand approach based on user equilibrium analysis, in which the different pricing schemes includes multiple time periods and mixed traffic. We established proofs for the equivalent conditions and the uniqueness conditions of the models. By simulation and sensitivity analyses of the key parameters, the main findings and policy insights are discussed.

1 Introduction

Economic growth and rapid urbanization have a dark side – traffic congestion. Today, policy makers concerned about sustainable development need to manage not only the issues on congestion but also, with more vehicles, tail gas emissions are now a major source of environmental pollution. This affects the urban air quality, environment, and society (Chen, 2013).

According to Raux (2010), transport contributes to 25-30% of global CO_2 emissions and nearly two-thirds of the total transport-related emissions are from road transport (Davis et al. 2010). In China, the transport sector accounts for 348.19 million tons of coal equivalent, and the total vehicle emissions in 2013 was 45.71 million tons (He and Qiu, 2016). In the UK, air pollution from road traffic is also a significant public health problem, accounting for 34% of nitrogen oxide (NOx), 14% of PM10 and 13% of PM2.5 emissions in 2015 (Barnes and Williams, 2017). In 2000, the externalities from transport (excluding congestion) were estimated to account for 7.3% of the total GDP in EU15 plus Norway and Switzerland, with freight transport being responsible for a third of that value (Lindholm and Behrends, 2012).

To build a sustainable urban transportation system, urban authorities have introduced and implemented various mitigation strategies and traffic policies to stem congestion and transport-related pollution. However, there are limitations to the expansion of urban transportation networks. Building more roadway capacity to handle higher traffic volumes will only increase exhaust emissions and worsen the air quality (Sathaye et al., 1994). Hence, traffic demand management (TDM) policies are viewed as effective, sustainable and environment-friendly ways to improve the efficiency, speed, safety, reliability, comfort, and the overall operation of the urban transport system (Meyer, 1999; Kennedy et al., 2005; Habibian and Kermanshah, 2013).

The TDM policy for sustainable urban transportation seeks to encourage travellers to change their travel behaviour and use lower-emission alternative modes, such as modal substitution, telecommunications substitutions, pricing incentives/disincentives,1 and land use –transportation strategies (Deakin, 2001). Among the pricing incentives/disincentives alternatives of the TDM, road pricing has gained a special attention and been implemented in metropolitan areas, including Singapore, Orange County (California State Route 91), London, Edinburgh, Hong Kong and the cities of Trondheim, Oslo, and Bergen in Norway (Palma, 2006; Noordegraaf et al., 2014). In the EU, more than 200 cities across 10 countries are now operating Low Emission Zones where the most polluting vehicles are either banned or charged an access fee (Wolff, 2014), with several cities implementing a congestion charging scheme/ pricing policy to restrict certain types of vehicles from entering the inner city (Rakowska et al., 2014). To some extent, London has succeeded in controlling the vehicle tail gas emissions through reducing traffic volume by the congestion pricing scheme, with the target set to reduce the normalised CO_2 emissions by 20 percent by 2017/18. This was met ahead of schedule in 2014/15 (Transport for London, 2015).

Aside from residential trips, urban freight transportation adds to traffic and environmental woes too. In China, the urban freight transportation demand is fueled by the online shopping with 467 million parcel delivery trips in 2016 (Davidson et al., 2017). In order to reduce urban congestion, studies on shifting freight transportation to the off-peak have attracted attention from academia and policy makers. For example, the off-peak freight delivery problem was investigated by Glasmeier and Kibler (1996), Vilain and Wolfrom (2000), Holguín-Veras (2008) and Dablanc et al. (2013), while in-practice, a new industry-led programme for reducing the emissions of London's freight and fleet operators was launched in January 2016 (Transport for London, 2016). Given the imparotance and urgency of this topic, our paper chooses to address the impact of congestion pricing policy on urban transportation, especially on the temporal shift of freight transportation from peak to off-peak periods to reduce congestion, while addressing pollutant emissions. Specifically, we investigate the use of congestion tolls to control/shift the traffic volume temporally, leading to lesser pollutant emissions. This paper attempts to answer the following research questions:

1. How does the congestion pricing policy impact the traffic volume, travel speed, and emissions in different time periods? We consider two traffic types - freight transport and residential trips.
2. How does the congestion pricing scheme of the first-best and the second-best policies impact the

temporal shift in traffic volume for freight transportation? Specifically, we consider the impact of the value of time (VOT) to the user and traffic capacity of the road/link.

The paper is organized as follows: Section 2 reviews the extant literature. Section 3 analyses the urban transportation network, including transport demand, traffic flow, and the cost of the links and routes. In Section 4, equivalent minimization models of no-toll, first-best and second-best congestion pricing scenarios are presented through an excess-demand approach. The second-best congestion pricing scenario includes different pricing schemes for multiple time periods and mixed traffic. In Section 5, a simulation study is conducted to examine the impact of the congestion pricing policies in traffic volume reallocation, time period shifting, and automobile toxic pollutant emissions reduction. The sensitivity analyses of the key parameters and managerial insights are discussed. The final section summarizes the major findings and some directions for future research.

2 Literature review

The literature covered in this paper follows two streams: sustainable urban freight transportation, and congestion pricing with network equilibrium.

2.1 *Sustainable urban freight transportation*

According to the definition of the Brundtland Commission, sustainable development is "(the) development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (McManus, 1996; Mebratu, 1998; Du Pisani, 2006; Goldemberg, 2007; Holden et al., 2014). Sustainable development is a major concern for policymakers and planners when considering broadly the effects on the environment (Spangenberg, 2002), economy (Ferretti, 2007), and social (White and Lee, 2009; Dempsey, 2011), with academe focusing on the trans-dimensional research of the combination (Rennings and Wiggering, 1997; Lehtonen, 2004). Transportation is itself a vital component of sustainable development, for transport facilities and activities have significant sustainability impact, such as traffic congestion, air and water pollution, which leads to other human health related impacts. A 'comprehensive' perspective requires sustainability to be a broad set of integrated problems that cannot be solved by using existing transportation decision–making practices, because the solutions to one problem may exacerbate others (Litman and Burwell, 2006).

Sultana et al. (2017), in a review of the sustainable urban transportation literature, highlighted the need to investigate the sustainability implications of urban freight movement in the e-shopping era. In recent years, demand for freight transport services has increased as a result of urbanization and economic growth, especially when the movement of goods and services are largely contributed by the extensive commercial establishments. With most consumption taking place in urban areas, the need for frequent urban freight transportation service is inevitable (Kin et al., 2017). However, this surge in urban traffic contributes toward urban traffic congestion and atmospheric pollution (Yannis et al., 2006), influencing a variety of social, environmental, and economic externalities. In an e-shopping era, urban freight flow has become more uncertain and fragmented, with greater growth of commercial vehicles.

This has compelled various methods applied to the area of sustainability in urban transportation; for instance, vehicle routing and scheduling optimization (see the review by Pillac et al. (2013)), urban freight transport planning (Ballantyne et al., 2013), and advanced freight transportation systems (Crainic et al., 2004). Figliozzi (2011) examined the different levels of congestion and time-definite customer demands on CO_2 emissions, and found that the impact of congestion or speed limits on commercial vehicle emissions are significant but difficult to predict. Go et al. (2012) studied the effect of integrated land use and transport policies on the environmental objectives for sustainable urban transport, and found that the CO_2 emissions reduction effects of the policy scenarios of integrated land use and transport is greater than those of existing policies. Korzhenevych et al. (2014) covered the factors of location (urban, interurban), time of the day (peak, off-peak, night) and vehicle characteristics (Euro-standards) as explanatory variables of external costs. Other studies have focused on traffic mitigation strategies and traffic restriction policies on sustainable urban transportation and urban air quality, such as the black carbon monitoring campaign (Invernizzi et al., 2011), low emission zones directed at heavy vehicles (Boogaard et al., 2012; Holman et al., 2015), and the Congestion Charging Scheme (CCS) curtailing certain vehicles from entering the inner city (Atkinson et al., 2009; Gibson and Carnovale, 2015).

2.2 Congestion pricing and network equilibrium

Congestion pricing, first proposed by Pigou (1920) and later Knight (1924), aims to reduce congestion and traffic volume by reducing the demand for peak travel on congested facilities. Two other scholars of influence include Beckmann and Vickrey. Beckmann et al. (1956) pointed that users should pay directly for the costs they impose as an incentive to use the resources efficiently and to reduce externalities, whereas Vickrey (1963) identified the potential of road pricing in influencing travellers' choice of route and travel mode; they are both basic economic principles and fundamental to the congestion pricing research. A substantial literature has since then, which can be classified as the first-best pricing and second-best pricing. The first-best congestion pricing policy is to determine the toll of each individual link equal to the marginal external cost of the link, also known as a marginal social cost pricing (Armstrong-Wright, 1986; Arnott and Small, 1994). Based on Vickrey's bottleneck model, Arnott and Kraus (1995) found that the first-best pricing for the morning rush-hour vehicle congestion with heterogeneous users is feasible when the time variation of the toll is constrained. The second-best congestion pricing policy is to reduce the demand by discouraging peak-period travel, limit access to congested areas by using permit systems and parking restrictions, and impose bans on commercial vehicles during certain hours (Lindsney and Verhoef, 2001). The second-best congestion pricing policy is more practical in urban areas where tolls may not be implemented widely due to technical or political constraints (McDonald et al., 1999; Liu and McDonald, 1999). The second-best congestion pricing in the road network was studied within static and dynamic situations (Verhoef,1996; Verhoef et al., 2002), the simple and general network (Liu and McDonald, 1999; Liu and Boyce, 2002), the single and multiple time periods (Liu and McDonald, 1999; Liu and Boyce, 2002), fixed and variable demands (May et al, 2000; Yang and Zhang, 2003), fixed and variable pricing (Zhang and Ge, 2004; Liu and Chen, 2009; Chen, 2013), and single and multi-class users (Di et al. 2016; Li et al., 2017). In terms of the research methodology in urban transportation networks, there are broadly 3 models: economic optimization model (Liu and McDonald, 1999; Verhoef, 2002), Vickrey's bottleneck model (Arnott et al., 1993), and network equilibrium model (Boyce, 1984).

In this paper, network equilibrium refers to 'equilibrium in a network' as stated by Beckmann et al. (1956), which is a model of origin-destination flows (demand) and user equilibrium route flows for a congested road network (Boyce, 1984; Boyce, 2013). In a seminal contribution, Wardrop (1952) stated two principles that formalize the network equilibrium, among which the user equilibrium (UE) is characterized by Wardrop's first principle, and the system optimum (SO) is characterized by Wardrop's second principle[1]. Network equilibrium has been a primary tool used to evaluate proposals and plans for urban road and transit systems throughout the world (Inoue and Maruyama, 2012). The main models of network equilibrium used in congestion pricing include: queueing network equilibrium (Yan and Lam, 1996; Shirmohammadi and Yin, 2016), elastic demand network equilibrium (Yang and Bell, 1997; Chen, 2013; Amirgholy and Gao, 2017) and dynamic/stochastic network equilibrium (Ying and Yang 2005; De Palma et al., 2005; Aboudina, 2016). Our paper focuses on the network equilibrium with elastic demand. By transforming the elastic-demand problem into a fixed-demand problem with an excess demand variable, (Sheffi, 1985), Liu and Chen (2009) proposed second-best congestion pricing models to evaluate the temporal, spatial, and modal impacts of congestion toll policies for a general traffic network. Later, Chen (2013) proposed an equivalent second-best congestion pricing model with UE and SO conditions and analysed the second-best congestion pricing schemes in traffic volume reallocation, modal shifts, and vehicular pollutants emissions control in urban road systems.

As a traffic congestion mitigation strategy, the congestion pricing policy/scheme has a large impact on freight transportation since this compels vehicles/trucks that need to pay additional costs to access a certain area may change their routing patterns or trip times. Additionally, charging urban road users additional costs could reduce the external social costs generated by its trip. However, to the best of the authors' knowledge, the congestion pricing imposed on this form of mixed traffic flow, i.e. freight transportation and residential trip, has yet to be

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[1] Wardrop's first principle refers to "the journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route", and Wardrop's second principle refers to "the average journey time is a minimum". See Sheffi (1985) for details.

investigated. Thus, the key contribution of this paper is its investigation on the impact of congestion pricing policies on the mixed traffic flow in the urban transportation system.

3 Model and Analysis

3.1 Urban transportation network and congestion pricing

Here, we provide a generalization to the prior studies (e.g. Liu, 2008; Liu and Chen, 2009; Chen, 2013) on urban transportation network by incorporating residential trips and freight transport. The transformation of the urban transportation network is a directed network $G = \{N, A\}$, with a set of nodes N and a set of links A. Each link $\forall a \in A$ with traffic x_a^i in time i has an associated flow-dependent transportation cost, i.e. the transportation cost per unit traffic flow or average transportation cost depending on peak and off-peak periods. S is the set pair of origin-destination (OD) nodes in the urban transportation network, each pair of OD nodes is denoted as s and $s \in S$, R_s is the set of routes/paths on an OD pair s. The purpose of this paper is to investigate the impact of the congestion pricing schemes on the temporal traffic shifting and toxic air pollutant emissions in the urban transportation networks for both freight transportation and residential trips. Similar to Liu and Chen (2009) and Tirachini and Hensher (2012), three congestion pricing policies (i.e. no-toll, first-best and second-best) will be discussed in this paper. The first-best congestion pricing is based on the marginal cost pricing (Marcucci, 2001; Lindsey, 2006), in which the optimal public transport fare equals total marginal cost minus the average user cost (Else, 1985). The second-best pricing considers the scenarios where tolls are not allowed on a major portion of the urban transportation network because of technical or political constraints (Liu and Chen, 2009).

