USING EMISSION FUNCTIONS IN MATHEMATICAL PROGRAMMING MODELS FOR SUSTAINABLE URBAN TRANSPORTATION: AN APPLICATION IN BILEVEL OPTIMIZATION

by

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to my family

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Abstract

Sustainability is an emerging issue as a direct consequence of the population increase in the world. Urban transport systems play a crucial role in maintaining sustainability. Recently, sustainable urban transportation has become a major research area. Most of these studies propose evaluation methods that use simulation tools to assess the sustainability of different transportation policies. Despite all studies, there seems to be lack of mathematical programming models to determine the optimal policies. Conventional mathematical programming techniques have been used in several transportation problems such as toll pricing and traffic assignment problems. To demonstrate the possible applications of mathematical programming within sustainability, we propose a bi-level structure for several optimization models that incorporate the measurement of gas emissions throughout a traffic network. The upper level of the problem represents the decisions of transportation managers who aim to make the transport systems sustainable, whereas the lower level problem represents the decisions of the network users that are assumed to choose their routes to minimize their total travel cost. By using emission factor tables provided by several institutions, we determine the emission functions in terms of traffic flow to reflect the real emission values in case of congestion. Proposed emission functions are plugged into different proposed mathematical programming models that incorporate different policies or actions for sustainability. Among the incorporated policies are toll pricing, district pricing and capacity enhancement. We conduct a thorough computational study with the proposed models on a testing network by a state-of-the-art solver. The thesis ends with a thorough discussion of the solution effort as well as the interpretation of the results.

SÜRDÜRÜLEBİLİR KENTSEL ULAŞIM İÇİN MATEMATİKSEL PROGRAMLAMA MODELLERİNDE EMİSYON FONKSİYONLARININ KULLANILMASI: İKİ SEVİYELİ ENİYİLEMEDE BİR UYGULAMA

Ahmet Esat Hızır

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Anahtar sözcükler: Sürdürülebilirlik, kentsel ulaşım, iki seviyeli programlama, emisyon fonksiyonları, gişe optimizasyon modelleri

Özet

Sürdürülebilirlik son yıllarda dünya nüfusunun artmasının doğal bir sonucu olarak önemli bir konu haline geldi. Kentsel ulaşım sistemleri sürdürülebilirliğin devam ettirilmesinde önemli bir rol oynamaktadır. Son zamanlarda ise sürdürülebilir kentsel ulaşım önemli bir araştırma konusu olmuştur. Yapılan çalışmaların birçoğu değişik ulaşım politikalarının sürdürülebilirliğini değerlendirmek için benzetim araçlarını kullanan değerlendirme metodları önermektedir. Tüm yapılan araştırmalara rağmen optimum politikaların belirlenmesine yönelik matematiksel programlama modellerinin eksikliği görülmektedir. Geleneksel matematiksel programlama teknikleri gişe ücretlendirme ve trafik atama problemleri gibi bir çok ulaşım probleminde kullanılagelmiştir. Bu çalışmada matematiksel programlamanın sürdürülebilirlik olgusu içerisindeki olası uygulamalarını göstermek için, çeşitli optimizasyon modellerinin trafik ağı üzerindeki gaz emisyon ölçümlerini hesaba katan iki seviyeli bir yapı önerilmektedir. Üst seviye problem ulaşım sistemini sürdürülebilirliğini hedefleyen ulaşım ağı yöneticilerinin kararlarını temsil ederken, alt seviye problem kullanıcıların yol kararlarını verirken toplam ulaşım giderlerini en aza indirmek istedikleri varsayımına dayanmaktadır. Trafik tıkanıklığı durumlarında oluşan gerçek emisyon değerlerinin daha iyi yansıtılması için, emisyon fonksiyonları, emisyon faktör tabloları kullanılarak, trafik akışına bağlı olarak belirlenmiştir. Ayrıca önerilen emisyon fonksiyonları farklı sürdürülebilirlik politika ve uygulamalarını içeren matematiksel programlama modelleri içinde kullanılmıştır. Bu politikalardan bir kaçı gişe ücretlendirme, bölge ücretlendirme ve kapasite genişletme uygulamalarıdır. Önerilen modellerin örnek bir ağ üzerinde uygulanmasını içeren geniş kapsamlı bir sayısal çalışma gerçekleştirilmiştir. Son olarak çözüm sürecinin detaylı bir analizi ile sonuçların yorumu yapılmıştır.

