University Transportation Research Center - Region 2

# Final Report

## Network System Effects of Mileage Fee

Performing Organization: Rensselaer Polytechnic Institute

September 2015

Sponsor:
University Transportation Research Center - Region 2

## University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

### Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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**Principal Investigator(s):**

**Dr. Xuegang (Jeff) Ban**
Department of Civil and Environmental Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180
Email: banx@rpi.edu

**Performing Organization:**
Rensselaer Polytechnic Institute

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University Transportation Research Center (UTRC)

To request a hard copy of our final reports, please send us an email at utrc@utrc2.org

**Mailing Address:**

University Transportation Reserch Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: 212-650-8051
Fax: 212-650-8374
Web: www.utrc2.org

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# Executive Summary

To address the critical needs in transportation finance, the concept of mileage fee (MF) has been revisited and received much attention lately as an alternative way to generate transportation revenue. Under this concept, drivers are charged based on the total number of miles traveled and/or where and when the travel took place. Compared with fuel taxes, MF can generate sustainable revenue which is one of the major reasons for decreasing or steady revenue from fuel taxes. There are three commonly used MF policies: flat fees, stacked fees, and multiplied fees. An ideal MF policy should meet the requirements for revenue adequacy and sustainability, efficiency, environmental sustainability and feasibility, and equity to the maximum level.

The current research on MF mainly focuses on the technologies, MF policies related issues such as public acceptance (e.g., privacy issues), and other financial considerations. Few studies looked at the system effects of MF policies. MF, similar to other major transportation policies (such as congestion pricing), is expected to have significant impacts on driver behaviors. Since drivers make their decisions individually, who are however connected by the traffic network, MF policy may generate complicated network effects as a result of drivers' (potentially heterogeneous) responses. The implication is that, if not thoroughly investigated and properly designed, MF may produce unintended consequences that is not desirable from either the system manger's or the public's perspective.

This project presents a comprehensive investigation about the network effects of MF to facilitate the developments of proper MF policies. After a practice scan and a review of the recent literature on MF, a multi-class mathematical programming with equilibrium constraint (MC-MPEC) is proposed to capture the optimal MF charging problem from a network perspective. The MC-MPEC problem is then solved and tested on two illustrative networks to show the MF network effect. Two important implications for practical implementations arising in the investigation are to model the target revenue as a constraint and to model the upper bound of the unit flat fee. The model is general, which can capture the three fee polices and model different objectives commonly used for MF. Different scenarios are tested and analyzed using two hypothetical traffic networks.

From the results, one can see that the three different fee policies are mathematically the same. If the upper bound of the flat fee is too large, one may consider the stacked fee or multiplied fee, which makes the MF policies easier to be accepted by the public and easier to be implemented. One important issue when studying the network effect of MF is the non-uniqueness of the path flows. It has important implications to MF policy design and implementation, which needs to be carefully investigated. It is also shown that the existence of restricted truck flow can have important implication to the network flow pattern, which can bring some complications for the fee implementation.

In practice, MF policies should be determined with many factors; how to capture these factors in a unified function should be further studied in future research. In this report, only the two-class model is tested/validated. Testing/validation of the proposed model and method on more vehicle classes needs further investigation. The MF policies on larger networks will also need to be tested in future research. Moreover, the theoretical analysis on the non-uniqueness path flow problem is interesting and merits further investigations.

# 1 Introduction

Fuel taxes have been the main source of transportation funding in the US for the last six decades, thanks to the Highway Trust Fund established in 1956. Recently, there have been increasing concerns regarding this funding mechanism because the revenue from fuel taxes cannot keep up with the increasing needs for transportation infrastructure repair and rebuild (Forkenbrock and Kuhl, 2002). In fact, the National Surface Transportation Infrastructure Financing Commission (2009) indicated that the cumulative gap between the federal investment needed to improve the transportation and the fuel tax revenue will reach $400 Billion during the period of 2010 – 2015, which is shown in Figure 1. Such a gap will keep increasing as shown in the figure below if fuel taxes are kept as is.

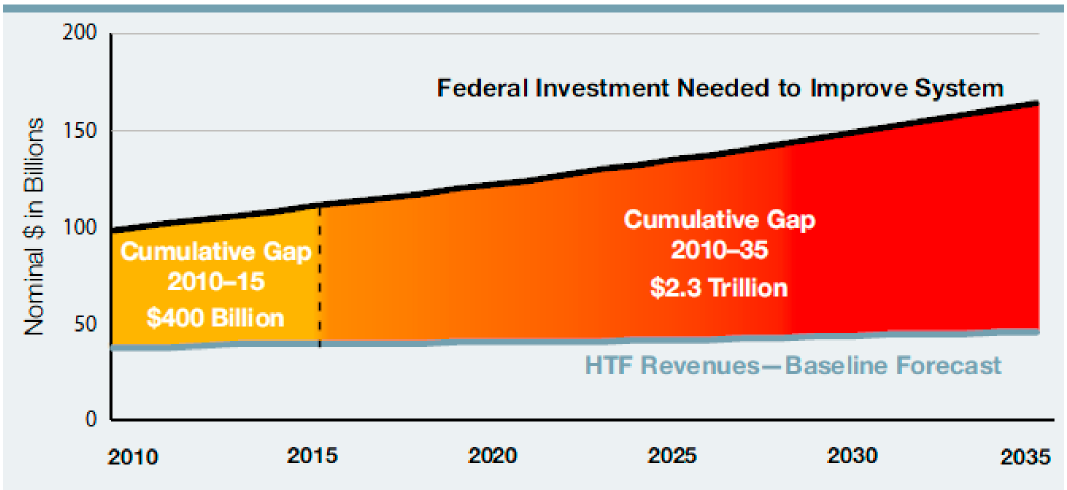


**Figure 1: Critical Needs in Transportation Finance**

The financial crisis is mainly caused by increasing fuel efficiencies of vehicles, increasing demands for transportation roads and other facilities, high erosion of fuel tax purchasing power, as well as stagnant fuel tax rate (Forkenbrock and Kuhl, 2002; Whitty and Svadlenak, 2009; Coyle et. al., 2011). To address the critical needs in transportation finance, the concept of mileage fee (MF) has been revisited and received much attention lately as an alternative way to generate transportation revenue. Under this concept, drivers are charged based on the total number of miles traveled and/or where and when the travel took place. Compared with fuel taxes, MF can generate sustainable revenue regardless of fuel efficiency or alternative fuels, which is one of the major reasons for decreasing or steady revenue from fuel taxes.

Extensive research has been conducted on MF design and implementation. After a comprehensive review of previous studies, existing MF policies can be largely grouped into three categories: flat rate, stacked rate, and multiplied rate (Whitty and Svadlenak, 2009; Coyle et al., 2011). First, a flat rate is the simplest charging scheme, meaning that all vehicles are charged at the same rate regardless of vehicle make and model, traffic volume, road types, emission characteristics, etc. Obviously its simplicity makes it easy to implement, but it could also result in equity issues by creating disparities between income groups, ethnicity groups, and ages (Forkenbrock and Kuhl, 2002; Minnesota DOT, 2011; Robitaille et al., 2010; Sana et al., 2011; Zhang et al., 2009; Zhang et al., 2011; Burris et al., 2013; Whitty and Svadlenak, 2009; Coyle et al., 2011).