3.2 Analysis of the urban transportation network

3.2.1 Transportation demand and traffic flow

The demand for transportation in of each OD pair is a function of transportation cost in both peak and off-peak periods. The income effect is assumed to be negligible and the substitution effect is positive. Similar to Liu (2008), Liu and Chen (2009), and Chen (2013), the elastic demand functions of the freight transportation and the residential trip on OD pair s at the peak period ($i = 1$) and off-peak period ($i = 2$) are as follows:

$$
\begin{cases}
\overline{q}_s^1 = \overline{Q}_s^1 - \overline{\beta}_{11,s}\mu_s^1 + \overline{\beta}_{12,s}\mu_s^2 \\
\overline{q}_s^2 = \overline{Q}_s^2 + \overline{\beta}_{21,s}\mu_s^1 - \overline{\beta}_{22,s}\mu_s^2 \\
\hat{q}_s^1 = \hat{Q}_s^1 - \hat{\beta}_{11,s}\mu_s^1 + \hat{\beta}_{12,s}\mu_s^2 \\
\hat{q}_s^2 = \hat{Q}_s^2 + \hat{\beta}_{21,s}\mu_s^1 - \hat{\beta}_{22,s}\mu_s^2
\end{cases}
\tag{1}
$$

where $\overline{q}_s^i$ is demand for transportation in OD pair s in period i of freight transportation, while $\hat{q}_s^i$ is that of the residential trip, and μ_s^i is the equilibrium minimum transportation cost on an OD pair s in period i. Hence, $\overline{Q}_s^i$ and $\hat{Q}_s^i$ present the expected fixed-demand on OD pair s in period i respectively, and $\overline{\beta}_{ii',s}$ and $\hat{\beta}_{ii',s}$ present the elasticity coefficient of freight transportation and residential trip respectively.

For the elasticity coefficient $\overline{\beta}_{ii',s}$, when $i = i'$ (for example $\hat{\beta}_{11,s}$), then $\overline{\beta}_{ii',s}$ is the own-price elasticity coefficient at the same time period ($i = i'$) for the freight transportation. That is, it is the elasticity of demand with respect to the traveller's cost/price in the same time period. Similarly, $\hat{\beta}_{ii',s}$ is the cross-price elasticity coefficient for the residential trip, when $i \neq i'$ (for example $\hat{\beta}_{12,s}$). We introduce the following assumption to ensure that the elastic demand function is reasonable and consistent with practice.

Assumption 1. For the elastic demand function of the freight transportation and the residential trip on OD pair s during the peak and off-peak periods, the following must be satisfied:

  i) the expected fixed-demand in the peak period is higher than the off-peak period;

  ii) the negative own-price effect and positive cross-price effect hold in each time period; and

  iii) the own-price effects outweigh the cross-price effects for each time period. That is:

$$\begin{cases} \overline{Q}_s^1 > \overline{Q}_s^2 > 0 \ \text{and} \ \hat{Q}_s^1 > \hat{Q}_s^1 > 0 \\ \overline{\beta}_{ii',s} > 0 \ \text{and} \ \hat{\beta}_{ii',s} > 0 \\ \overline{\beta}_{11,s}\overline{\beta}_{22,s} - \overline{\beta}_{12,s}\overline{\beta}_{21,s} > 0 \ \text{and} \ \hat{\beta}_{11,s}\hat{\beta}_{22,s} - \hat{\beta}_{12,s}\hat{\beta}_{21,s} > 0 \end{cases} \tag{2}$$

To simplify the following analysis, we set the elastic demand functions of the freight transportation and the residential trip as follows

$$\begin{cases} \overline{q}_s^i = \overline{D}_s^i\left(\mu_s^1, \mu_s^2\right) \\ \hat{q}_s^i = \hat{D}_s^i\left(\mu_s^1, \mu_s^2\right) \end{cases} \tag{3}$$

where $\overline{D}_s^i(\cdot)$ and $\hat{D}_s^i(\cdot)$ are the demand functions of the freight transportation and the residential trip, respectively. The inverse functions are represented by $\overline{D}_s^{i^{-1}}(\cdot)$ and $\hat{D}_s^{i^{-1}}(\cdot)$ correspondingly.

Let x_a^i note the traffic flow on link a (where $a \in A$, A is the set of OD pair of links in given traffic networks) in period i, and $\overline{x}_a^i$ and $\hat{x}_a^i$ represent the freight transportation and the residential trip respectively, thus similar to Guo and Xu (2016), we have

$$x_a^i = n\overline{x}_a^i + \hat{x}_a^i \tag{4}$$

where n is the congestion PCE of the freight transportation.

Let $f_{s,r}^i$ be the traffic flow $\forall r \in R_s$ route on OD pair s (where $\forall s \in S$, S is the set of OD pairs in given traffic networks), then there is a relation between the traffic flow of the link and the route, respectively for the freight transportation and residential trip, as follows

$$\begin{cases} x_a^i = \sum_{s \in S} \sum_{r \in R_s} f_{s,r}^i \delta_{a,r}^s \\ \overline{x}_a^i = \sum_{s \in S} \sum_{r \in R_s} \overline{f}_{s,r}^i \delta_{a,r}^s \\ \hat{x}_a^i = \sum_{s \in S} \sum_{r \in R_s} \hat{f}_{s,r}^i \delta_{a,r}^s \end{cases} \tag{5}$$

where, $\delta_{a,r}^s$ is the route-link switch parameter. When link a is one of the links of route r on an OD pair s, then $\delta_{a,r}^s = 1$, otherwise $\delta_{a,r}^s = 0$.

The flow on all the routes connecting each OD pair has to equal the OD traffic volume for each period, and the total traffic of the freight transportation and the residential trip on the same OD pair, i.e.

$$q_s^i = n\overline{q}_s^i + \hat{q}_s^i = n\sum_{r \in R_s} \overline{f}_{s,r}^i + \sum_{r \in R_s} \hat{f}_{s,r}^i = \sum_{r \in R_s} f_{s,r}^i \tag{6}$$

3.2.2 Transportation cost

The transportation average cost function is assumed to be monotone increasing with a non-negative second order derivatives of the traffic flow x_a^i on each link. Based on the Bureau of Public Roads (BRP) function (Branston, 1976; Small, 1992), we adopt the following transportation cost:

$$c_a^i\left(x_a^i\right) = \gamma T_a\left[1 + 0.15\left(\frac{x_a^i}{K_a}\right)^4\right] = \gamma T_a\left[1 + 0.15\left(\frac{n\overline{x}_a^i + \hat{x}_a^i}{K_a}\right)^4\right] \tag{7}$$

where c_a^i represents the transportation cost of link a in period i; T_a represents the free-flow transportation cost of the given link; n represents the congestion PCE of the freight transportation; K_a represents the traffic capacity of the given link in PCE units; and γ denotes the VOT.

Then, the transportation cost of route r on the OD pair s in period i can be defined as

$$C_{s,r}^i = \sum_{r \in R_s} c_a^i\left(x_a^i\right) \cdot \delta_{a,r}^s = \sum_{r \in R_s} c_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right) \cdot \delta_{a,r}^s \tag{8}$$

4 Equivalent urban transportation network minimization models with congestion pricing

Given the congestion pricing policies, based on the UE condition proposed by Wardrop (1952), and similar to Dial (2006), a stable condition is reached only when no unit traffic can reduce its transportation cost by unilaterally changing route/path. That is, UE occurs when every traffic goes from its origin to destination via the lowest cost route. For the problem discussed in this paper, when new traffic emerges, the determination of which

link will be used to compose a new route is based on the cost of this route. In other words, the traffic flow of each OD pair is determined by the assignment of the traffic flow on the network according to the minimum transportation cost of the routes belonging to the OD pair. An efficient solution is to formulate it as an equivalent minimization program (Sheffi, 1985), where the link flows, the link transportation cost, OD traffic volume and the congestion pricing satisfies the UE condition by solving the equivalent minimization program.

4.1 Equivalent minimization model for No-toll congestion pricing policy (*NT-scenario*)

We propose the equivalent UE minimization model for the urban transportation network with elastic-demand and congestion pricing as[2]:

$$
\min Z(\mathbf{x}, \bar{\mathbf{q}}, \hat{\mathbf{q}}) = \sum_i \sum_{a \in A} \int_0^{x_a^i} c_a^i(w)dw - \sum_{s \in S} \int_{(0,0)}^{(\bar{q}_s^1, \bar{q}_s^2)} \left[\bar{D}_s^{1^{-1}}(w_1, w_2)dw_1 + \bar{D}_s^{2^{-1}}(w_1, w_2)dw_2 \right]
$$
$$
- \sum_{s \in S} \int_{(0,0)}^{(\hat{q}_s^1, \hat{q}_s^2)} \left[\hat{D}_s^{1^{-1}}(w_1, w_2)dw_1 + \hat{D}_s^{2^{-1}}(w_1, w_2)dw_2 \right]
$$

$$
s.t. \quad \begin{cases} n\bar{q}_s^i + \hat{q}_s^i = \sum_{r \in R_s} f_{s,r}^i & \forall i, s, r \\ f_{s,r}^i, \bar{q}_s^i, \hat{q}_s^i \geq 0 & \forall i, r, s \end{cases}
$$

$$(9)$$

where $x_a^i = \sum_{s \in S} \sum_{r \in R_s} f_{s,r}^i \delta_{a,r}^s$, $\forall i, a$.

The elastic-demand problem can be solved with a more efficient fixed-demand formulation, through a network representation, where the variable e denotes the excess demand, that is, the traffic of the freight transportation and the residential trip that are not accommodated by the OD pair s are addressed in Eq. (10) and depicted in **Figure 1**. In Figure 1, the excess-demand of the traffic flows are presented in orange and blue for freight transportation and residential trip, and as dotted and dashed lines for different OD pairs respectively.

$$
\begin{cases} \bar{e}_s^1 = \bar{Q}_s^1 - \bar{q}_s^1 = \bar{\beta}_{11,s} \mu_s^1 - \bar{\beta}_{12,s} \mu_s^2 \\ \bar{e}_s^2 = \bar{Q}_s^2 - \bar{q}_s^2 = -\bar{\beta}_{21,s} \mu_s^1 + \bar{\beta}_{22,s} \mu_s^2 \\ \hat{e}_s^1 = \hat{Q}_s^1 - \hat{q}_s^1 = \hat{\beta}_{11,s} \mu_s^1 - \hat{\beta}_{12,s} \mu_s^2 \\ \hat{e}_s^2 = \hat{Q}_s^2 + \hat{q}_s^2 = -\hat{\beta}_{21,s} \mu_s^1 + \hat{\beta}_{22,s} \mu_s^2 \end{cases}
$$

$$(10)$$

From Eq.(10), the inverse excess-demand function for OD pair s can be found as a function of the excess-demand traffic volume in both the peak and off-peak periods, and E_s^i denotes the equilibrium average transportation cost for excess-demand traffic on OD pair s in period i, i.e.[3]

$$
\begin{cases} \bar{E}_s^1(\bar{e}_s^1, \bar{e}_s^2) = \dfrac{\bar{\beta}_{22,s}}{\bar{\beta}_{11,s}\bar{\beta}_{22,s} - \bar{\beta}_{12,s}\bar{\beta}_{21,s}} \bar{e}_s^1 + \dfrac{\bar{\beta}_{12,s}}{\bar{\beta}_{11,s}\bar{\beta}_{22,s} - \bar{\beta}_{12,s}\bar{\beta}_{21,s}} \bar{e}_s^2 \\[2ex] \bar{E}_s^2(\bar{e}_s^1, \bar{e}_s^2) = \dfrac{\bar{\beta}_{21,s}}{\bar{\beta}_{11,s}\bar{\beta}_{22,s} - \bar{\beta}_{12,s}\bar{\beta}_{21,s}} \bar{e}_s^1 + \dfrac{\bar{\beta}_{11,s}}{\bar{\beta}_{11,s}\bar{\beta}_{22,s} - \bar{\beta}_{12,s}\bar{\beta}_{21,s}} \bar{e}_s^2 \\[2ex] \hat{E}_s^1(\hat{e}_s^1, \hat{e}_s^2) = \dfrac{\hat{\beta}_{22,s}}{\hat{\beta}_{11,s}\hat{\beta}_{22,s} - \hat{\beta}_{12,s}\hat{\beta}_{21,s}} \hat{e}_s^1 + \dfrac{\hat{\beta}_{12,s}}{\hat{\beta}_{11,s}\hat{\beta}_{22,s} - \hat{\beta}_{12,s}\hat{\beta}_{21,s}} \hat{e}_s^2 \\[2ex] \hat{E}_s^2(\hat{e}_s^1, \hat{e}_s^2) = \dfrac{\hat{\beta}_{21,s}}{\hat{\beta}_{11,s}\hat{\beta}_{22,s} - \hat{\beta}_{12,s}\hat{\beta}_{21,s}} \hat{e}_s^1 + \dfrac{\hat{\beta}_{11,s}}{\hat{\beta}_{11,s}\hat{\beta}_{22,s} - \hat{\beta}_{12,s}\hat{\beta}_{21,s}} \hat{e}_s^2 \end{cases}
$$

$$(11)$$

Consider the objective function of the equivalent elastic-demand formulation Eq. (9), where each term in the second sum and third sum can be decomposed into two integrals as follows:

---

[2] The equivalent UE minimization model demonstrates that minimizing this program is, in fact, equivalent to solving the equilibrium equations and that the program has a unique solution (Sheffi, 1985).