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CHAPTER 1

INTRODUCTION

In the last few decades with the advances in technology, changes in the needs of societies and life style, and especially with the considerable increase in urban population, sustainable development issues have raised significant interest among scientific communities. Sustainable development can be defined as “the concept of meeting the needs of the present without compromising the ability of future generations to meet their needs [32].”

Having many potential negative externalities like congestion, high energy consumption and air pollution, urban transport systems play a very crucial role in maintaining sustainability. Defined as “the transportation that meets mobility needs while also preserving and enhancing human and ecosystem health, economic progress and social justice now and in the future [9],” sustainable urban transportation has become a major research area.

There are several issues in sustainable transportation that should be taken into account, and these can be divided into three categories: economic, social and environmental issues [19]. The first, economic issues involve business activity, employment and productivity. Some of the social issues are equity, human health, and public involvement. Environmental issues consist of pollution prevention, climate protection and habitat preservation. Sustainability planning does not always require trade offs between economical, social and environmental objectives; rather, strategies that achieve all the objectives should be used.

As a major research area, sustainable urban transportation has become the subject of many studies. In these studies, traffic congestion (economic impact) and air pollution (environmental impact) of transportation systems, are always in the center of attention. Therefore, the main goal of these studies is to alleviate congestion and transport emissions through use of different methods and policies. Most of the studies involve simulation tools to evaluate the sustainability of different transportation policies. TREMOVE is an evaluation tool which is developed to support the European policy making process concerning emission standards for vehicles and fuel specifications. It is an integrated simulation model to study the effects of different transport and environment policies on the emissions of the transport sector.

There are also studies that exploit mathematical programming instruments. Some studies use a general optimization model with emission factors per vehicle kilometer. A collection of analytical tools, such as spatial statistics and travel preference functions, which can be used in assessing or maintaining sustainability, are proposed. Nagurney introduces the term, emission pricing, which is defined as the toll price setting to satisfy predetermined emission levels. Nagurney also provides sustainable urban transportation models with basic emission factors and emission constraints [21]. In these and similar studies, average emission factors are used for the sake of computational simplicity. However this approach prevents models from including real emission amounts and, hence, the resulting obesrvations do not reflect the actual effects of traffic flow on the emission amounts.

1.1 Contributions of this Research

Despite the number of studies in the literature, there seems to be a lack of optimization models for sustainability for transportation networks. This study is an investigation of using mathematical programming tools in sustainable urban transportation.

To build a model for this purpose an understanding of the real nature of transportation systems is required. In this study, we first determine the basic requirements of an optimization model for sustainability in transportation networks. In a transportation network, traffic flow on each arc plays a crucial role in the decision making process. Therefore, from a sustainability point of view, the relationship between traffic flows and emission amounts should be studied. We introduce emission functions in terms of traffic flow that can be used in mathematical programming models.

We also discuss several techniques and models that incorporate the determined emission functions. The proposed models exploit various policies, some of which are toll pricing, capacity enhancement and district pricing. To analyze different policies, we conduct computational experiments which demonstrate that mathematical programming models constitute important tools besides the simulation and evaluation tools. After introducing these emission functions, we observe that the proposed models' solutions (optimal policies) give realistic emission values.

1.2 Outline

This thesis is organized as follows: Chapter 2 includes an extensive literature survey for quantitative and mathematical approaches to sustainable transportation. The concepts of bilevel programming and toll pricing that establish the basis of this study are also described. Starting with determination of emission functions, Chapter 3 consists of the proposed mathematical programming models as well as the necessary explanations. Computational results and analysis are provided in Chapter 4. Finally, we conclude the thesis and give some possible ideas for future research in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

Being a fast developing research area, sustainability has become the subject of many recent studies in the literature. Sustainable transportation, which has a crucial role for maintaining sustainability, has also been a popular topic. Among the concepts studied are evaluation and simulation tools to assess sustainability of transportation systems, and quantitative approaches to sustainable transportation. There are also studies that exploit mathematical programming tools. We review, in this chapter, this recent body of work related to sustainable urban transportation.