Secondly, a stacked rate involves stacking another rate on top of the flat rate to allow rate variability, which is used to accommodate vehicle fuel efficiency, vehicle type, emission, congestion, or other externalities. In 2010, Nevada Department of Transportation (DOT) proposed the dual fee policy that used stacked rate for trucks to differentiate them from cars, which would be more equitable compared with the flat rate policy since trucks creates more damages to the road system and more externalities. Stacked rate was also proposed to accommodate fuel efficiency where an additional charge based on vehicle fuel efficiency was stacked on top of a base fee (Zhang et al., 2011; Whitty and Svadlenak, 2009; Coyle et al., 2011). Regression analysis showed that such a policy could hurt low income families more while benefiting rural states with fuel inefficient vehicles (Zhang et al., 2011). Thus in practice, it is recommended to compensate the low income families. Similar results were also found when applying the stacked rate to accommodate emissions (Zhang et al., 2011; Whitty and Svadlenak, 2009; Coyle et al., 2011). Studies on stacked rate to account for congestion showed that peak-hour VMT may be reduced but with no significant spillover to off-peak hours (Guo et al., 2011; Whitty and Svadlenak, 2009; Coyle et al., 2011). Such a MF policy also received complaints from regular commuters during peak hours (Fichtner and Riggleman, 2007). While all the above stacked rate policies only concerned one aspect of externalities, Nevada DOT (2010) proposed the generalized user fee (also belongs to stacked fee) where a coefficient as a function of vehicle make and model, road condition, and traffic level was added to the MF fee. Its implementation difficulties root in the challenge to determine the coefficients that require sufficient data for quantitative analysis.

Thirdly, a multiplied rate uses a coefficient to incorporate the diversities in MF. Nevada DOT (2010) proposed multiplied fee with coefficients based on vehicle types and ages as well as multiplied fee with coefficients as a function of vehicle make and model, road condition, and traffic level. Zhang et al. (2011) proposed the multiplied rate with coefficients varying with congestion levels measured by the travel time indices (TTI) ranging from 1 to 1.83. Linear interpolation method was adopted to calculate the MF based on TTI and a given maximum MF. Regression analysis results showed that this policy decreases VMT and hurts urban residents and certain ethnic groups. In particular, Asian and Hispanics residents were hurt mostly since most of them live in urban areas.

A summary of the existing MF studies is given in Table 1, including the advantages, disadvantages, and the implications to the current MF studies.

**Table 1: Summary of the existing MF studies**

| MF policies | | Pros | Cons | Implications |
|---|---|---|---|---|
| Flat rate | Conceptual proposal | Easy to calculate;<br>Ensure sustainable revenue;<br>More equitable compared with tax increase; | Create equity issues with disparities between income groups, ethnic groups and regions, age | Mileage fee should be charged based on vehicle type and weight, road type, traffic volume, emission, incomes. |
| | Network test<br>with flat rate for all vehicles or flat rate for each vehicle type (truck or car) | Test network performance with fuel tax and mileage based fee;<br>Before system optimum for the same level of revenue, mileage fee achieves higher performance | Used flat rate | Mileage rate considers types of road and vehicles, weight, traffic, emission and congestion, etc. |
| Stacked rate | Green VMT fee=base fee + fuel efficiency charge | Ensure sustainable revenue;<br>More equitable compared with flat rate;<br>Encourage fuel efficient vehicles; Rural state with fuel inefficient vehicles benefits more; Decrease of VMT; | Low income families decrease VMT most;<br>Impact younger generations more; | Low-income families should be compensated;<br>Target at fuel efficiency, emission and congestion; |
| | Emission tax=base fee + emission rating charge | Ensure sustainable revenue;<br>More equitable compared with flat rate;<br>Consider environmental cost; Rural state with fuel inefficient vehicles benefits more;<br>Decrease of VMT; | Low income families decrease VMT most;<br>More decrease in *low-income families* VMT compared to green VMT and congestion pricing;<br>Impact younger generations more; | Low-income families should be compensated; Target at fuel efficiency congestion and congestion |
| | Congestion pricing=base fee + peak hour additional charge | Ensure sustainable revenue;<br>More equitable compared with flat | Tested on a small area; complaints from commuters during rush hours; | Test it statewide or in multiple states;<br>Consider other aspects such as vehicle type |

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| | | rate;<br>Reduced VMT during peak hour without significant spillover; | | and weight, road type, traffic volume, incomes. |
| | Marginal cost=Private average cost + externality costs of pollution, noise, congestion and accidents | Ensure sustainable revenue;<br>More equitable compared with flat rate; | Need data for calculating the indirect cost | Data collection |
| Multiplied rate | Congestion pricing | Ensure sustainable revenue;<br>More equitable compared with flat rate;<br>Congested state benefits more; Decrease of VMT; | Low income families decrease VMT most;<br>*Urban residents get hurt*; Asians and Hispanics hurt more; VMT most;<br>Impact younger generations more; | Low-income families should be compensated; Target at fuel efficiency, emission and congestion; |
| | Multiplied fee based on vehicle types and ages | Ensure sustainable revenue;<br>More equitable compared with flat rate; | No consideration for congestion | Consider other factors; |
| | Generalized user fee | The coefficient is a function of vehicle make and model, road condition and traffic level, | Difficult to determine the coefficient | Collect data for quantitative analyses; |

In summary, an ideal MF policy should meet the requirements for revenue adequacy and sustainability, efficiency, environmental sustainability and feasibility, and equity to the maximum level. Thus, it should account for vehicle types and weights, road types, traffic volumes, emissions, ethnic groups and incomes. All the above three categories of MF policies have their own advantages and disadvantages. Flat rate policy is easy to implement but creates equity issues with disparities between income groups, ethnic groups and regions, ages, etc. Stacked rate, based on either fuel efficiency, emission, congestion, or vehicle type, still has the equity issue, though it is more equitable compared with the flat rate. Marginal cost, as one of the stacked rate policies, seems promising but requires large datasets and produces difficulties in calculating the indirect costs. Equity issues also exist in multiplied rate policies except the generalized user fee. However, it is a challenging task to obtain the coefficients for all the variables contributing to MF in the generalized user fee.

As discussed above, the current research on MF mainly focuses on the technologies, and MF policies related issues such as public acceptance (e.g., privacy issues), and other financial considerations. Few studies looked at the system effects of MF policies. MF, similar to other major transportation policies (such as congestion pricing), is expected to have significant impacts on driver behaviors. Since drivers make their decisions individually, who are however connected by the traffic network, MF policies may generate complicated network effects as a result of drivers' (potentially heterogeneous) responses. The implication is that, if not thoroughly investigated and properly designed, MF may produce unintended consequences that is not desirable from either the system manger's or the public's perspective. In transportation, such examples are not rare. For instance, banning large trucks in an urban area with the good intent to reduce truck traffic (and associated emissions, noise, etc.) may be counterproductive in terms of congestion and emissions. This is because under such a policy, more small trucks will be needed to travel to the urban area to deliver the same amount of goods (Holguin-Veras et al., 2013), thus likely producing more congestion and emissions.

Therefore, a comprehensive investigation about the network effects of MF is conducted in this research to facilitate the developments of proper MF policies. As far as we know, only a handful of papers focused on the network effect of flat mileage fee. In Jia et al. (2012), the potential traffic mobility effects of MF was investigated from a traffic operational point of view under user equilibrium conditions. MF was incorporated into the generalized travel time using users' value of time. The results showed that to achieve a certain level of total system revenue, the MF could produce lower average path travel time compared with the fuel tax policy for a given demand and network. However, if the desired system revenue was beyond a certain level, the results may be opposite. Their simulation results also showed that the level of MF not only influences the total system revenue but also the system average travel time. The optimal MF to optimize the system average travel time depends strictly on the characteristics of the underlying transportation network, such as alternative path lengths and total demand level. The study was based on fixed demand without considering the flexibility of demand caused by the change in generalized travel times. Further studies on the potential traffic mobility effects can be conducted based on a flexible demand, which is more realistic, instead of a fixed demand. Moreover, the study only modeled the single-class flat fee.

This project tries to fill this gap and focuses on the network effect of MF. Different from Jia et al. (2012), the optimal MF charges on the network is the focus of this report, considering the total emission, or a weighted combination of total travel times and total emissions of the traffic network. With the model in this research, the following question may be answered.

*In order to obtain the lowest total emission (or a weighted combination of total travel times and total emissions) of the traffic network, what MF fee should be charged on different links of the traffic network?*

In this research, a multi-class mathematical program with equilibrium constraint (MC-MPEC) is proposed to capture different MF policies. The model can be used to minimize the total emissions or the weighted sum of total travel times and total emissions of the traffic network. A GAMS-based heuristic method is proposed to solve the model. Different scenarios are tested, including the single-class scenario and multi-class scenario, different fee policies, and so on. From the results, it can be found that different fee policies can have important effect on the path flow distribution and the optimal fees charged on each link, and, subsequently on the performance of the network system. Furthermore, the non-uniqueness of path flows needs to be carefully handled when implementing the MF policies.