[3] The reason for the inverse excess-demand function is to apply the solution methodology for changing the variable-demand problem into a fixed-demand problem. Hence, the demand model has to be inverted and expressed in terms of the excess-demand variable, i.e. $\bar{e}_s^i$ and $\hat{e}_s^i$. For further information, please refer to section 6 of User equilibrium with variable demand in Sheffi (1985).

$$\left\{ \begin{aligned} &-\sum_{s\in S}\int_{(0,0)}^{(\bar{q}_s^1,\bar{q}_s^2)}\left[\bar{D}_s^{1^{-1}}(w_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \\ &=-\sum_{s\in S}\int_{(0,0)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(w_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]+\sum_{s\in S}\int_{(\bar{q}_s^1,\bar{q}_s^2)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(w_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \\ &-\sum_{s\in S}\int_{(0,0)}^{(\hat{q}_s^1,\hat{q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \\ &=-\sum_{s\in S}\int_{(0,0)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]+\sum_{s\in S}\int_{(\hat{q}_s^1,\hat{q}_s^2)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \end{aligned} \right. \tag{12}$$

The first-term on the right-hand-side of Eq. (12), i.e $-\sum_{s\in S}\int_{(0,0)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(nw_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(nw_1,w_2)dw_2\right]$ and

$-\sum_{s\in S}\int_{(0,0)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]$, are constant respectively[4]; thus, it can be dropped from the objective function since it will not affect the optimization problem.

The second-terms $\sum_{s\in S}\int_{(\bar{q}_s^1,\bar{q}_s^2)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(w_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]$ and $\sum_{s\in S}\int_{(\hat{q}_s^1,\hat{q}_s^2)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]$

represent the excess-demand of the freight transportation and the residential trip respectively. With the excess demand variable in Eq. (10), the second-term can be re-defined as follows:

$$\left\{ \begin{aligned} &\sum_{s\in S}\int_{(\bar{q}_s^1,\bar{q}_s^2)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(w_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \\ &=\sum_{s\in S}\int_{(\bar{Q}_s^1-\bar{q}_s^1,\bar{Q}_s^2-\bar{q}_s^2)}^{(0,0)}\left[\bar{D}_s^{1^{-1}}(\bar{Q}_s^1-w_1,\bar{Q}_s^2-w_2)(-dw_1)+\bar{D}_s^{2^{-1}}(\bar{Q}_s^1-w_1,\bar{Q}_s^2-w_2)(-dw_2)\right] \\ &=\sum_{s\in S}\int_{(0,0)}^{(\bar{e}_s^1,\bar{e}_s^2)}\left[\bar{E}_s^1(w_1,w_2)dw_1+\bar{E}_s^2(w_1,w_2)(-dw_2)\right] \\ &\sum_{s\in S}\int_{(\hat{q}_s^1,\hat{q}_s^2)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right] \\ &=\sum_{s\in S}\int_{(\hat{Q}_s^1-\hat{q}_s^1,\hat{Q}_s^2-\hat{q}_s^2)}^{(0,0)}\left[\hat{D}_s^{1^{-1}}(\hat{Q}_s^1-w_1,\hat{Q}_s^2-w_2)(-dw_1)+\hat{D}_s^{2^{-1}}(\hat{Q}_s^1-w_1,\hat{Q}_s^2-w_2)(-dw_2)\right] \\ &=\sum_{s\in S}\int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(w_1,w_2)dw_1+\hat{E}_s^2(w_1,w_2)(-dw_2)\right] \end{aligned} \right. \tag{13}$$

Using the excess demand variable, similar to Sheffi (1985) and Ryu et al. (2014, 2017), the equivalent elastic-demand formulation Eq. (8) can be expressed as a fixed-demand problem:

$$\min Z(\mathbf{x},\bar{\mathbf{e}},\hat{\mathbf{e}})=\sum_i\sum_{a\in A}\int_0^{x_a^i}c_a^i(w)dw+\sum_{s\in S}\int_{(0,0)}^{(\bar{e}_s^1,\bar{e}_s^2)}\left[\bar{E}_s^1(w_1,w_2)dw_1+\bar{E}_s^2(w_1,w_2)dw_2\right]$$
$$+\sum_{s\in S}\int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(w_1,w_2)dw_1+\hat{E}_s^2(w_1,w_2)dw_2\right] \tag{14}$$

$$s.t.\quad \left\{ \begin{aligned} &n\bar{Q}_s^i+\hat{Q}_s^i=n\bar{e}_s^i+\hat{e}_s^i+\sum_{r\in R_s}f_{s,r}^i \quad \forall i,s,r \\ &f_{s,r}^i,\bar{e}_s^i,\hat{e}_s^i\geq 0 \quad \forall i,r,s \end{aligned} \right.$$

where $x_a^i=\sum_{s\in S}\sum_{r\in R_s}f_{s,r}^i\delta_{a,r}^s$, $\forall i,a$; n represents the congestion PCE of the freight transportation.

Assumption 2. According to Pressman (1970), to ensure $\sum_{s\in S}\int_{(0,0)}^{(\bar{e}_s^1,\bar{e}_s^2)}\left[\bar{E}_s^1(w_1,w_2)dw_1+\bar{E}_s^2(w_1,w_2)dw_2\right]$ and

$\sum_{s\in S}\int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(w_1,w_2)dw_1+\hat{E}_s^2(w_1,w_2)dw_2\right]$ are integrable, the following conditions must be satisfied.

---

[4] Take $-\sum_{s\in S}\int_{(0,0)}^{(\bar{Q}_s^1,\bar{Q}_s^2)}\left[\bar{D}_s^{1^{-1}}(nw_1,w_2)dw_1+\bar{D}_s^{2^{-1}}(nw_1,w_2)dw_2\right]$ for example, since $(\bar{Q}_s^1,\bar{Q}_s^2)$ is given and $\bar{D}_s^i(\cdot)$ is the demand function of the freight transportation, the result is a fixed constant according to Newton-Leibniz formula. Hence, it applies for $-\sum_{s\in S}\int_{(0,0)}^{(\hat{Q}_s^1,\hat{Q}_s^2)}\left[\hat{D}_s^{1^{-1}}(w_1,w_2)dw_1+\hat{D}_s^{2^{-1}}(w_1,w_2)dw_2\right]$. For further information, please refer to 'Chapter 7: Epilogue: Newton and Leibniz' in Baron (1969).

$$\begin{cases} \dfrac{\partial \overline{E}_s^1\left(\overline{e}_s^1,\overline{e}_s^2\right)}{\partial \overline{e}_s^2} = \dfrac{\partial \overline{E}_s^2\left(\overline{e}_s^1,\overline{e}_s^2\right)}{\partial \overline{e}_s^1} \\[4mm] \dfrac{\partial \hat{E}_s^1\left(\hat{e}_s^1,\hat{e}_s^2\right)}{\partial \hat{e}_s^2} = \dfrac{\partial \hat{E}_s^2\left(\hat{e}_s^1,\hat{e}_s^2\right)}{\partial \hat{e}_s^1} \end{cases} \tag{15}$$

In order to ensure that the UE conditions are met at the point where Eq. (14) is minimized, the first order conditions of the model must be equivalent to the equilibrium conditions. The equilibrium condition stated above is repeated in a network view based on Wardrop's first principle (Wardrop, 1952), where the cost of all chosen routes between any OD pair are equal, and must also be equal to or less than the cost of any unused routes. In order to design the algorithm to solve the model in the following section, an equivalent elastic-demand UE model of Eq. (14) must have a unique solution. Then the first-order conditions can be re-stated as follows:

$$\begin{cases} \left(\displaystyle\sum_{a\in A} c_a^i\left(x_a^i\right)\delta_{a,r}^s - \mu_s^i \right)\cdot f_{s,r}^i = 0, \quad \displaystyle\sum_{a\in A} c_a^i\left(x_a^i\right)\delta_{a,r}^s - \mu_s^i \geq 0, \quad f_{s,r}^i \geq 0 \\[3mm] \left[\overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i \right]\cdot \overline{e}_s^i = 0, \quad \overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\[3mm] \left[\hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i \right]\cdot \hat{e}_s^i = 0, \quad \hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\[3mm] n\overline{Q}_s^i + \hat{Q}_s^i - n\overline{e}_s^i - \hat{e}_s^i - \displaystyle\sum_{r\in R_s} f_{s,r}^i = 0 \end{cases} \tag{16}$$

For the analysis of the *Equivalent conditions* and *Uniqueness conditions* see **Appendix A**.

4.2 Equivalent model for first-best congestion pricing policy (*FB-scenario*)

Based on Section 4.1, we propose an equivalent minimization model for first-best congestion pricing policy as follows, in which congestion tolls are imposed on freight transportation and residential trips for both time periods, except the excess-demands. The congestion toll for the same period is set to be the same price for the mixed traffic for both periods.

$$\min Z(\mathbf{x},\overline{\mathbf{e}},\hat{\mathbf{e}}) = \sum_i \sum_{a\in A} c_a^i(x_a^i)\cdot x_a^i + \sum_{s\in S} \int_{(0,0)}^{(\overline{e}_s^1,\overline{e}_s^2)}\left[\overline{E}_s^1(w_1,w_2)dw_1 + \overline{E}_s^2(w_1,w_2)dw_2 \right]$$
$$+ \sum_{s\in S} \int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(w_1,w_2)dw_1 + \hat{E}_s^2(w_1,w_2)dw_2 \right] \tag{17}$$

$$s.t. \quad \begin{cases} n\overline{Q}_s^i + \hat{Q}_s^i = n\overline{e}_s^i + \hat{e}_s^i + \displaystyle\sum_{r\in R_s} f_{s,r}^i \quad \forall i,s,r \\[3mm] f_{s,r}^i,\overline{e}_s^i,\hat{e}_s^i \geq 0 \quad \forall i,r,s \end{cases}$$

where $x_a^i = \displaystyle\sum_{s\in S}\sum_{r\in R_s} f_{s,r}^i \delta_{a,r}^s$, and $\forall i,a$.

Similar to the No-toll congestion pricing policy (*NT-scenario*), we have the analysis for the *FB-scenario* (see **Appendix B**). The first-order conditions can be rewritten as follows, based on *Appendix B.1*. The first-order conditions states that for the used routes, the marginal transportation cost of the traffic on route r connecting OD pair s in period i is equal to the equilibrium minimum transportation cost on OD pair s in period i.

$$\begin{cases} \left(\displaystyle\sum_{a\in A} c_a^i\left(x_a^i\right)\delta_{a,r}^s + \displaystyle\sum_{a\in A} \dfrac{dc_a^i\left(x_a^i\right)}{dx_a^i}x_a^i - \mu_s^i \right)\cdot f_{s,r}^i = 0, \quad \displaystyle\sum_{a\in A} c_a^i\left(x_a^i\right)\delta_{a,r}^s + \displaystyle\sum_{a\in A} \dfrac{dc_a^i\left(x_a^i\right)}{dx_a^i}x_a^i - \mu_s^i \geq 0, \quad f_{s,r}^i \geq 0 \\[3mm] \left[\overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i \right]\cdot \overline{e}_s^i = 0, \quad \overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\[3mm] \left[\hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i \right]\cdot \hat{e}_s^i = 0, \quad \hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\[3mm] n\overline{Q}_s^i + \hat{Q}_s^i - n\overline{e}_s^i - \hat{e}_s^i - \displaystyle\sum_{r\in R_s} f_{s,r}^i = 0 \end{cases} \tag{18}$$

We now introduce the following notation

$$\begin{cases} mc_a^i\left(x_a^i\right) = c_a^i\left(x_a^i\right) + \dfrac{dc_a^i\left(x_a^i\right)}{dx_a^i}x_a^i \\[4mm] MC_{s,r}^i = \displaystyle\sum_{a\in A} c_a^i\left(x_a^i\right)\delta_{a,r}^s + \displaystyle\sum_{a\in A} \dfrac{dc_a^i\left(x_a^i\right)}{dx_a^i}x_a^i\delta_{a,r}^s = C_{s,r}^i + T_{s,r}^i \end{cases} \tag{19}$$

9

where $mc_a^i(x_a^i)$ is the marginal cost on link a in period i; MC_a^i is the marginal cost on route r connecting OD pair s in period i for the traffic of both freight transportation and residential trip; and $T_{s,r}^i$ is the total external cost as a result of the first-best congestion pricing policy on route r.

Here, we consider the external cost of the link resulting from the first-best congestion pricing policy as the efficient congestion tolls for each link in period i because of relationship between the first-best congestion pricing and the marginal cost pricing (Marcucci, 2001; Lindsey, 2006). The congestion toll of each link, an endogenous variable in the equivalent minimization model, can be expressed as

$$\tau_a^i = \frac{dc_a^i(x_a^i)}{dx_a^i} x_a^i \tag{20}$$

where $x_a^i = n\bar{x}_a^i + \hat{x}_a^i$, and n represents the congestion PCE of the freight transportation.

4.3 Equivalent minimization models for second-best congestion pricing policies (*SB-scenario*)

The second-best considers the scenarios where tolls are not allowed on a major portion of the urban transportation network because of technical or political constraints. Based on the analytical process of the above scenarios, it is interesting to find that the *NT-scenario* and the *FB-scenario* are two extreme forms of the *SB-scenario*. Here, we propose three equivalent minimization models for second-best congestion pricing policy as follows, where congestion tolls can be imposed on 1) both traffic at the peak period (*SB1-scenario*), 2) the traffic of the freight transportation at both time periods (*SB2-scenario*), and 3) the traffic of the freight transportation at the peak period (*SB3-scenario*), and the excess-demands are excluded in all models.