2.1 Sustainable Transportation

Sustainable transportation is defined as "the transportation that meets mobility needs while also preserving and enhancing human and ecosystem health, economic progress and social justice now and in the future [9]." The transportation system should be affordable, operate efficiently and offer choice of transport mode.

Sustainability has three components: environment, society, and economy. The relationship between these components is depicted in the Figure 2.1 [27]. Environment can be defined as the surroundings of human beings that support and limit their activity according to basic physical laws. Society consists of human interactions and how they are organized. Economy describes available resources and how the resources are organized to meet human needs and goals. Sustainable transportation can be defined with respect to these three dimensions of sustainability [27].

With respect to society, transportation systems should:

- meet basic human needs for health, comfort, and convenience without affecting social life;
- allow and support development, and provide for a reasonable choice of transport modes;

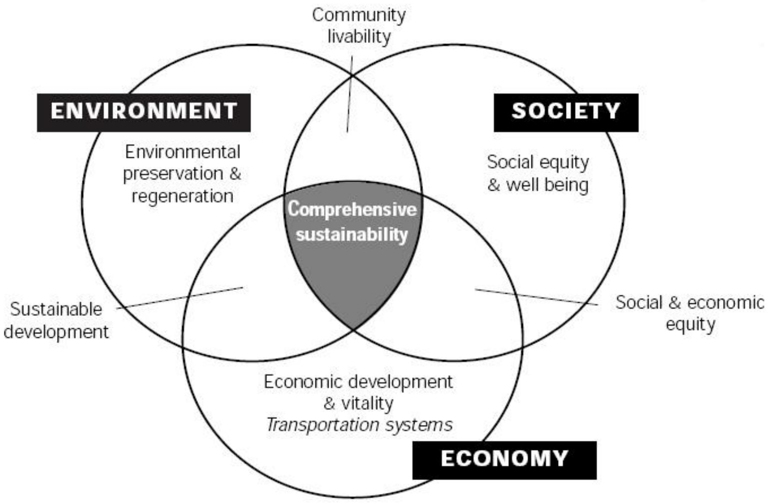


Figure 2.1: Components of sustainability

- produce no more noise than is acceptable by communities;
- be safe for people and their property.

With respect to economy, transportation systems should:

- provide cost-effective service and capacity;
- be financially affordable in each generation;
- support sustainable economic activity.

With respect to environment, transportation systems should:

- make use of land with little impact on the integrity of ecosystems;
- use renewable or inexhaustible energy sources;
- produce no more emissions and waste than can be accommodated by the earths restorative ability.

There are several issues in sustainable transportation that should be taken into account. They can be divided into three categories [19]. Table 2.1 summarizes the sustainability issues by category. Sustainability planning does not always require trade-offs between economical, social and environmental objectives. Strategies that achieve all the objectives should be used [28].

Economic	Social	Environmental
Productivity	Human health	Pollution emission
Business activity	Community livability	Climate change
Employment	Cultural values	Habitat preservations
Tax burden	Public involvement	Aesthetics

Table 2.1: Sustainable transportation issues

During the planning period of strategies for sustainable urban transportation, there are some possible obstacles that have significant effect. Uncertainties about the environmental problems make it difficult to clarify the need of change. Technological changes contribute significantly to sustainability actions but there is no guarantee that within a certain time a technological advance will emerge. Public opinion and support for action are crucial in that any policy that is not supported by the public cannot be applied, even though it is the most effective one Therefore any strategy that does not take the aforementioned issues into account cannot be successful.

The impacts of transportation facilities and activities can also be analyzed in three categories. Table 2.2 summarizes the impacts of sustainable transportation, according to these categories. These impacts should be quantified by sustainability indicators for evaluation studies.