The main contributions of this report are summarized as follows:

(1) A multi-class mathematical program with equilibrium constraint (MC-MPEC) is proposed to capture different MF policies. The MC-MPEC can be solved with the NLPEC solver in GAMS.

(2) The MC-MPEC is general enough, which can capture the MF policies of flat fee, stacked fee and multiplied fee. Furthermore, the MC-MPEC can be used to minimize the total emissions or the weighted sum of total travel times and total emissions of the network.

(3) Different scenarios are tested with the MC-MPEC model. From the results, it can be found that the path flow distribution and the optimal fees charged on each link, and subsequently the performance of the network system can be affected by different fee policies. The implication of the non-uniqueness of path flow for the fee implementation is discussed.

The remainder of the report is organized as follows. Section 2 lists all the MF policies and presents the mathematical expressions of these policies. In Section 3, the MC-MPEC model is proposed to capture the optimal MF charge problem. The GAMS-based heuristic algorithm is also proposed in this section. In Section 4, the optimal MF charge problem is tested on different scenarios, followed by conclusions and major findings in Section 5.

## 2 Mileage fee policies and their mathematical representations

Before the proposed MF model is given, the main ideas of different MF policies are shown first including their mathematical representations. For details, one can refer to Whitty and Svadlenak (2009) and Coyle et al. (2011). The current MF policies consist of flat fee, stacked fee and multiplied fee.

The idea of flat fee is simple by charging a constant fee on each and every link in the network. The stacked fee is based on the flat fee, where the flat fee is the base and some additional fees are charged on that. The additional fees can be determined by the vehicle characteristics (e.g., vintage, vehicle type, and fuel efficiency). The multiplied fee is also based on the flat fee (or the stacked fee), multiplied by a coefficient to account for vehicle external environmental factors. Those vehicles with the least impact could be assigned a multiplier of 1.0 and those with the greatest impact could be assigned a multiplier that could be as large as 6.0 (Whitty and Svadlenak, 2009; Coyle et al., 2011).

From the above discussion on different MF policies, the following mathematical representations of different policies can be derived.

(1) The unit flat fee

$\alpha_a^{ff} = c_a$, for each link $a$, where $\alpha_a^{ff}$ is the flat fee on link , and $c_a$ is the unit flat fee, i.e., the fee charged on a single vehicle traveling on link $a$.

(2) The unit stacked fee

$\alpha_a^{sf} = c_a + \gamma_a$, for each link $a$, where $\alpha_a^{sf}$ is the stacked fee on link $a$, and $\gamma_a$ is the unit stacked fee on link $a$. The unit stacked fee is determined by the vehicle attributes (e.g., the vintage, the type and the fuel efficiency). See Whitty and Svadlenak (2009) and Coyle et al. (2011) for more details.

(3) The unit multiplied fee

$\alpha_a^{mf} = \kappa\left(c_a + \gamma_a\right)$, for each link $a$, where $\alpha_a^{mf}$ is the stacked fee on link $a$, $\gamma_a$ is the unit stacked fee on link $a$, and $\kappa$ is the coefficient (or multiplier). The multiplier $\kappa$ is determined by the vehicle's external environmental factors, which is in the interval $\left[1, 6\right]$ (Whitty and Svadlenak, 2009; Coyle et al., 2011).

**Remark 1**. For a specific vehicle, the unit stacked fee on link $a$, $\gamma_a$, and the multiplier $\kappa$ are all constants. The variable to be determined is $c_a$ for the link. Therefore, the three fee policies are essentially the same mathematically and the outputs of different formulations are all unit flat fees on network links. However, as will be shown later, stacked fee or multiplied fee can have important implications on the MF charges and also on the systematic performance.

## 3 Optimal mileage fee charging model

In this section, a multi-class mathematical program with equilibrium constraint (MC-MPEC) is proposed to capture the optimal MF charging problem in a traffic network. As conveyed in the introduction, reducing the total emissions or the weighted sum of total travel times and total emissions through the optimal MF charges is the focus of this research. That is to say, the objective of the MPEC model is to minimize the total emission or the weighted sum of total travel times and total emissions of the traffic network.

Before the MC-MPEC model is shown, the notation used in this report is summarized.

$r$ : The origin

$s$ : The destination

$m$ : The vehicle class

$p$ : The path connecting origin $r$ and destination $s$

$a$ : The link

$f_{pm}^{rs}$ : The path flow on path p connecting origin $r$ and destination $s$ of class $m$

$e_{pm}^{rs}$ : The path emission on path p connecting origin $r$ and destination $s$ of class $m$

$C_{pm}^{rs}$ : The generalized path cost on path p connecting origin $r$ and destination $s$ of class $m$

$\pi_{pm}^{rs}$ : The minimal generalized path cost in the route choice on path p connecting origin $r$ and destination $s$ of class $m$

$d_{m}^{rs}$ : The demand between origin $r$ and destination $s$ of class $m$

$B$ : The minimal revenue requirement

$l_a$ : The length of link $a$

$e_a^m$ : The emission of link $a$ of class $m$

$\eta_{pm}^{rs}$ : The path travel time of class $m$

$\delta_{ap}^{rs}$ : The indicator function. If link $a$ belongs to path $p$, it is 1; otherwise, it is 0

$\theta$: The value of travel time

$t_a$: The link travel time

$\alpha_a^m$: The unit link mileage fee on link $a$ of class $m$

$\alpha_{\max}$: The upper bound of unit link mileage fee

$\alpha_a^{ff}$: The unit flat fee on link $a$

$\alpha_a^{sf}$: The unit stacked fee on link $a$

$\alpha_a^{mf}$: The unit multiplied fee on link $a$

The proposed MC-MPEC model can be shown as follows.

$$\min\ F(f)$$

$$\text{s. t.}\quad 0 \le f_{pm}^{rs} \perp \left[C_{pm}^{rs} - \pi_{pm}^{rs}\right] \ge 0 \tag{1}$$

$$\sum_p f_p^{rs} = d_m^{rs} \tag{2}$$

$$\sum_{rs}\sum_p\sum_a\sum_m f_{pm}^{rs}\delta_{ap}^{rs}\alpha_a^m l_a \ge B \tag{3}$$

$$0 \le \alpha_a^m \le \alpha_m^{\max} \tag{4}$$

$$C_{pm}^{rs} = \theta\eta_{pm}^{rs} + \sum_a \delta_{ap}^{rs}\alpha_a^m l_a = \theta\sum_a \delta_{ap}^{rs} t_a + \sum_a \delta_{ap}^{rs}\alpha_a^m l_a \tag{5}$$

$$e_{pm}^{rs} = \sum_{a\in p} e_a^m l_a \tag{6}$$

$F(f)$ is the objective function, which can be $\sum_{rs}\sum_p\sum_m f_{pm}^{rs}e_{pm}^{rs}$ to minimize the total emissions or $\sum_{rs}\sum_p\sum_m f_{pm}^{rs}\eta_{pm}^{rs} + \lambda\sum_{rs}\sum_p\sum_m f_{pm}^{rs}e_{pm}^{rs}$ to minimize the weighted sum of the total emissions and total travel times, where $\lambda$ is conversation factor from emissions to travel times. Here $\alpha_a^m$ can be the flat fee ($\alpha_a^{ff}$), stacked fee ($\alpha_a^{sf}$), or multiplied fee ($\alpha_a^{mf}$). Therefore the model (1) – (6) is general enough to capture the three MF polices in Section 2. In particular, (1) and (2) are the user equilibrium route choice and the demand conservation constraint; (3) is the minimal revenue requirement; (4) is the bound constraints of MF charges on each link; (5) is the generalized route travel cost, which is the weighted sum of route travel time and MF charges; and (6) is the path emission that is the sum of the emissions of all links comprising the path. Notice here that the upper bounds in (4) is class specific. This will allow one to set different upper bounds for different types of vehicles, thus leading to flexibility of MF charges. See the numerical section for more discussions about the practical implication of doing so.