4.3.1 Equivalent minimization program for SB1-scenario

In this scenario, the congestion pricing scheme is that there is no-toll for both traffic types in an off-peak period. Thus, the equivalent minimization model is

$$\min Z(\mathbf{x}, \bar{\mathbf{e}}, \hat{\mathbf{e}}) = \sum_{a \in A} c_a^1(x_a^1) \cdot x_a^1 + \sum_{s \in S} \int_{(0,0)}^{(\bar{e}_s^1, \bar{e}_s^2)} \left[\bar{E}_s^1(w_1, w_2) dw_1 + \bar{E}_s^2(w_1, w_2) dw_2 \right]$$

$$+ \sum_{a \in A} \int_0^{x_a^2} c_a^2(w) dw + \sum_{s \in S} \int_{(0,0)}^{(\hat{e}_s^1, \hat{e}_s^2)} \left[\hat{E}_s^1(w_1, w_2) dw_1 + \hat{E}_s^2(w_1, w_2) dw_2 \right] \tag{21}$$

$$s.t. \quad \begin{cases} n\bar{Q}_s^i + \hat{Q}_s^i = n\bar{e}_s^i + \hat{e}_s^i + \sum_{r \in R_s} f_{s,r}^i & \forall i, s, r \\ f_{s,r}^i, \bar{e}_s^i, \hat{e}_s^i \geq 0 & \forall i, r, s \end{cases}$$

where $x_a^i = \sum_{s \in S} \sum_{r \in R_s} f_{s,r}^i \delta_{a,r}^s$, $\forall i, a$ and $x_a^i = n\bar{x}_a^i + \hat{x}_a^i$.

Based on the analysis of the *Equivalent conditions* and *Uniqueness conditions* of the equivalent minimization model for the *NT-scenario* and the *FB-scenario*, Eq. (21) has a unique solution and the equivalent conditions of UE are satisfied. Similar to the *FB-scenario*, the first-order conditions state that, for the used routes, the marginal transportation cost of the traffic on route r connecting OD pair s in period i is equal to the equilibrium minimum transportation cost on OD pair s in time period i.

$$\begin{cases} \left(\sum_{a \in A} c_a^1(x_a^1) \delta_{a,r}^s + \sum_{a \in A} \frac{dc_a^1(x_a^1)}{dx_a^1} x_a^1 \delta_{a,r}^s - \mu_s^1 \right) \cdot f_{s,r}^1 = 0, \quad C_{s,r}^i + \sum_{a \in A} \frac{dc_a^1(x_a^1)}{dx_a^1} x_a^1 \delta_{a,r}^s - \mu_s^i \geq 0, \quad f_{s,r}^1 \geq 0 \\ \left(\sum_{a \in A} c_a^2(x_a^2) \delta_{a,r}^s - \mu_a^2 \right) \cdot f_{s,r}^2 = 0, \quad C_{s,r}^2 - \mu_a^2 \geq 0, \quad f_{s,r}^2 \geq 0 \\ \left[\bar{E}_s^i(\bar{e}_s^1, \bar{e}_s^2) - \mu_s^i \right] \cdot \bar{e}_s^i = 0, \quad \bar{E}_s^i(\bar{e}_s^1, \bar{e}_s^2) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\ \left[\hat{E}_s^i(\hat{e}_s^1, \hat{e}_s^2) - \mu_s^i \right] \cdot \hat{e}_s^i = 0, \quad \hat{E}_s^i(\hat{e}_s^1, \hat{e}_s^2) - \mu_s^i \geq 0, \quad \hat{e}_s^i \geq 0 \\ n\bar{Q}_s^i + \hat{Q}_s^i - n\bar{e}_s^i - \hat{e}_s^i - \sum_{r \in R_s} f_{s,r}^i = 0 \end{cases} \tag{22}$$

Here, we introduce the following notation.

$$
\begin{cases}
\overline{mc}_a^1\left(x_a^1\right) = c_a^1\left(x_a^1\right) + \dfrac{dc_a^i\left(x_a^1\right)}{dx_a^1}x_a^1 \\[4mm]
\overline{MC}_{s,r}^1 = \displaystyle\sum_{a\in A}c_a^1\left(x_a^1\right)\delta_{a,r}^s + \sum_{a\in A}\dfrac{dc_a^i\left(x_a^1\right)}{dx_a^1}x_a^1\delta_{a,r}^s = C_{s,r}^i + T_{s,r}^i
\end{cases}
\tag{23}
$$

where $\overline{mc}_a^1\left(x_a^1\right)$ is the marginal cost on link a in peak period $i=1$ for both traffic, $\overline{MC}_{s,r}^i$ is the marginal cost on route r connecting OD pair s in peak period $i=1$ for both traffic; and $T_{s,r}^i$ is the total external cost as a result of the first-best congestion pricing policy.

Similarly, the endogenous congestion toll of the links for both traffic types in a peak period is:

$$
\tau_a^1 = \dfrac{dc_a^1\left(x_a^1\right)}{dx_a^1}x_a^1
\tag{24}
$$

where $x_a^1 = n\overline{x}_a^1 + \hat{x}_a^1$, and n represents the congestion PCE of the freight transportation.

4.3.2 Equivalent minimization program for SB2-scenario

In this scenario, the congestion pricing scheme is that there is no-toll on residential travel for both time periods, and only freight transportation is charged on all links for both periods, as in the following model.

$$
\begin{aligned}
\min Z(\mathbf{x},\overline{\mathbf{e}},\hat{\mathbf{e}}) = {}& \sum_i\sum_{a\in A}c_a^i(n\overline{x}_a^i + \hat{x}_a^i)\cdot n\overline{x}_a^i + \sum_{s\in S}\int_{(0,0)}^{(\overline{e}_s^1,\overline{e}_s^2)}\left[\overline{E}_s^1(w_1,w_2)dw_1 + \overline{E}_s^2(w_1,w_2)dw_2\right] \\
& + \sum_i\sum_{a\in A}\int_0^{\hat{x}_a^i}c_a^i(n\overline{x}_a^i + w)dw + \sum_{s\in S}\int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(w_1,w_2)dw_1 + \hat{E}_s^2(w_1,w_2)dw_2\right]
\end{aligned}
\tag{25}
$$

$$
s.t. \quad
\begin{cases}
n\overline{Q}_s^i + \hat{Q}_s^i = n\overline{e}_s^i + \hat{e}_s^i + \displaystyle\sum_{r\in R_s}f_{s,r}^i & \forall i,s,r \\[3mm]
f_{s,r}^i, \overline{e}_s^i, \hat{e}_s^i \ge 0 & \forall i,r,s
\end{cases}
$$

where $x_a^i = \displaystyle\sum_{s\in S}\sum_{r\in R_s}f_{s,r}^i\delta_{a,r}^s$ and $x_a^i = n\overline{x}_a^i + \hat{x}_a^i$, $\forall i,a$.

For the analysis of the *Equivalent conditions* and *Uniqueness conditions*, see **Appendix C**. The first-order conditions can be addressed as follows, which is the same as Eq. (18). Similar to the *FB-scenario* and the *SB1-scenario*, the first-order conditions state that for the used routes, the marginal transportation cost of the traffic on route r connecting OD pair s in period i is equal to the equilibrium minimum transportation cost on OD pair s in period i.

$$
\begin{cases}
\left(n\displaystyle\sum_{a\in A}c_a^i\left(\overline{x}_a^i + \hat{x}_a^i\right)\delta_{a,r}^s + n\dfrac{dc_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)}{dx_a^i}\overline{x}_a^i\delta_{a,r}^s - \mu_s^i\right)\cdot f_{s,r}^i = 0, \ \ n\displaystyle\sum_{a\in A}c_a^i\left(\overline{x}_a^i + \hat{x}_a^i\right)\delta_{a,r}^s + n\dfrac{dc_a^i\left(\overline{x}_a^i + \hat{x}_a^i\right)}{dx_a^i}\overline{x}_a^i\delta_{a,r}^s - \mu_s^i \ge 0, \ \ f_{s,r}^i \ge 0 \\[4mm]
\left[\overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i\right]\cdot\overline{e}_s^i = 0, \ \ \overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right) - \mu_s^i \ge 0, \ \ \hat{e}_s^i \ge 0 \\[2mm]
\left[\hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i\right]\cdot\hat{e}_s^i = 0, \ \ \hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right) - \mu_s^i \ge 0, \ \ \hat{e}_s^i \ge 0 \\[2mm]
n\overline{Q}_s^i + \hat{Q}_s^i - n\overline{e}_s^i - \hat{e}_s^i - \displaystyle\sum_{r\in R_s}f_{s,r}^i = 0
\end{cases}
\tag{26}
$$

Here, we introduce the following notation.

$$
\begin{cases}
\widehat{mc}_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right) = nc_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right) + n\dfrac{dc_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)}{dx_a^i}\overline{x}_a^i \\[4mm]
\widehat{MC}_{s,r}^i = n\displaystyle\sum_{a\in A}c_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)\delta_{a,r}^s + n\sum_{a\in A}\dfrac{dc_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)}{dx_a^i}\overline{x}_a^i\delta_{a,r}^s = C_{s,r}^i + T_{s,r}^i
\end{cases}
\tag{27}
$$

where $\widehat{mc}_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)$ is the marginal cost on link a in period i for freight transportation traffic; $\widehat{MC}_{s,r}^i$ is the marginal cost on route r connecting OD pair s in period i for the traffic of the freight transportation; and $T_{s,r}^i$ is the external cost as a result of the first-best congestion pricing policy.

Similarly, the congestion toll of the freight transportation on each link in both periods is:

$$
\tau_a^i = n\dfrac{dc_a^i\left(n\overline{x}_a^i + \hat{x}_a^i\right)}{dx_a^i}\overline{x}_a^i
\tag{28}
$$

4.3.3 Equivalent minimization program for SB3-scenario

In this scenario, the congestion pricing scheme specifies that there is no-toll for a residential trip, and only charges the freight transportation on all links and in peak periods as follows

$$\min Z(\mathbf{x},\overline{\mathbf{e}},\hat{\mathbf{e}}) = \sum_{a\in A} c_a^1(n\overline{x}_a^1+\hat{x}_a^1)\cdot n\overline{x}_a^1 + \sum_{a\in A}\int_0^{\overline{x}_a^2} c_a^2(nw+\hat{x}_a^2)dw + \sum_i\sum_{a\in A}\int_0^{\hat{x}_a^i} c_a^i(n\overline{x}_a^i+w)dw$$

$$+ \sum_{s\in S}\int_{(0,0)}^{(\overline{e}_s^1,\overline{e}_s^2)}\left[\overline{E}_s^1(nw_1,w_2)dw_1 + \overline{E}_s^2(nw_1,w_2)dw_2\right] + \sum_{s\in S}\int_{(0,0)}^{(\hat{e}_s^1,\hat{e}_s^2)}\left[\hat{E}_s^1(nw_1,w_2)dw_1 + \hat{E}_s^2(nw_1,w_2)dw_2\right]$$

(29)

$$s.t. \begin{cases} n\overline{Q}_s^i+\hat{Q}_s^i = n\overline{e}_s^i+\hat{e}_s^i+\sum_{r\in R_s} f_{s,r}^i & \forall i,s,r \\ f_{s,r}^i,\overline{e}_s^i,\hat{e}_s^i \geq 0 & \forall i,r,s \end{cases}$$

where $x_a^i = \sum_{s\in S}\sum_{r\in R_s} f_{s,r}^i \delta_{a,r}^s$, $\forall i,a$ and $x_a^i = n\overline{x}_a^i+\hat{x}_a^i$.

Based on the analysis of the *Equivalent conditions* and *Uniqueness conditions* for the *NT-scenario*, the *FB-scenario* and the *SB2-scenario*, Eq. (24) has a unique solution and the equivalent conditions of UE are satisfied. The first-order conditions can be addressed as follows. Similar to the *FB-scenario*, the *SB1-scenario* and the *SB2-scenario*, the first-order conditions state that for the used routes, the marginal transportation cost of the traffic on route r connecting OD pair s in period i is equal to the equilibrium minimum transportation cost on OD pair s in period i.

$$\begin{cases} \left(\sum_{a\in A} c_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)\delta_{a,r}^s + n\frac{dc_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)}{dx_a^1}\overline{x}_a^1\delta_{a,r}^s-\mu_s^1\right)\cdot f_{s,r}^1 = 0, \quad \sum_{a\in A} c_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)\delta_{a,r}^s + n\frac{dc_a^1\left(\overline{x}_a^1+\hat{x}_a^1\right)}{dx_a^1}\overline{x}_a^1\delta_{a,r}^s-\mu_s^1 \geq 0, \ f_{s,r}^1 \geq 0 \\[4mm] \left(\sum_{a\in A} c_a^2\left(n\overline{x}_a^2+\hat{x}_a^2\right)\delta_{a,r}^s-\mu_s^2\right)\cdot f_{s,r}^2 = 0, \quad \sum_{a\in A} c_a^2\left(n\overline{x}_a^2+\hat{x}_a^2\right)\delta_{a,r}^s-\mu_s^2 \geq 0, \ f_{s,r}^2 \geq 0 \\[4mm] \left[\overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right)-\mu_s^i\right]\cdot\overline{e}_s^i = 0, \ \overline{E}_s^i\left(\overline{e}_s^1,\overline{e}_s^2\right)-\mu_s^i \geq 0, \ \hat{e}_s^i \geq 0 \\[4mm] \left[\hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right)-\mu_s^i\right]\cdot\hat{e}_s^i = 0, \ \hat{E}_s^i\left(\hat{e}_s^1,\hat{e}_s^2\right)-\mu_s^i \geq 0, \ \hat{e}_s^i \geq 0 \\[4mm] n\overline{Q}_s^i+\hat{Q}_s^i-n\overline{e}_s^i-\hat{e}_s^i-\sum_{r\in R_s} f_{s,r}^i = 0 \end{cases}$$

(30)

The first-order conditions have the same meaning as that in the *FB-scenario* and the *SB1-scenario*.
We now introduce the following notation.

$$\begin{cases} \tilde{m}\tilde{c}_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right) = c_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right) + n\frac{dc_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)}{d\overline{x}_a^1}\overline{x}_a^1 \\[4mm] \tilde{m}\tilde{c}_a^2\left(n\overline{x}_a^2+\hat{x}_a^2\right) = c_a^2\left(n\overline{x}_a^2+\hat{x}_a^2\right) \\[4mm] \tilde{M}\tilde{C}_{s,r}^1 = \sum_{a\in A} c_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)\delta_{a,r}^s + n\sum_{a\in A}\frac{dc_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)}{d\overline{x}_a^1}\overline{x}_a^1\delta_{a,r}^s \\[4mm] \tilde{M}\tilde{C}_{s,r}^2 = \sum_{a\in A} c_a^2\left(n\overline{x}_a^2+\hat{x}_a^2\right)\delta_{a,r}^s \end{cases}$$

(31)

where $\tilde{m}\tilde{c}_a^i\left(\overline{x}_a^i+\hat{x}_a^i\right)$ is the marginal cost on link a in period i for the freight transportation traffic; $\tilde{M}\tilde{C}_{s,r}^i$ is the marginal cost on route r connecting OD pair s in period i for the freight transportation traffic.

Similarly, the congestion toll of the freight transportation on each link in peak period is:

$$\tau_a^1 = n\frac{dc_a^1\left(n\overline{x}_a^1+\hat{x}_a^1\right)}{dx_a^1}\overline{x}_a^1$$

(32)

5. Simulation Case Study

The equivalent models are solved by the Frank-Wolfe algorithm (Frank and Wolfe, 1956), which is a convex minimization program with linear constraints for the traffic assignment problem (LeBlanc et al., 1975; Gutjahr and Dzubur, 2016). Applying the Frank-Wolfe algorithm, and similar to Tzeng and Chen (1993), the assignment problem is simplified into an 'all-or-nothing assignment' for the edge cost which is currently flow-independent.

5.1 Urban transportation network for simulation study

With the rapid development of e-commerce, the urban freight transport is facing a rising transportation demand and greater customer expectations. Given the constraints of transport resources in urban areas, meeting unfettered demand for travel/transpot is impractical. High expectancy levels of customer satisfaction would require carriers to offer short delivery service, thus resulting in fluctuant VOT of the freight transport and residential trips.

Hangzhou is the capital city of East-China's Zhejiang Province, and has a prosperous e-commerce industry, not only led by the e-commerce giant Alibaba Group, but it is also home to 23.26 billion express parcels delivered in 2017 (Guo and Zhao, 2018). The main logistics-distribution facilities are located at the north and south part of the city, and the east part is inhabited by the universities which is a main source of e-commerce customers. The urban transportation network depicted in **Figure 1** simulates the main roads of Hangzhou with two origins (the area of logistics-distribution facilities) and one destination (the area of e-commerce customers), the roads/links are presented as black solid lines. The transportation network consists of 7 nodes, 2 OD pairs and 14 links. There are two types of traffic flow, i.e. freight transportation and residential trips, which run on the same network. The excess-demand of the traffic flows are presented in orange and blue for freight transportation and residential trip, and as dotted and dashed lines for different OD pairs respectively. The parameters of transportation demands are listed in **Table 1**.

Insert Figure 1 here.

Insert Table 1 here.

Table 2 lists the parameters of the links. Using data from the Urban Transportation Planning in the US and travel cost function of Eq. (7), this paper assumes a VOT of 11 cents/min (Small, 1982; Brownstone and Small, 2005) and the congestion PCE of the freight transportation as $n=2$ (de Palma et al., 2008).

Insert Table 2 here.

The relationship between traffic volume and travel speed on the emissions level of vehicular pollutants have been established by studies on toxic pollutants data in Hangzhou (Guo, 2007), impact analysis of travel speeds on vehicle exhaust (Zhang, 2007), and congestion pricing and urban transportation sustainable development (Chen et al., 2005). Since CO is almost solely emitted by vehicles (Yin and Lawphongpanich, 2006), some researchers (e.g., Alexopoulos and Assimacopoulos, 1993) consider CO as an important indicator for the level of atmospheric pollution generated by vehicular traffics. For this reason and to simplify our presentation, we consider only carbon monoxide. **Table 3** shows the average CO emissions level.

Insert Table 3 here.

When the traffic volume and average travel speed of each link are obtained, we can calculate the emissions amount of toxic pollutants by the different traffic modes based on the data in **Table 3**.

5.2 Simulation results and sensitivity analysis
5.2.1 Simulation results and basic analysis
After specifying the functions, we obtain the simulation results using Matlab 2015a, as shown in Tables 4-7 for the analysis of the traffic volume, congestion tolls, average travel speed, and vehicular pollutant emissions.

Insert Table 4 here.

In **Tables 4**, the volume of freight transportation is computed in PEC unit, which equals to $n \times$ real volume. From **Tables 4**, for any two OD pairs, the total traffic volume for the NT-scenario is the largest and that of the FB-scenario is the smallest, so is the total traffic volume of each traffic in both periods. The SB1-scenario has the smallest total traffic volume in a peak period when both traffic types incur charges, and SB1 has the highest total traffic volume in an off-peak period for traffic shifting. As only freight transportation is tolled in both time periods for the SB2-scenario, the total volume of the freight transported is less than that in the SB1-scenario in off-peak period, and the residential trip is larger than that in the SB1-scenario in peak period. The SB3-scenario has a larger total traffic volume than the SB2-scenario, and has a larger increase for freight transportation in PEC unit as compared to the residential trip in an off-peak period. It should be noted that the freight transportation traffic of link 1 in the SB3-scenario does not decrease with the other links when compared to the SB2-scenario. However, the residential trip traffic is higher than that in the SB1-scenario as now no toll is imposed on residential trips in the SB3-scenario. Moreover, the residential trip traffic for the link and the entire urban transportation network in the peak period have decreasesd in the SB3-scenario as compared to the SB2-scenario. This arises from the interaction of both traffic types in the transportation cost as shown in Eq. (7).

From our analysis, we note that different pricing policies affect the total traffic volume differently. Hence, we can effectively reduce the traffic volume and temporally shift the traffic distribution by a congestion pricing mechanism. If a residential trip needs to be prioritized in a peak period, the SB3-scenario will be considred as more residential trip traffic can be gained than that without priority consideration, i.e. SB1-scenario.

Insert Table 5 here.

The congestion toll of each link is listed in **Table 5**, which is a variable/dynamic pricing defined by the difference between the transportation cost and the average cost of each congestion pricing policy, i.e. Eq. (20), Eq. (24) and Eq. (28) respectively. The unit of link tolls in **Table 5** is cents per vehicle-kilometer, so it is comparable between the links. The congestion toll is imposed on both traffic types in the FB-scenario and the SB1-scenario, and the freight transportation in both SB2-scenario and SB3-scenario. For each link in the FB-scenario, the congestion toll in the peak period is higher than the off-peak period because the traffic volume in the peak time period on each link outweighs that in the off-peak time period as shown in **Table 4**. In addition, the FB-scenario has a higher toll than the SB1-scenario on the same link and in the same period. In the SB3-scenario, the toll of each link is at most that in the SB2-scenario, but the total traffic volume and the average travel speed are higher, as shown in **Table 4** and **Table 5**.

For the travel speed listed in **Table 5**, for each link in both periods, besides the average travel speed in peak period of SB1-scenario, the FB-scenario has the highest average travel speed, and the NT-scenario has the lowest. The lowest average travel speed of each link is found in the off-peak period in the SB1-scenario, when both traffic types incur toll charges in the peak period, which result in a higher traffic increase in the off-peak period. Given two periods and the total traffic volume, comparing with the free-flow speed, the outputs of the SB3-scenario appear efficient.

Therefore, the congestion pricing scheme impacts the traffic volume, and a variable/dynamic pricing suits demand management, i.e. the SB3-scenario, under which the performance of the urban transportation network can handle higher total traffic volume and travel speed.

The emissions level for different traffic modes in each link in different periods is also listed in **Table 5**, which are calculated based on the vehicular pollutants emission parameters, the volume of both traffic types on each link and the average travel speed of each link, as listed in **Tables 3**, **4**, and **5**. Again, the FB-scenario has the best output and the NT-scenario has the worst. For the three second-best congestion pricing policies, the SB1-scenario shows better performance in terms of lower traffic volume and emissions level with higher travel speed.

The results show that both the FB and SB policies are more effective than the NT policy in controlling

vehicular pollutants emission, demonstrating that congestion pricing is an environment-friendly method.

5.2.2 Policy insights from sensitivity analysis

Insight 1 Impact of VOT on traffic volume, travel speed, and emission

Figure 2 shows the relationship between total traffic volume of each congestion pricing policy and VOT. Specifically, **Figure 2a** indicates that the total traffic volume decreases with increasing VOT, where VOT is the marginal rate of substitution of travel time for money in a traveller's indirect utility function (Brownstone and Small, 2005). When VOT is zero, the total traffic volume of each congestion pricing is the same and higher than the total initial demand as shown in **Figures 2a** and **2b**, a non-occurrence in reality. **Figure 2c** shows the SB3-scenario, where with higher VOT, the rate of decline in the traffic volume in the peak period is less than that of the off-peak period.

Insert Figure 2 here.

Insert Figure 3 here.

The average travel speed changes with increasing VOT as illustrated in **Figure 3**, with links 1 and 2 in the SB3-scenario for both periods. There are variations in the curves, which reflects the definition of the transportation cost, i.e. Eq. (7). Besides the variations, the average travel speed increases with VOT because a higher VOT leads to lower traffic volume for both periods (c.f. **Figure 2**). This suggests that the congestion pricing policy improves the performance of the urban transportation through lowering traffic volume and improving average travel speed.

Insert Figure 4 here.

For the CO emission, the emission amount also decreases with higher VOT. The curves are not strictly smooth, due to the calculation method of CO emission according to the average emission level for each speed-interval taken from Chen at al. (2005). The emission amount of freight transportation is computed based on the real volume, so as the emission amounts in **Insight 2** and **Insight 3**. Similar to the finding in Section 5.2.1, the FB-scenario has a better output than the NT-scenario (see **Figure 4a**). For the three second-best congestion pricing policies, the SB3-scenario always has a higher emission amount than the SB2-scenario, precisely controlling the freight transportation in a peak period. While the variation in the SB1-scenario is irregular, there is still a clear trend of emission reduction with higher VOT than the NT-scenario and the SB3-scenario. Similar to the change of each congestion pricing policy, the total emissions amount of the link in both periods have the same decreasing trend with higher VOT, as shown by curves in **Figure 4b** for link 1 and link 4 in the SB3-scenario.

In sum, based on the above analysis of the relationship between VOT on traffic volume, average travelling speed and CO emission, when the marginal rate of substitution of travel time for money increases, we provide the following managerial insights: with higher VOT 1) the impact of the congestion pricing policy on the traffic volume control and reduction will lessen; 2) the average travel speed increases; and 3) the total emissions amount of the urban transportation network and its links decrease, and similar to traffic shifting, the emission amount of the link in off-peak may increase.

The VOT of freight carriers will decrease as the need to meet customer expectations (increase in customer satisfaction) outweighs the travelling cost. If the authority subsidizes the residential trips, VOT for both traffic will decrease. Then for the freight transportation regulation policy, it is an efficient way to subsidise the residential trips in a mixed traffic network, which is a better outcome gained for the entire transportation system.

- **Insight 2** Impact of traffic capacity on traffic volume, travel speed, and emissions

Given the symmetric structure of the urban transportation network, we take traffic capacity improvement of the link 1, 2 and 3 as examples, and set the traffic capacity increase at a rate of 0.1 to 2. **Figures 5a**, **5b,** and **5c** show the total traffic volume of each congestion pricing policy with increased traffic capacity for links 1, 2, and 3 respectively. It is found that improving the traffic capacity of link 3 has a better output than those of links 1 and 2. This comparison suggests that improving the traffic capacity in link 3 is more efficient than that of the other links. The following analysis of the impact on travel speed and emissions are based on the improvement of link 3.

Insert Figure 5 here.

For the average travel speed analysis, we treat the scheme where the traffic capacity of link 3 is improved. In **Figure 6**, the average travel speed of links 1 and 2 in the SB3-scenario for both time periods are illustrated. Similar to **Insight 1**, there are variations in the curves. Besides the variations, the average travelling speed of link 2 and link 5 in both periods increase, and that of link1, 3, and 4 in both periods decrease except that of link 4 in peak period, which decreases first and then increases. All these are caused by the volume shift by increasing the capacity of link 3. This trend of average travelling speed confirms that the improvement of the traffic capacity of the link does impact the average travelling speed of the other links in the urban transportation, hence improving the performance of the urban transportation network by reducing traffic volume.

Insert Figure 6 here.

For the CO emission, from the trendline, the emissions amount increases with the improved traffic capacity of link 3. The SB3-scenario has the best output and the NT-scenario has the worst, as shown in **Figure 7a**, which implies that improving the traffic capacity of link 3 can enhance the performance in the SB3-scenario. Further, the FB-scenario always performs better than the SB1-scenario and SB2-scenario. Similar to the change of each congestion pricing policy, the emissions amount of the link in both time periods increases with the traffic capacity improvement of link 3, as illustrated in **Figure7b** with the SB3-scenario.

Insert Figure 7 here.

In sum, based on the above analysis of the relationship between traffic capacity improvement on traffic volume, average travel speed and CO emissions, we have the following managerial insights by comparing with **Insight 1**. Here, we define the key link as the link with better outcomes as a result of traffic capacity improvement. First, a higher VOT will lead to higher transportation cost and lower traffic volume, while the traffic capacity improvement of the key link (e.g. link 3) results in lower transportation cost and higher traffic volume. Second, with traffic capacity improvement 1) the impact of the congestion pricing policy on the traffic volume will decrease; 2) the average travel speed in a peak period increases but the speed decreases in the off-peak period; and 3) the total emissions amount of the urban transportation network and its links decrease.

● **Insight 3** Impact of transportation demand on traffic volume, travel speed, and emissions
The change is the freight transportation demand is taken as an example, and the initial freight transportation demand in peak period increases at a rate of 0.1 to 2. **Figure 8** shows the total traffic volume of each congestion pricing policy with increasing initial freight transportation demand. The total traffic volume of the NT-scenario and the SB3-scenario increase, while that of the other congestion pricing policies decrease.

Insert Figure 8 here.