The main motivation of MF is to raise proper revenue. In practice, if one only focuses on the revenue maximization (e.g., as the objective function), it may cause some issues (e.g., whether it is ethical to do so). A more practical method is to use the minimal revenue as a constraint, as shown in the constraint (3). Also in the practical implementation of MF, the flat fee charged on network links cannot be too large since they are normally for passenger cars, although higher fees may be charged for vehicles that are likely to generate more emissions or other externalities such as trucks. In this research, the upper bound of the charged fee for each vehicle class is imposed separately, as shown in constraint (4).

The MC-MPEC model (1) – (6) is a non-convex mathematical program and has a close relationship with the bilevel programming problem. It has wide applications in Stackelberg games, network design (transportation and communication networks), and robotics (Dempe, 2002). As a nonlinear programming problem, the standard Mangasarian–Fromovitz constraint qualification (MFCQ) is violated at any feasible points in the solution set of MPEC. Therefore, the standard solution algorithms for NLP cannot be used directly for the MEPC problem (Ye and Zhu, 1995). However, in practice, under some mild conditions (e.g., MPEC-MFCQ, Hoheisel et al., 2013) some state-of-the-art solvers may work well. In this report, the NLPEC solver in GAMS is used (Ferris, 2004). The basic solution idea is shown in Figure 2. It is a heuristic method and no convergence is guaranteed. The input to this solver is the upper bound of unit flat fee and the network information. The output of the solver is the equilibrium results and the unit flat fee on each link.

Another important feature of the model is that it is path based. It is well known that path flow can be non-unique for UE or network design problems (Ban et al., 2009; 2013). This has important effect in designing network wide policies, such as pricing and MF, as will be shown later in the numerical section.

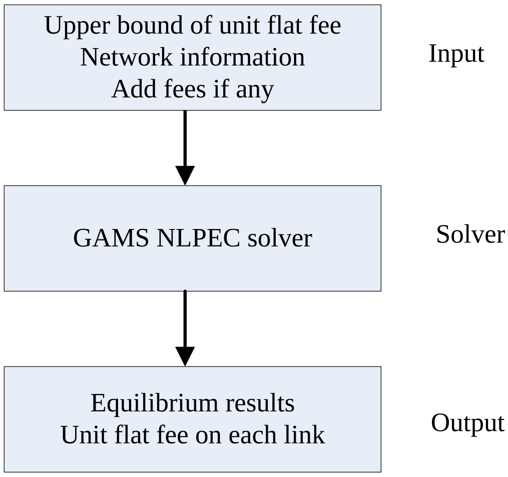


**Figure 2: The solution idea**

# 4 Numerical Results

The testing network is shown in Figure 3, in which different line types represent different road types. The dotted links belong to local roads, the dashed link belongs to freeway and the broken link belongs to a major arterial. The characteristics of the testing traffic network are shown in Table 2. The origin is node 1 and the destination is node 4. The demand between the origin and destination is 10. The link cost function used in this report follows the BPR function, which is written as follows. Here $t_a$ is link travel time, $t_o$ is link free flow time, and $v_a$ is link flow; all other parameters are shown in Table 2.

$$t_a = t_o * \left( 1 + B_a * \frac{v_a^{PWR}}{CAP_a} \right)$$

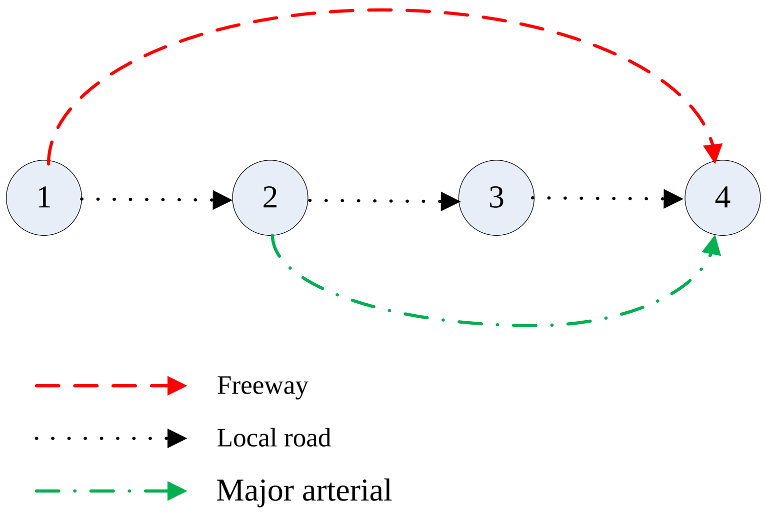


**Figure 3: The testing traffic network**

**Table 2: Testing network characteristics**

| Links | SN | EN | Len | FFT | B | PWR | CAP |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0.5 | 1 | 1 | 1 | 1 |
| 2 | 1 | 4 | 2.5 | 1 | 1 | 1 | 1 |
| 3 | 2 | 3 | 0.5 | 1 | 1 | 1 | 1 |
| 4 | 2 | 4 | 1.5 | 3 | 1 | 1 | 1 |
| 5 | 3 | 4 | 0.5 | 2 | 1 | 1 | 1 |

*Note*: SN denotes Starting Node; EN denotes Ending Node; Len denotes Length; FFT denotes Free Flow Time; B denotes Base parameter in the link cost function; PWR denotes Power parameter in the link cost function; CAP denotes

Capacity.

There are three paths connecting the origin and destination, and the link-path relationship is shown in Table 3.

**Table 3: Link-path relationship**

| Path number | Link sequence |
|---|---|
| 1 | 1→4 |
| 2 | 1→2→3→4 |
| 3 | 1→2→4 |

Section 4.1 focuses on the single-class vehicle case with flat fee. It consists of three subsections, which are called total emissions with flat fee, weighted sum of total emissions and travel times with flat fee, and the non-unique path flow issue. Section 4.2 focuses on the multi-class vehicle case. It consists of two subsections, which are called the basic multi-class test and the truck-route test.

## 4.1 Single-class vehicle with flat fee

The single-class scenario (i.e., $m=1$ in the MPEC model) with flat fee is tested first. Two objectives are used here: the total emissions, and the weighted sum of total travel times and total emissions. The model to minimize the total emissions serves as the benchmark for subsequent comparisons. The model to minimize the weighted sum of total travel times and total emissions is to show the tradeoff between the two different aspects, which can bring some important implications for the MF policy implementation. The value of travel time is 1, the emission rate is 0.1, and the minimal revenue is 70. All these parameters are the same in the following testing scenarios.

### 4.1.1 Total emissions with flat fee

Here the flat fee to minimize the total emissions is shown. Given different upper bounds on the unit flat fee, the resulting total emissions, path flows, and optimal fees are shown in Table 4. The evolution trend of the total emissions and the path flow patterns is shown in Figure 4. When the starting value of the max alpha is smaller than 3.1, the model becomes infeasible to satisfy the minimum revenue requirement. Thus, the starting value is 3.1 here and also in subsequent scenarios.