In **Figure 9**, the average travel speed of links 1 and 2 in the SB3-scenario for both time periods is illustrated.

Similar to **Insight 1**, there are variations in the curves. Besides the variation, according to the added trendlines, the average travel speeds of links 1 and 2 in a peak period increases but in off-peak period, it decreases.

Insert Figure 9 here.

From the trendline, the emissions amount of the urban transportaion network increases with growing transportation demand (see **Figure 10a**). This suggests that higher transportation demand hampers the performance of the congestion pricing policies. The SB3-scenario has the best output and the NT-scenario has the worst, and the FB-scenario always has a better performance than the SB1-scenario and the SB2-scenario. The emissions amount of the link in both time periods increases as illustrated in **Figure 10b**.

Insert Figure 10 here.

In summary, based on the above analysis of the impact of a growing transportation demand on traffic volume, average travel speed, and CO emissions, we show that when the initial freight transportation demand in a peak period increases, the following managerial insights are observed: 1) the impact of the SB3-scenario on the traffic volume control and reduction will lessen, while that of the other congestion pricing policies will increase; 2) the average travel speed in a peak period increases and that in an off-peak period decreases; and 3) the total emissions of the urban transportation network and its links increase.

6. Conclusion

In this paper, we have extended the previous second-best congestion pricing models by considering a mixed traffic situation on a ground transport network, i.e. freight transportation and residential trip. The new model formulations are tested in a simple network to examine the temporal impacts of the traffic reduction and the vehicular pollutants emissions control based on certain congestion pricing policies. The key findings from the simulation study are that the congestion pricing policies are effective in reallocating traffic volume, improving travel speed, and reducing emissions. On the other hand, the congestion pricing scheme in the SB3-scenario, i.e. only the freight transportation is charged on all links and in peak periods, brings about a reduction in the total emissions of vehicular pollutants due to traffic volume reallocation and travel speed improvement.

Compared to the NT policy, the FB policy and SB policies are more effective in controlling vehicular pollutants emissions, which demonstrates that congestion pricing is an efficient solution for sustainable transportation. Based on the impact of VOT on traffic volume, average travel speed and CO emissions, policy makers involved in congestion pricing policies should note that the impact of the congestion pricing policy on the traffic volume control and reduction will decrease with higher VOT, traffic capacity, and transportation demand.

From the perspective of the fundamental supply, improving the key link's traffic capacity is a cost-efficient way for traffic control with congestion pricing. In summary, congestion pricing policies have a major impact on: (1) reducing the total traffic volume while increasing the average travel speed in the tolled period; (2) diverting the traffic volume from a tolled period to a no-tolled period; (3) reducing the total emissions of vehicular pollutants; (4) shifting the freight transportation traffic from a tolled period to a no-tolled period by imposing a toll in the peak period; (5) on reducing the traffic volume and emissions under higher VOT, traffic capacity, and transport demand; (6) improving the traffic capacity of the key links can enhance the effect of the congestion pricing policies; and (7) rising customer satisfaction and subsiding residential trips can improve the effect of congestion pricing policies.

In future, it would be interesting to extend the problem to more than one type of freight transportation according to the VOT and the emissions level (e.g. a higher VOT freight transportation by electric vans). In addition, research can seek improvement by imposing a congestion toll on different links/roads, and analyse the spatial impact of such congestion policies.

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Table 1. Parameters of transportation demands

Traffic	OD pair s	Time period i	Initial Demand $\overline{Q}_s^i$ (veh/h)	Elasticity Coefficient (veh$^2\cdot$(cents/h)$^{-1}$)			
				$\beta_{11,s}$	$\beta_{12,s}$	$\beta_{21,s}$	$\beta_{22,s}$
Freight transportation	1	1	9 500	21	12	15	25
		2	8 000				
	2	1	4 500	20	15	14	22
		2	3 500				
Residential trip	1	1	12 500	18	12	12	20
		2	11 800				
	2	1	9 500	16	11	10	18
		2	7 500				

Table 2. Parameters of transportation cost function

link	1	2	3	4	5
Free-flow transportation cost T_a (min)	12	18	12	12	21
Traffic capacity K_a (veh/h)	3 500	4 000	3 500	2 500	3 000
Length L (km)	10	12	16	13	14

Table 3. Average CO emission level of automobiles under different travel speed (mg/veh)

Average travel speed (km/h)	>60	30~60	10~30	10
Freight transportation	20.2	20.9	33.1	44.6
Residential trip	22.6	41.2	89.9	120

Source: The data are modified from Chen at al. (2005), in which the traffic is classified as a heavy diesel vehicle and private car, and the original data of CO emissions level is an interval-value. For simplicity, we adopt the average emissions level for each speed-interval.

Table 4. Traffic volume of freight transportation and residential trip in each link ($\times 10^3$ veh/h)

Period	Traffic type	Link	NT	FB	SB1	SB2	SB3
Peak	Freight	1	0.645843	0.212077	0.234374	0.246863	0.252382
	transportation	2	2.338811	1.189772	1.183863	1.940342	1.921365
		3	1.699493	0.628359	0.815689	1.132359	1.086621
		4	1.053651	0.416282	0.600125	0.885495	0.83424
		5	1.265636	0.588703	0.257205	1.033752	0.999437
		Total traffic volume	7.003433	3.035193	3.091256	5.238812	5.094046
	Residential trip	1	2.537263	2.273826	2.226527	2.615283	2.599039
		2	5.116782	4.281952	4.280974	4.454149	4.400426
		3	5.08115	4.420792	4.147684	5.138964	5.119182
		4	2.543887	2.146966	1.939967	2.523681	2.520143
		5	4.25316	3.453773	3.747663	3.891623	3.867146
		Total traffic volume	19.53224	16.57731	16.34282	18.6237	18.50594
		Total traffic volume in peak period	26.53568	19.6125	19.43407	23.86251	23.59998
Off-peak	Freight	1	0.588899	0.088747	0.530447	0.388812	0.701439
	Transportation	2	1.486409	0.640588	1.666431	1.308178	1.565129
		3	1.394926	0.657477	1.599698	0.936972	1.524259
		4	0.806026	0.56873	1.06748	0.548159	0.822821
		5	1.399086	0.890426	1.537752	1.227285	1.477599
		Total traffic volume	5.675347	2.845968	6.401808	4.409406	6.091246
	Residential trip	1	2.353248	2.052965	2.350335	2.511641	2.421377
		2	5.206999	4.430504	5.337538	4.745952	5.291878
		3	4.478105	3.974664	4.592808	4.616648	4.535644
		4	2.124857	1.921699	2.240702	2.105008	2.114267
		5	3.402495	2.741702	3.491734	2.97438	3.43254
		Total traffic volume	17.5657	15.12153	18.01312	16.95363	17.79571
		Total traffic volume in off-peak period	23.24105	17.9675	24.41492	21.36303	23.88695
Total traffic volume in both period			49.77672	37.58	43.849	45.22555	47.48693

Period	Traffic type	Link	NT	FB	SB1	SB2	SB3
Peak	Freight	1	0.322921	0.106039	0.117187	0.123432	0.126191
	transportation	2	1.169405	0.594886	0.591932	0.970171	0.960683
		3	0.849747	0.314179	0.407844	0.566179	0.543311
		4	0.526825	0.208141	0.300063	0.442748	0.41712
		5	0.632818	0.294352	0.128603	0.516876	0.499719
		Total traffic volume	3.501717	1.517597	1.545628	2.619406	2.547023
	Residential trip	1	2.537263	2.273826	2.226527	2.615283	2.599039
		2	5.116782	4.281952	4.280974	4.454149	4.400426
		3	5.08115	4.420792	4.147684	5.138964	5.119182
		4	2.543887	2.146966	1.939967	2.523681	2.520143
		5	4.25316	3.453773	3.747663	3.891623	3.867146
		Total traffic volume	19.53224	16.57731	16.34282	18.6237	18.50594
		Total traffic volume in peak period	23.03396	18.09491	17.88844	21.2431	21.05296
Off-peak	Freight	1	0.29445	0.044374	0.265224	0.194406	0.350719
	Transportation	2	0.743205	0.320294	0.833215	0.654089	0.782565
		3	0.697463	0.328739	0.799849	0.468486	0.76213
		4	0.403013	0.284365	0.53374	0.27408	0.41141
		5	0.699543	0.445213	0.768876	0.613642	0.738799
		Total traffic volume	2.837673	1.422984	3.200904	2.204703	3.045623
	Residential trip	1	2.353248	2.052965	2.350335	2.511641	2.421377
		2	5.206999	4.430504	5.337538	4.745952	5.291878
		3	4.478105	3.974664	4.592808	4.616648	4.535644
		4	2.124857	1.921699	2.240702	2.105008	2.114267
		5	3.402495	2.741702	3.491734	2.97438	3.43254
		Total traffic volume	17.5657	15.12153	18.01312	16.95363	17.79571
		Total traffic volume in off-peak period	20.40338	16.54452	21.21402	19.15833	20.84133
Total traffic volume in both period			43.437335	34.639423	39.102464	40.401436	41.894286

Table 5. Congestion toll, travel speed and CO emission of each link in each pricing scenario (cents/(veh·km))

Time period	Link	Congestion toll					Travel speed					CO emission				
		NT	FB	SB1	SB2	SB3	NT	FB	SB1	SB2	SB3	NT	FB	SB1	SB2	SB3
Peak	1	—	30.736421	30.494235	35.003093	34.864496	46.864959	48.446572	48.536129	47.337954	47.387278	214.39211	181.40738	196.55910	217.87205	216.80854
	2	—	105.723718	105.437024	151.037340	146.945687	20.888202	30.042665	30.066776	26.538182	26.953687	691.99065	181.40738	196.55910	636.74493	629.06573
	3	—	90.565836	87.161849	152.804401	148.766871	35.765330	53.246541	55.924463	38.854308	39.454340	214.39211	181.40738	196.55910	217.87205	216.80854
	4	—	65.825767	64.908714	112.016604	108.204930	48.456142	58.132584	59.269681	50.102162	50.551147	214.39211	181.40738	196.55910	217.87205	216.80854
	5	—	159.237033	156.111422	250.654179	243.419909	19.461043	29.293748	28.207137	23.536751	23.903161	614.35109	500.03440	560.86779	586.17381	581.12393
Off-peak	1	—	27.813419	—	35.506633	—	47.658814	49.051269	47.765446	47.456365	47.213141	214.39211	181.40738	196.55910	217.87205	216.80854
	2	—	90.217492	—	132.674964	—	23.061698	30.805213	21.626537	26.697976	22.249804	298.80609	181.40738	298.85898	295.11955	303.82003
	3	—	75.084947	—	113.031285	—	46.586989	59.576092	43.352502	47.950473	44.757878	214.39211	181.40738	196.55910	217.87205	216.80854
	4	—	62.997548	—	69.546823	—	56.189421	59.581087	52.951965	57.879690	56.215820	214.39211	181.40738	196.55910	217.87205	216.80854
	5	—	128.190123	—	173.123648	—	26.241035	33.584544	24.841178	30.606281	25.629995	294.88091	181.40738	293.07485	217.87205	299.88553
Total CO emission												3186.38138	2132.70085	2528.71533	3043.14267	3114.74647
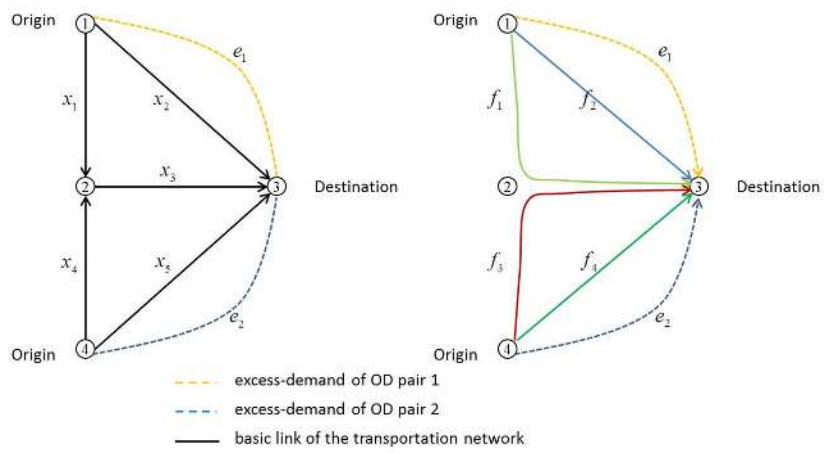
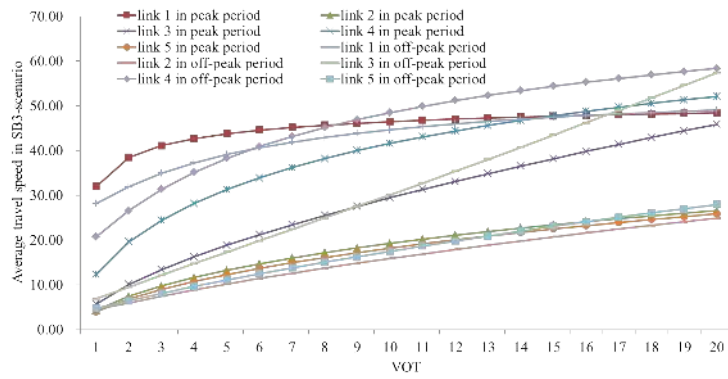**Figure 1.** Network for congestion problem simulation study
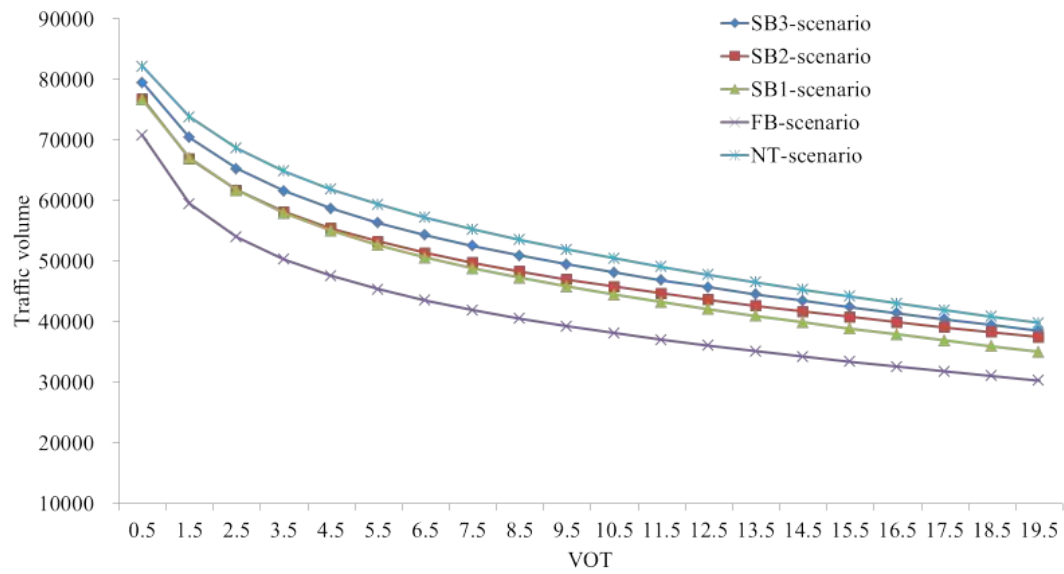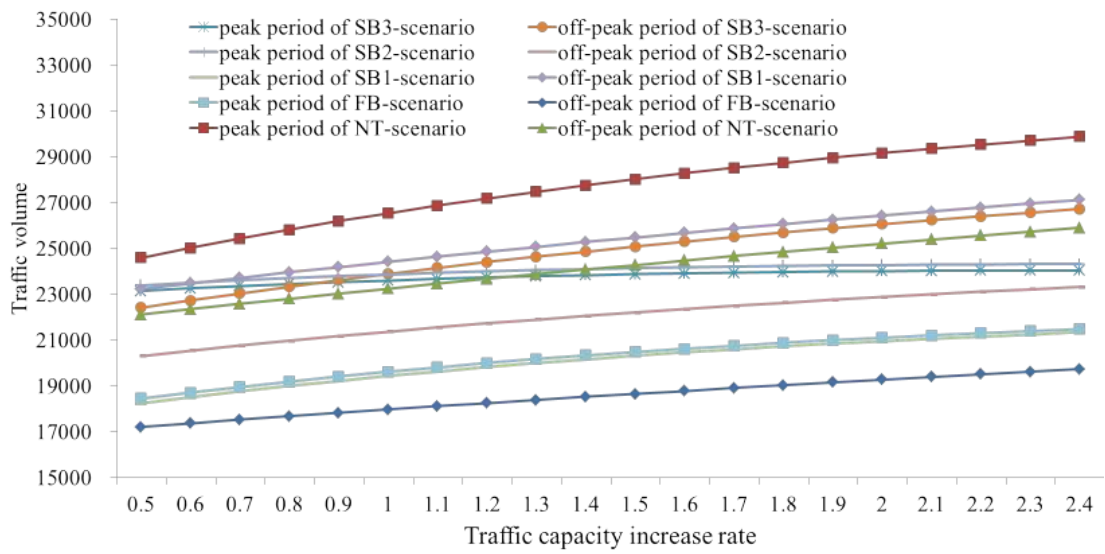
a)
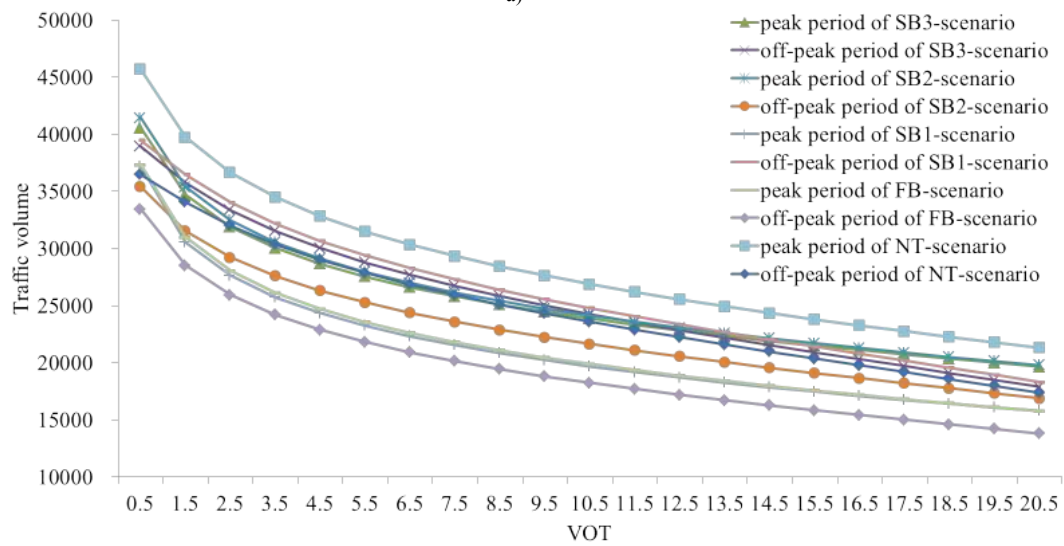
b)
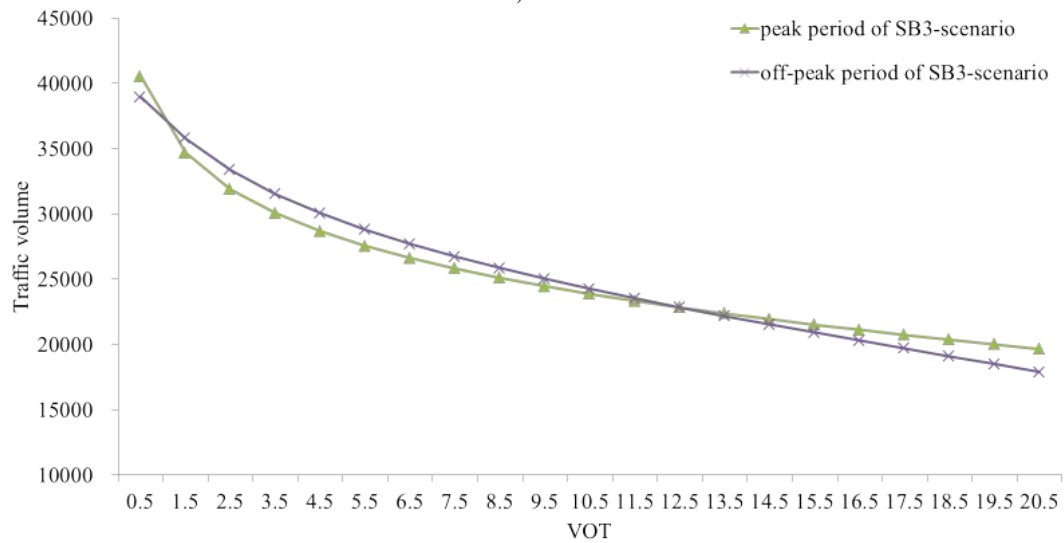
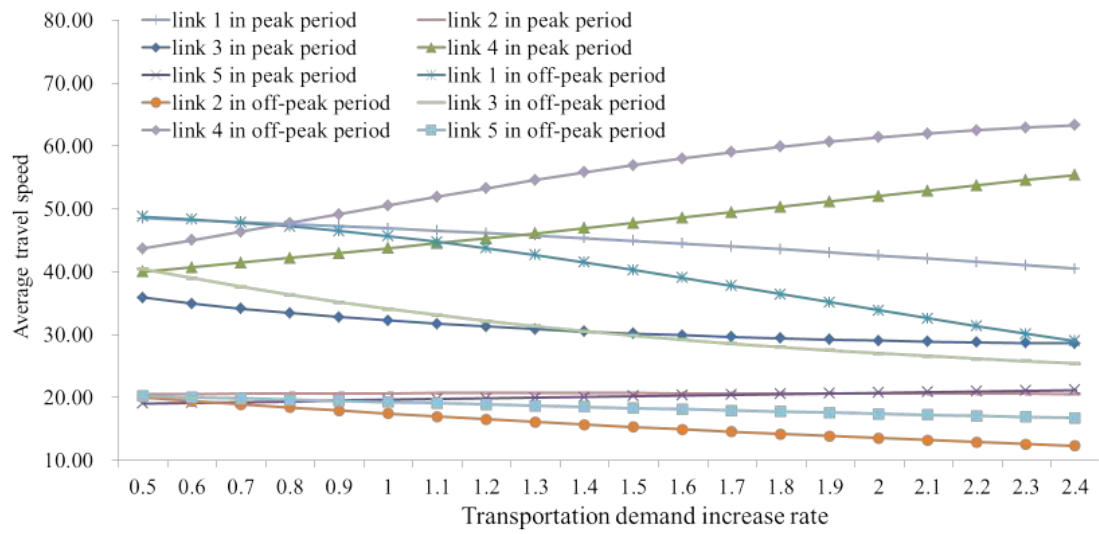c)

Figure 2. Traffic volume changes with VOT

a)

b)
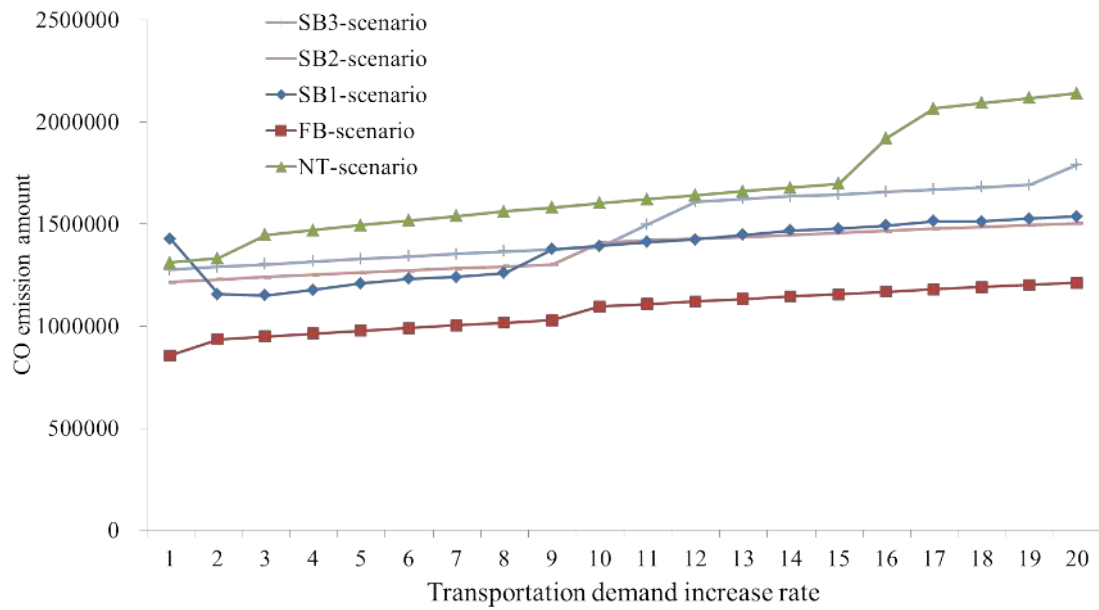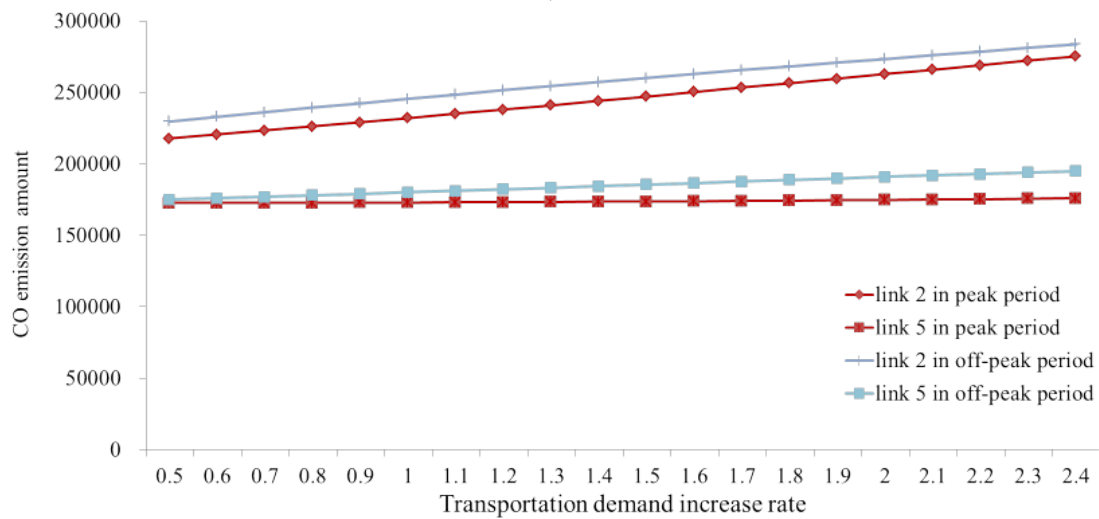**Figure 3.** Average travel speed changes with VOT in SB3-scenario