**Table 4: The resulted total emissions, path flows, and optimal fees for different flat fee upper bounds**

| MA | TE | FP1 | FP2 | FP3 | OF1 | OF2 | OF3 | OF4 | OF5 |
|---|---|---|---|---|---|---|---|---|---|
| 3.1 | 2.280 | 7.279 | 1.685 | 1.036 | 3.100 | 3.100 | 2.405 | 3.100 | 3.000 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 5.1 | 2.086 | 4.912 | 3.192 | 1.896 | 0.000 | 5.100 | 0.000 | 2.591 | 0.000 |
| 7.1 | 1.978 | 3.418 | 3.862 | 2.719 | 0.000 | 7.100 | 0.000 | 2.286 | 0.000 |
| 9.1 | 1.877 | 2.340 | 4.810 | 2.850 | 0.000 | 9.100 | 0.000 | 3.921 | 0.000 |
| 11.1 | 1.781 | 1.590 | 5.977 | 2.433 | 0.000 | 11.100 | 0.000 | 7.089 | 0.000 |
| 13.1 | 1.698 | 1.305 | 7.340 | 1.355 | 0.000 | 13.100 | 0.204 | 12.196 | 0.473 |
| 15.1 | 1.632 | 0.600 | 7.967 | 1.433 | 1.534 | 15.100 | 1.282 | 13.922 | 1.282 |
| 17.1 | 1.570 | 0.000 | 8.594 | 1.406 | 4.238 | 17.100 | 1.849 | 15.609 | 1.849 |
| 19.1 | 1.520 | 0.000 | 9.610 | 0.390 | 9.859 | 19.100 | 0.991 | 19.100 | 0.991 |
| *21.1* | *1.500* | *0.000* | *10.000* | *0.000* | *10.700* | *20.000* | *2.610* | *21.100* | *0.690* |
| *23.1* | *1.500* | *0.000* | *10.000* | *0.000* | *7.897* | *20.000* | *3.051* | *22.034* | *3.051* |
| *25.1* | *1.500* | *0.000* | *10.000* | *0.000* | *7.897* | *20.000* | *3.051* | *22.034* | *3.051* |

*Note*: MA denotes max alpha; TE denotes total emissions; FP1 denotes flow on path 1; FP2 denotes flow on path 2; FP3 denotes flow on path 3; OF1 denotes optimal fee on link 1; OF2 denotes optimal fee on link 2; OF3 denotes optimal fee on link 3; OF4 denotes optimal fee on link 4; OF5 denotes optimal fee on link 5.

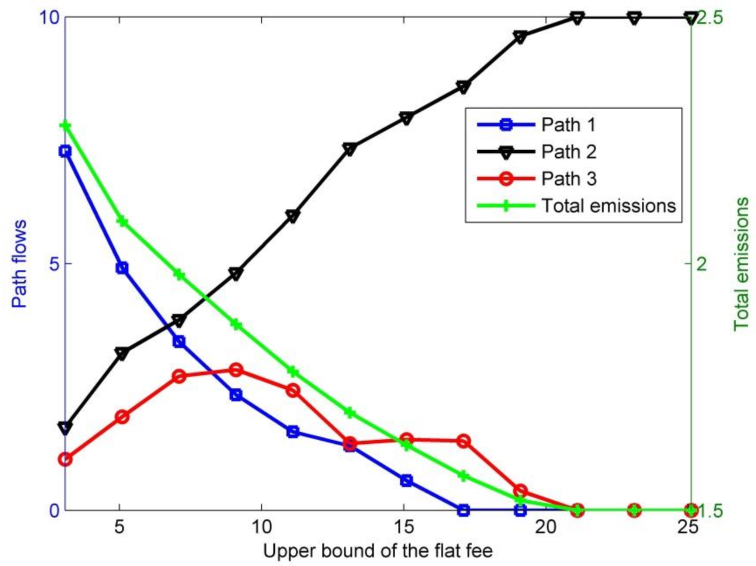


**Figure 4: The evolution trend of total emissions and path flow patterns with different flat fee upper bounds**

From the results, it can be found that with the increase of the upper bounds for the flat fee, the total network emission is reduced and is finally stabilized when the upper bound is increased to about 22. The similar trend appears in the change of path flows. With the increase of the upper bounds for the flat fee, the path flow first shifts from path 1 to path 2 and path 3, then shifts to path 2 in our case, and is finally stabilized. The reason why all the flow shifts to path 2 is that the length of path 2 is the shortest and drivers may be charged the smallest fee.

### 4.1.2 Weighted sum of total emissions and travel times with flat fee

Here the objective is to minimize the weighted sum of total emissions and total travel times. With this scenario, the Pareto effect of the two objectives is shown. The weighting parameter $\lambda$ is set to be 1.5. Given different upper bounds on the unit flat fee, the objective, path flows, and optimal fees are shown in Table 5. The evolution trends of total travel times and total emissions, and the path flow patterns are shown in Figure 5. Figure 6 shows the Pareto effect of the two objectives.

**Table 5: The resulted weighted sum of total travel times and total emissions, path flows, and optimal fees for different flat fee upper bounds**

| MA | WS | FP1 | FP2 | FP3 | OF1 | OF2 | OF3 | OF4 | OF5 |
|---|---|---|---|---|---|---|---|---|---|
| 3.1 | 93.274 | 7.294 | 1.543 | 1.163 | 3.100 | 3.076 | 3.100 | 2.825 | 3.100 |
| 3.3 | 93.070 | 7.364 | 1.459 | 1.177 | 3.300 | 3.040 | 3.300 | 2.763 | 3.300 |
| 3.5 | 92.931 | 7.432 | 1.377 | 1.191 | 3.500 | 3.006 | 3.500 | 2.704 | 3.500 |
| 3.7 | 92.853 | 7.499 | 1.296 | 1.205 | 3.700 | 2.976 | 3.700 | 2.649 | 3.700 |
| *3.9* | *92.833* | *7.555* | *1.229* | *1.216* | *3.900* | *2.952* | *3.855* | *2.595* | *3.855* |
| *4.1* | *92.833* | *7.555* | *1.229* | *1.216* | *4.100* | *2.952* | *3.755* | *2.529* | *3.755* |
| *4.3* | *92.833* | *7.555* | *1.229* | *1.216* | *4.300* | *2.952* | *3.655* | *2.462* | *3.655* |
| *4.5* | *92.833* | *7.555* | *1.229* | *1.216* | *4.499* | *2.954* | *3.561* | *2.399* | *3.561* |
| *4.7* | *92.833* | *7.555* | *1.229* | *1.216* | *3.890* | *2.952* | *3.861* | *2.599* | *3.861* |
| *4.9* | *92.833* | *7.555* | *1.229* | *1.216* | *4.091* | *2.952* | *3.760* | *2.532* | *3.760* |
| *5.1* | *92.833* | *7.555* | *1.229* | *1.216* | *3.435* | *2.952* | *3.076* | *2.750* | *5.100* |

*Note*: MA denotes max alpha; WS denotes weighted sum; FP1 denotes flow on path 1; FP2 denotes flow on path 2; FP3 denotes flow on path 3; OF1 denotes optimal fee on link 1; OF2 denotes optimal fee on link 2; OF3 denotes optimal fee on link 3; OF4 denotes optimal fee on link 4; OF5 denotes optimal fee on link 5.

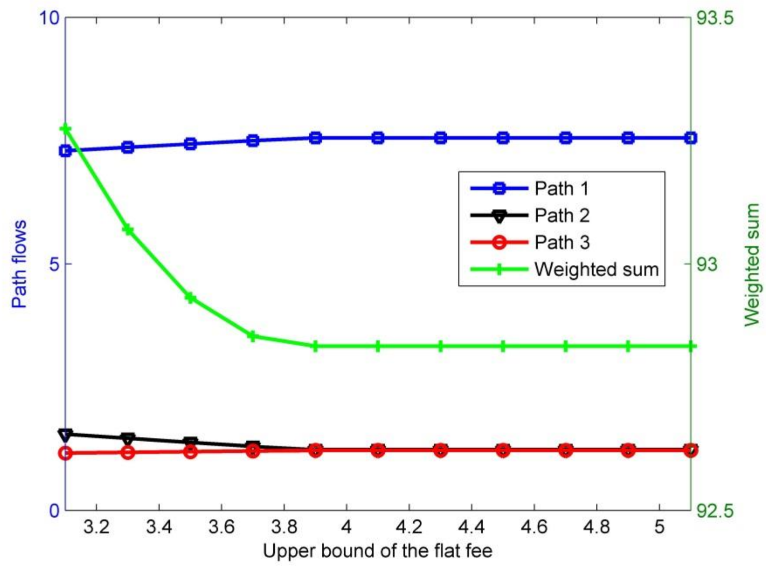

**Figure 5: The evolution trends of the objective and path flow patterns with different flat fee upper bounds**

From the table and the figures, it can be found that with the increase of upper bounds for the flat fee, the evolution of the weighted sum of emissions and travel times shows the similar trend to the evolution of total emissions in Subsection 4.1.1. That is to say, the weighted sum is reduced and is finally stabilized with the increase of the upper bound of flat fee (when the upper bound is around 4). The similar trends appear in the changes of path flows. With the increase of the upper bounds for the flat fee, the path flow shifts from path 2 to path 1 and path 3 and is finally stabilized. Also notice that when it is stabilized (upper bound larger than 4), the objective and path flows do not change with the upper bound. However, the optimal link fees may vary. This indicates that the optimal solution of MF charges (i.e., variable $\alpha$) in the MF model (1) – (6) is not unique. That is, in order to achieve the minimal objective (with the same flow pattern), there are multiple fee charging possibilities on network links (e.g., the rows shown in italic in Table 5).