Figure 8. Traffic volume changes with rising transportation demand

Figure 9. Average travel speed changes with growing transportation demand
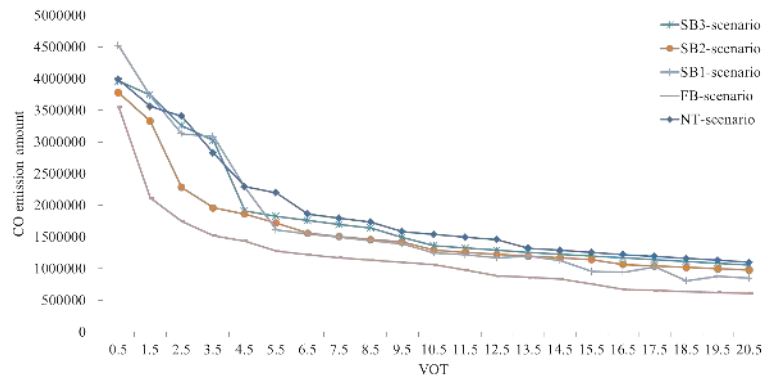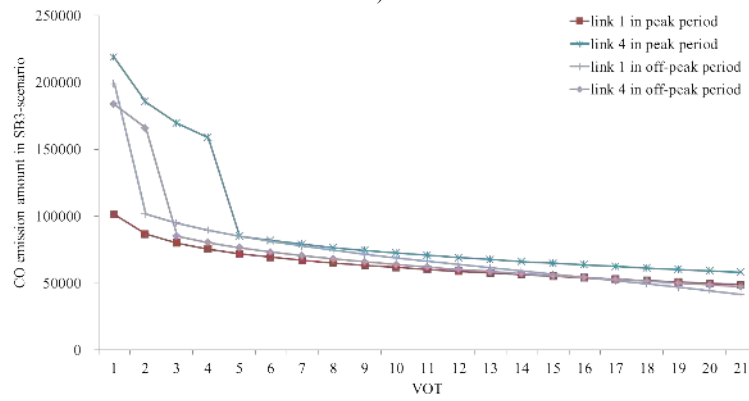
Figure 10. CO emission changes with rising transportation demand
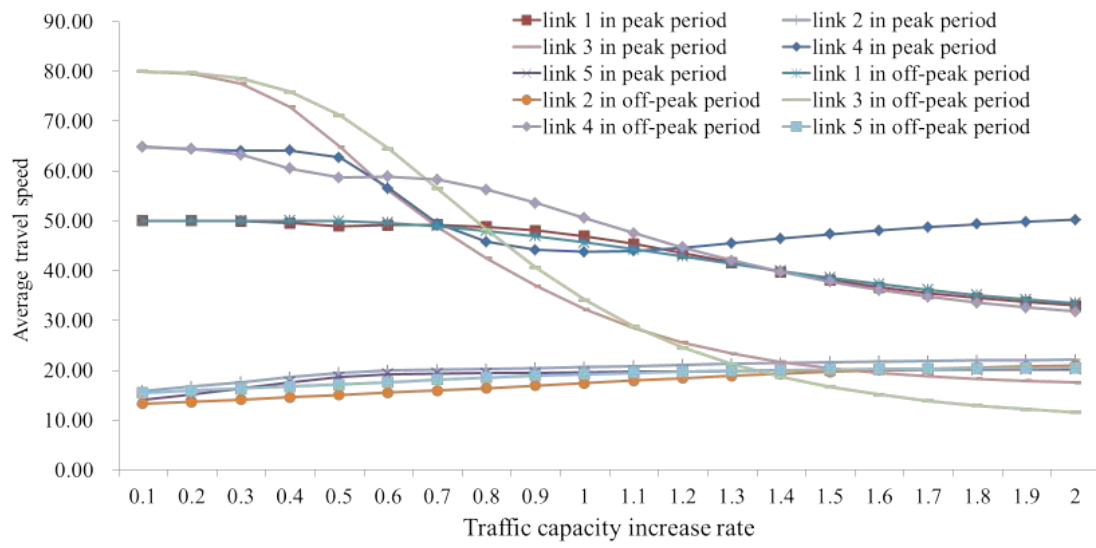
a)

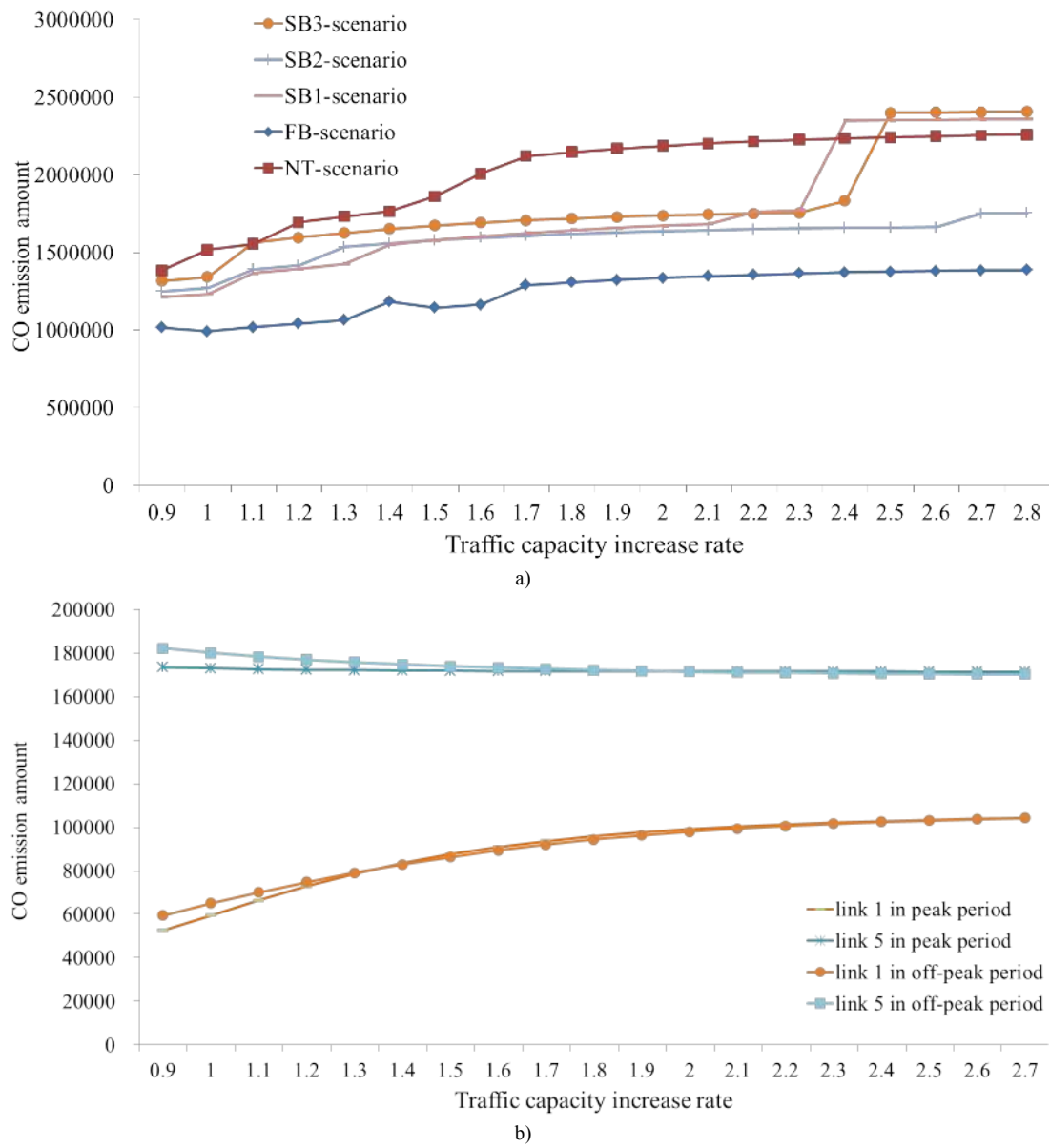b)

Figure 4. CO emission changes with increasing VOT
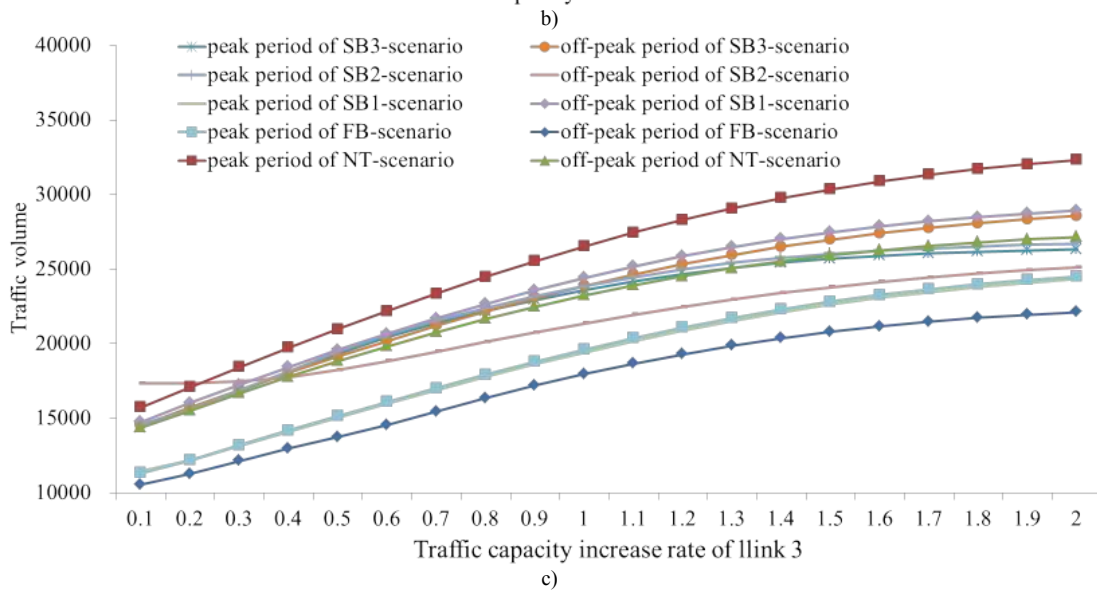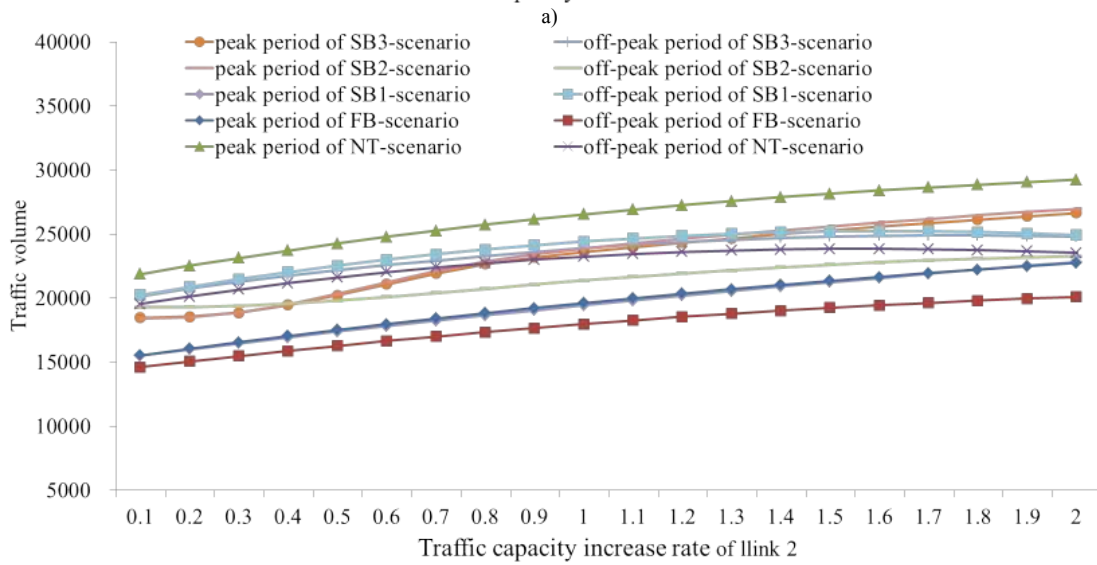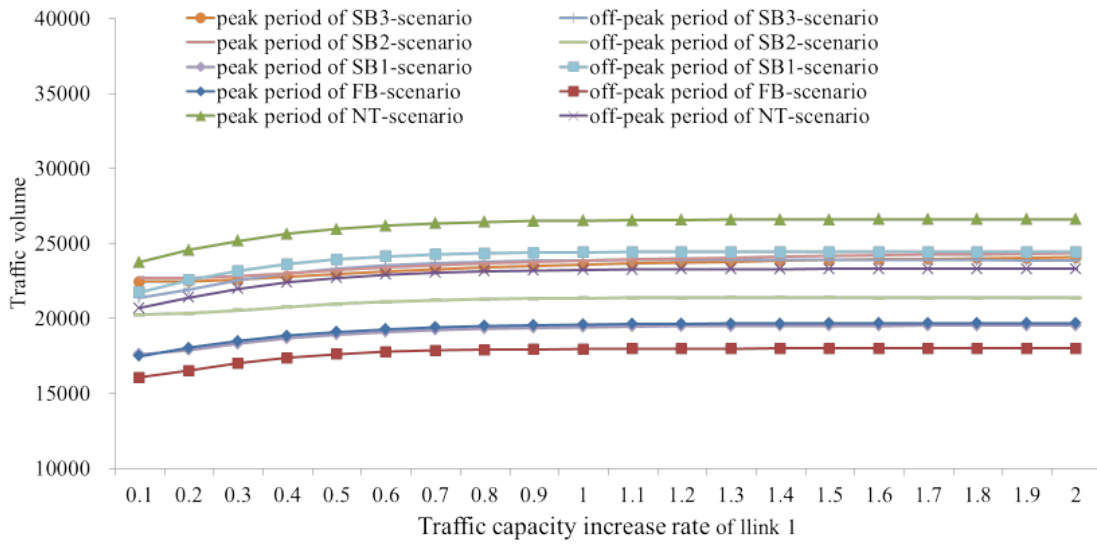
Figure 5. Traffic volume changes with traffic capacity improvement

Figure 6. Average travel speed changes with traffic capacity improvement

a)

b)

Figure 7. CO emission changes with traffic capacity improvement