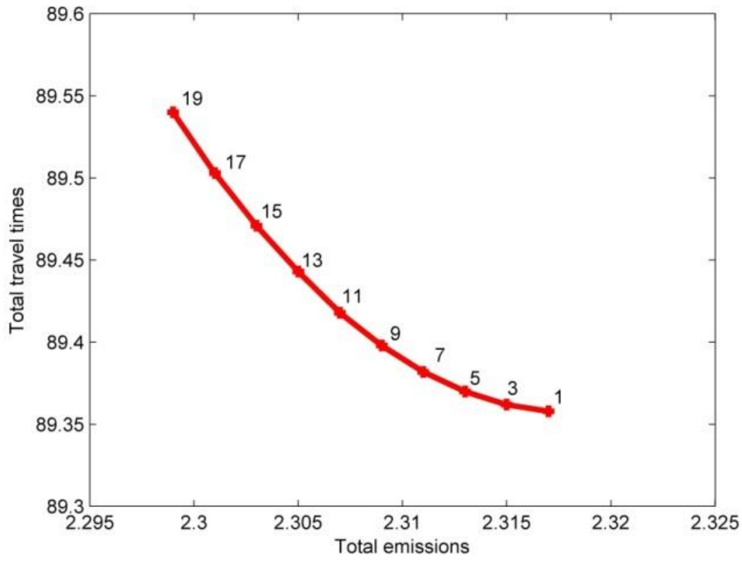


**Figure 6: Pareto effect of the two objectives**[1]

In Figure 6, the upper bound of unit flat fee is 5 and the range of the weighting parameter $\lambda$ changes from 1 to 19. From Figure 5 and Figure 6, it can be found that there is a clear tradeoff between the total travel times and total emissions when seeking optimal fee charges via solving the model (1)

[1] The numbers along the curve are values for the testing $\lambda$ s.

– (6). In practice, this implies that a proper selection of the weighting parameter $\lambda$ is crucial to the obtained mileage fee charges on links and the overall performance of the system.

### 4.1.3 Non-unique path flow issue

Here some empirical proof of the non-uniqueness of the path flows is given, which is also an intrinsic issue in other path-based formulations. If larger bounds on the flat fee are set and change the initial solution for the model in subsection 4.1.2, some interesting results will appear as shown in Figure 7. As expected, the weighted sum of total emissions and travel times should give a stabilized trend. However, when a different upper bound is set (e.g., 7.1 in Figure 7) for the flat fee with different initial solutions in the NLPEC solver, the resulting objective may not be the same. Similar observations can also be found in the path flow patterns and the optimal fees charged on links. Here, only the change of the flow on path 1 (the freeway) and the optimal fee on link 1->4 (i.e., also path 1) is shown. Similar patterns can be found on other paths and links. This is caused by the non-uniqueness issue of the path flow, which is well-known for path-based traffic network models. Note that the UE condition is satisfied for any of the obtained solutions. For example, if the UE condition on path 3 with upper bound being 7.1 is checked, it can be found that the flow is zero, while the difference between the cost of path 3 and the minimum path cost is 1.214. Therefore, the complementarity condition in (1) is satisfied, i.e., indicating that the UE condition is satisfied.

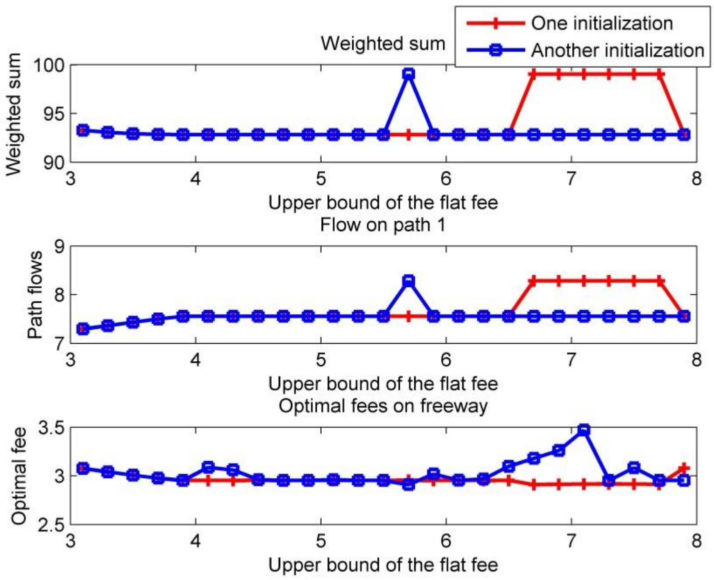


**Figure 7: Non-uniqueness of objective, path flow and optimal fee**

The non-uniqueness of the path flow may cause some significant issues in the MF charging. Using the results in Figure 7 as an example, if the network manager wants to reduce the weighted sum of total emissions and total travel times of the network, she may likely to have the blue dotted line in her mind and thus set the upper bound to 7.1. However, when the model is implemented in practice, the upper bound 7.1 may in fact produce the red line with plus signs, which will dramatically worsen the desired objective. This issue brings difficulty for decision makers to design viable policies (in this case, the upper bound of MF and the resulting optimal fee charges on links). More discussions of such non-uniqueness issues and how to deal with them in pricing scheme design can be found in Ban et al. (2009) and Ban et al. (2013).

## 4.2 Multi-class vehicle test with different MF policies

### 4.2.1 Basic multi-class test

In this subsection, the multi-class scenario with the objective to minimize the total network emissions is tested to demonstrate Remark 1 in Section 2. The stacked fee which is tested here is the Green VMT Fee in Zhang et al. (2011), which internalized vehicle fuel efficiency. The additional fee for the stacked fee is 1.38 and the multiplier for the multiplied fee is 2. The number of classes is 2 (i.e., cars and trucks). The demand for class 1 is 7 and the demand for class 2 is 3. The Passenger car equivalent (PCU) for the truck used in this report is 2. In the following test, the upper bound for the car is 11.1 and the upper bound for the truck is 25.1, which is believed to show some practical sense (truck causes more external influences).

(1) The flat fee

In this testing scenario, both cars and trucks are charged with the flat fee, i.e., no extra charges are imposed to trucks. This serves as a base scenario to compare with other scenarios. Given different upper bounds on the unit flat fee, the resulted total emissions, and path flows are shown in Table 6. The evolution trends of total emissions and the path flows are shown in Figure 8.

**Table 6: The total emissions and path flows for different flat fee upper bounds[2] (flat fee scenario)**

[2] Here, values of max alpha are upper bounds for unit flat fee of both car and truck if its value is less than or equal to 11.1. However, for the values being greater than 11.1, it is the upper bound for trucks only and the upper bound for cars remains to be 11.1. The upper bounds of trucks can be larger than that of cars is due to the more external effect of trucks (e.g., the pollution).

| Max alpha | Total emissions | Flow on path 1 for class 1 | Flow on path 1 for class 2 | Flow on path 2 for class 1 | Flow on path 2 for class 2 | Flow on path 3 for class 1 | Flow on path 3 for class 2 |
|---|---|---|---|---|---|---|---|
| 3.1 | 2.280 | 5.100 | 2.179 | 0.932 | 0.753 | 0.968 | 0.068 |
| 5.1 | 2.086 | 4.239 | 0.673 | 0.932 | 2.259 | 1.828 | 0.068 |
| 7.1 | 1.978 | 3.418 | 0.000 | 0.930 | 2.932 | 2.652 | 0.068 |
| 9.1 | 1.877 | 2.340 | 0.000 | 1.878 | 2.932 | 2.782 | 0.068 |
| 11.1 | 1.781 | 1.590 | 0.000 | 2.977 | 3.000 | 2.433 | 0.000 |
| 13.1 | 1.773 | 1.128 | 0.000 | 2.669 | 3.000 | 3.203 | 0.000 |
| 15.1 | 1.767 | 0.771 | 0.000 | 2.431 | 3.000 | 3.798 | 0.000 |
| 17.1 | 1.762 | 0.469 | 0.000 | 2.230 | 3.000 | 4.301 | 0.000 |
| 19.1 | 1.758 | 0.203 | 0.000 | 2.052 | 3.000 | 4.745 | 0.000 |
| *21.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *23.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *25.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |

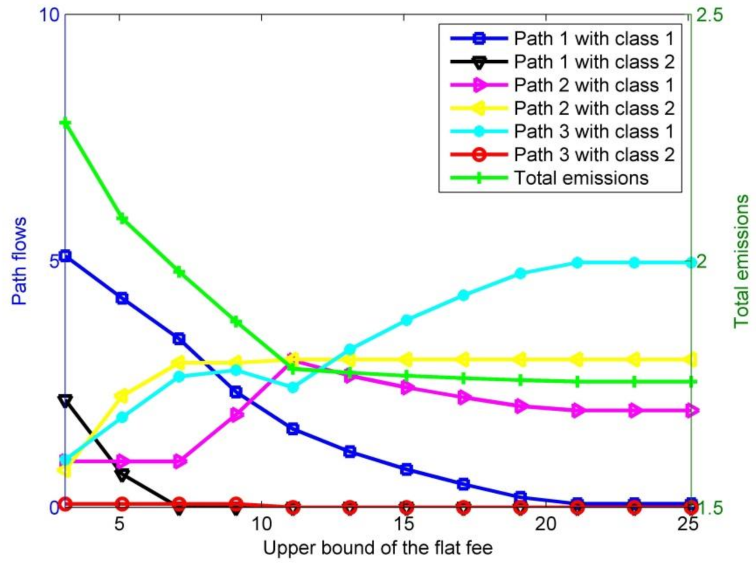


**Figure 8: Changes of total emissions and path flow patterns with different flat fee upper bounds**

(2) The stacked fee

The stacked fee is only charged on trucks, while cars are still charged with the flat fee. Given different upper bounds on the unit flat fee, the resulting total emissions and path flows are shown in Table 7. The changes of total emissions and the path flows are shown in Figure 9.

**Table 7: The total emissions and path flows for different flat fee upper bounds (stacked fee scenario)**

| Max alpha | Total emissions | Flow on path 1 for class 1 | Flow on path 1 for class 2 | Flow on path 2 for class 1 | Flow on path 2 for class 2 | Flow on path 3 for class 1 | Flow on path 3 for class 2 |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3.1 | 2.218 | 6.727 | 0.000 | 0.273 | 2.102 | 0.000 | 0.898 |
| 5.1 | 2.079 | 4.489 | 0.000 | 1.295 | 1.615 | 1.216 | 1.385 |
| 7.1 | 1.973 | 3.119 | 0.000 | 2.048 | 1.615 | 1.833 | 1.385 |
| 9.1 | 1.872 | 2.055 | 0.000 | 3.005 | 1.615 | 1.941 | 1.385 |
| 11.1 | 1.775 | 1.256 | 0.000 | 4.139 | 1.615 | 1.605 | 1.385 |
| 13.1 | 1.769 | 0.875 | 0.000 | 3.885 | 1.615 | 2.241 | 1.385 |
| 15.1 | 1.763 | 0.558 | 0.000 | 3.674 | 1.615 | 2.768 | 1.385 |
| 17.1 | 1.759 | 0.282 | 0.000 | 3.490 | 1.615 | 3.228 | 1.385 |
| *19.1* | *1.755* | *0.071* | *0.000* | *3.349* | *1.615* | *3.579* | *1.385* |
| *21.1* | *1.755* | *0.071* | *0.000* | *3.349* | *1.615* | *3.579* | *1.385* |
| *23.1* | *1.755* | *0.071* | *0.000* | *3.349* | *1.615* | *3.579* | *1.385* |
| *25.1* | *1.755* | *0.071* | *0.000* | *3.349* | *1.615* | *3.579* | *1.385* |

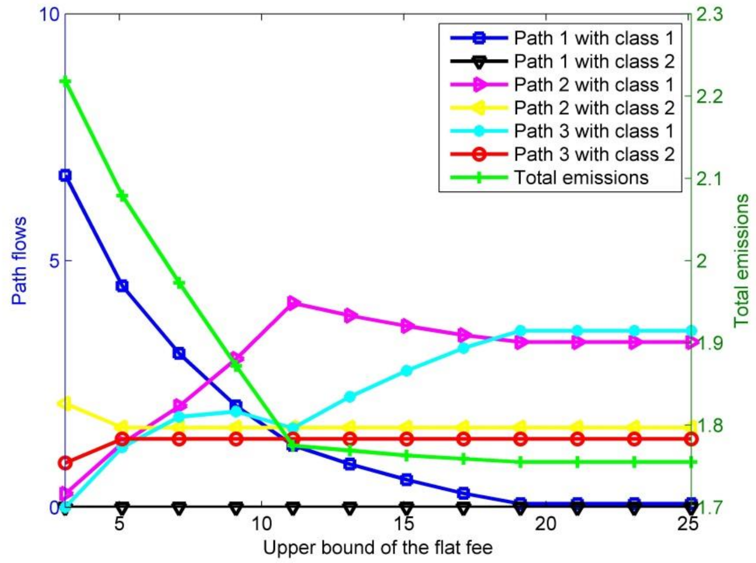


**Figure 9: Changes of total emissions and path flow patterns with different flat fee upper bounds**

(3) The multiplied fee

The multiplied fee is also charged on trucks only. Given different upper bounds of the unit flat fee, the resulting total emissions and path flows are shown in Table 8. The changes of total emissions and the path flows are shown in Figure 10.

**Table 8: The total emissions and path flows for different flat fee upper bounds (multiplied fee scenario)**

| Max alpha | Total emissions | Flow on path 1 for class 1 | Flow on path 1 for class 2 | Flow on path 2 for class 1 | Flow on path 2 for class 2 | Flow on path 3 for class 1 | Flow on path 3 for class 2 |
|---|---|---|---|---|---|---|---|
| 3.1 | 2.113 | 5.250 | 0.000 | 0.000 | 3.000 | 1.750 | 0.000 |
| 5.1 | 2.063 | 4.250 | 0.000 | 0.000 | 3.000 | 2.750 | 0.000 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7.1 | 1.970 | 2.929 | 0.000 | 0.536 | 3.000 | 3.536 | 0.000 |
| 9.1 | 1.862 | 1.500 | 0.000 | 1.250 | 3.000 | 4.250 | 0.000 |
| *11.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *13.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *15.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *17.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *19.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *21.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *23.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |
| *25.1* | *1.755* | *0.071* | *0.000* | *1.964* | *3.000* | *4.964* | *0.000* |

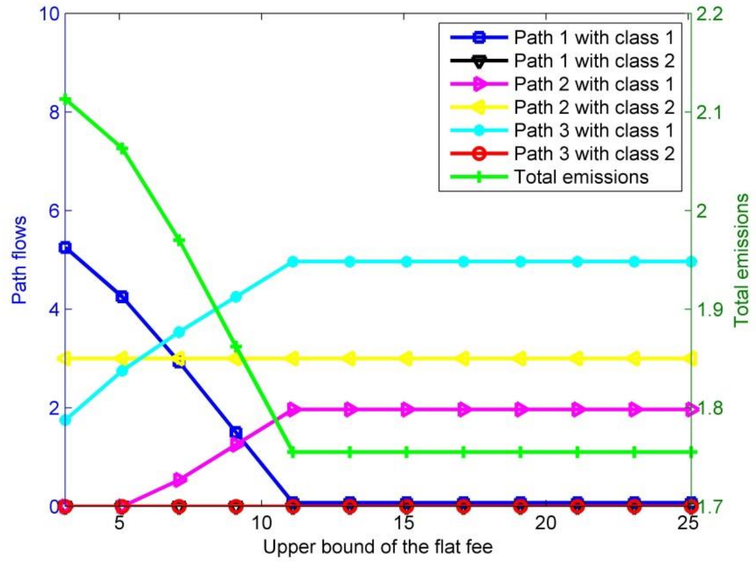


**Figure 10: Changes of total emissions and path flow patterns with different flat fee upper bounds**

From the results, it can be found that with the increase of the upper bounds for the flat fee, the total network emission is reduced and is finally stabilized. The similar trends appear in the changes of path flows. With the increase of the upper bounds for the flat fee, the path flow shifts from path 1 to path 2 and path 3 and is stabilized finally. The length of path 1 is the longest and flows on path 1 will be charged more fees with the increase of the upper bounds, which leads to the flow shift as shown here. If the total emissions in Figure 8, Figure 9 and Figure 10 are compared, it can be found that the stabilized values are the same. However, the path flow patterns are different for the three scenarios. This demonstrates Remark 1 in Section 2. From Figure 8, Figure 9 and Figure 10, it can be found that upper bounds need to be large enough to obtain the optimal emission objective when solving the MF model in this research. The corresponding upper bound is about 22 for the flat fee policy, 19 for the stacked fee policy, and 11 for the multiplied fee policy. In this sense, the basic flat fee policy may have two issues for implementation in practice. First, it does not distinguish among different vehicles, which may not be fair to some vehicles such as cars: cars consume less fuel and produce fewer emissions, but are charged with the same flat fee with trucks). Stacked or multiplied fees can address this issue directly by charging different fees based on vehicle types and characteristics. Secondly, to achieve the optimal performance, a higher upper bound and thus fees may be charged under the flat fee policy (for all vehicle classes), while for stacked or multiplied fee polies, the upper bound the optimal (flat) fees can be much smaller. This will make it harder for the public (who probably concerns more about the flat fee charges) to accept the flat fee policy, compared with the stacked or multiplied fee policies. It also implies that different MF policies have important effect to their implementation in practice.

### 4.2.2 Truck-route test

In this subsection, a more realistic scenario is tested. The combination of car flow and truck flow to minimize the total emissions is considered here. A restriction is added so that the truck flow can only travel on the freeway. With this scenario, some truck routes in practice can be modeled. In the test, only the flat fee is applied and other tests (on the stacked fee and multiplied fee) can be done similarly as in Subsection 4.2.1. The car flow demand is 7 and the truck flow demand is 3.

Given different upper bounds on the unit flat fee, the resulted total emission and path flow patterns are shown in Table 9. The evolution trend of total emission and path flows is shown in Figure 11.

**Table 9: The resulted total emission and path flow patterns for different flat fee upper bounds**

| Max alpha | Total emissions | Flow on path 1 | Flow on path 2 | Flow on path 3 |
|---|---|---|---|---|
| 3.1 | 2.280 | 7.279 | 1.685 | 1.036 |
| 5.1 | 2.086 | 4.912 | 3.192 | 1.896 |
| 7.1 | 1.978 | 3.418 | 3.862 | 2.719 |
| 9.1 | 1.888 | 3.000 | 5.250 | 1.750 |
| *11.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *13.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *15.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *17.1* | *1.836* | *3.000* | *6.275* | *0.725* |

| | | | | |
|---|---|---|---|---|
| *19.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *21.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *23.1* | *1.836* | *3.000* | *6.275* | *0.725* |
| *25.1* | *1.836* | *3.000* | *6.275* | *0.725* |

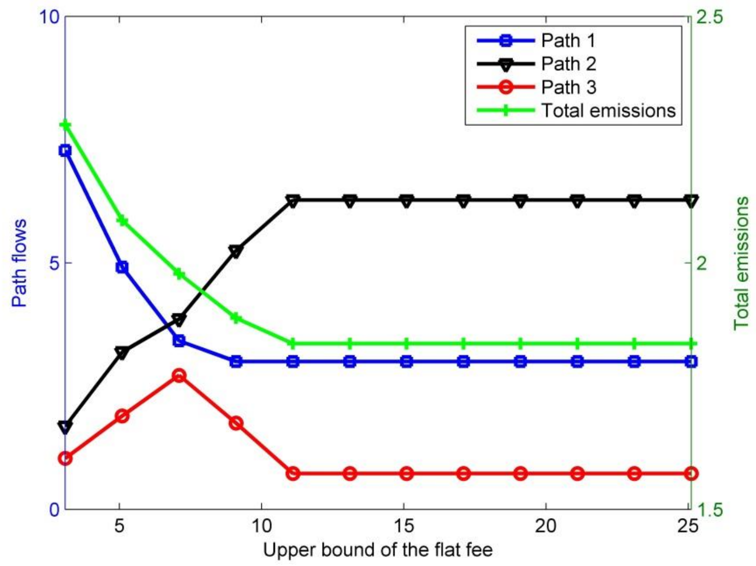


**Figure 11: The evolution trend of total emissions and path flow patterns with different flat fee upper bounds**

From the results, it can be found that with the increase of upper bounds for the flat fee, the total network emission is reduced and is finally stabilized, which is similar to the single-class scenario. The similar trends appear in the change of car flows on different paths. With the increase of the upper bounds for the flat fee, the car flow shifts from path 1 to path 2 and path 3 at beginning; finally, all the car flow travel on path 2. As shown before, this is because the length of path 2 is the shortest and less fees will be charged for the flow on this path. Comparing the base model in Figure 8 and the results in Figure 11, it can be found that if the truck flow is restricted on path 1, the total emission is larger. However, the charged flat fee is smaller. That is to say, the restriction of truck flow can have some important effect on the path flow pattern and the overall performance of the network (e.g., the total network emissions).

# 5 Conclusions and Major Findings

In this project, the network system effect of mileage fee (MF) policies was investigated, focusing on three policies that are commonly used: flat fees, stacked fees, and multiplied fees. First a multi-class mathematical program with equilibrium constraint (MC-MPEC) was proposed to capture the optimal MF charging problem from a network perspective. The MC-MPEC problem on two illustrative networks was tested and solved to show the network effect of MF policies. Two important implications for the practical implementations arising from the investigation are to model (i) the target revenue as a constraint, and (ii) the upper bound of the unit flat fee. The model is general, which can capture three fee polices and model different objectives commonly used for MF. The NLPEC solver in GAMS was used to solve the MC-MPEC model. Different scenarios using two hypothetical traffic networks were tested.

From the results, it can be found that the three different fee policies are mathematically the same. If the upper bound of the flat fee is too large, one may consider the stacked fee or multiplied fee, which makes the MF policies easier to be accepted by the public and easier to be implemented. One important issue when studying the network effect of MF is the non-uniqueness of the path flows. It has important implications to MF policy design and implementation, which needs to be carefully investigated. The results also show that the existence of truck routes can have important effect on the resulting path flow pattern and the overall network system performance. This may bring some important implications for the fee implementation in practice.

In practice, MF policies are determined by many factors and how to capture these factors in a unified function should be further studies in future research. In this research, only the two-class model is tested. Testing/validation of the proposed models and methods on more vehicles classes needs further research. The MF problem on larger, real world networks is also deserved to be investigated in the future. Moreover, the theoretical analysis of the non-uniqueness path flow problem is interesting and merits further investigations.

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Region 2 - University Transportation
Research Center
The City College of New York
Marshak Hall, Suite 910
160 Convent Avenue
New York, NY 10031
Tel: (212) 650-8050
Fax: (212) 650-8374
Website: www.utrc2.org