Economic	Social	Environmental
Traffic congestion	Social equity	Air and water pollution
Mobility barriers	Impacts on mobility disadvantaged	Climate change
Accident damages	Human health impacts	Noise impacts
Facility costs	Community cohesion	Habitat loss
Consumer costs	Community livability	Hydrologic impacts

Table 2.2: Sustainable transportation impacts

2.1.1 Sustainability Indicators

We use indicators to evaluate progress toward objectives. To provide useful information and to measure the objectives effectively, indicators must be carefully selected. For sustainable urban transportation, all the related impacts should be taken into account. In the literature sustainability of transportation systems is evaluated using a set of measurable indicators. There are several kinds of indicators. Conventional transport indicators like roadway level of service, average traffic speeds consider motor vehicle conditions. Simple sustainability indicators such as transportation fossil fuel consumption, vehicle pollution emissions, per capita motor vehicle usage rely on relatively available data. Because of the simplicity they may fail to provide effectiveness. Comprehensive sustainability indicators take into account a wide range of impacts reflecting all objectives. Like the impacts, sustainability indicators can also be divided into three categories. Table 2.3 summarizes a wide range of economic, social and environmental indicators.

Economic	Social	Environmental
Commute time	User rating	Climate change emissions
Employment accessibility	Safety	Air pollution
Land use mix	Community livability	Noise pollution
Electronic communication	Cultural preservation	Water pollution
Transport diversity	Non-drivers	Land use impacts
Congestion delay	Affordability	Habitat protection
Travel costs	Disabilities	Habitat fragmentation
Delivery services	Childrens travel	Resource efficiency

Table 2.3: Sustainable transportation indicators

2.1.2 Sustainability Strategies

Several strategies are proposed in the literature to make transport systems more sustainable. These strategies involve vehicle and fuel technology changes, road and vehicle operations improvements and demand management; see [9] for details. Though all these strategies have their advantages and drawbacks, the question is how effective these strategies would be in reducing congestion, lowering pollution and cutting fuel use. The Transportation Research Board investigated this topic in 1997 [28]. This study proposes that an effective sustainable urban transportation system requires a mixed use of these strategies.

There are several strategies proposed to make the transportation systems more sustainable. Table 2.4 demonstrates several sustainable transportation strategies proposed in transportation planning. A strategy that enables to implement a combination of these solutions should be devised and used.

Access vs. Mobility Basic Concepts
Bike- and Pedestrian-Friendly Cities
Transit, Paratransit, Ridesharing
Telecommuting / Teleconferencing
New Technologies for Improved Efficiency, Traffic Control Systems, Transportation Information Systems
Prices and Subsidies Aligned with Sustainability

Table 2.4: Sustainable transportation strategies

Achieving sustainability in transportation needs some changes and has some implications in transportation planning. One of the biggest changes is required in decision making mechanism. All the related parties should be a part of the decision making process. Public support is also vital. Reducing automobile dependency is one of the primary goals of sustainable transportation planning. To achieve this it is required to reduce some market distortions that contribute to dependency.

Several visions exist in transportation planning. Technical vision relies on technological innovations. Demand management vision involves changing travel behaviors where economic vision relies on creating an optimal transportation market. Alternative modes vision consists of improvements to public system in order to produce alternative transportation methods. Land use vision and community change visions involve changing land use patterns.

2.2 Mathematical and Quantitative Approaches

In the literature several mathematical or quantitative approaches are proposed for sustainable transportation. The main goal of these studies is to alleviate congestion and transport emissions through use of different methods. Most of the studies involve simulation tools to evaluate the sustainability of different transportation policies [31, 25]. There are also some studies exploiting mathematical programming tools [33, 34].

2.2.1 Simulation Tools

Simulation is basically defined as modeling the real world systems to understand their characteristics and functioning. In many studies, simulation techniques are used in evaluation models that assess the sustainability of different transportation policies. These models apply the policy measures and parameters on the model of the real transportation network. By the help of simulation models, the responses of network users to the measures and the consequences of applying the corresponding policy are calculated. The results are analyzed and used to evaluate the sustainability of the transportation policy. Among this type of evaluation models two of them are superior: TREMOVE and SUMMA models.

TREMOVE Model

TREMOVE is a policy assessment model to study the effects of different transport and environment policies on the emissions of the transport sector. It has been developed to support the European policy making process concerning emission standards for vehicles and fuel specifications. It is an integrated simulation model developed for strategic analysis of the costs and effects of a wide range of policy instruments and measures applicable to local, regional and European surface transport markets.

TREMOVE benefits from and uses many components of several models. The core of the TREMOVE model is the TRE(NEN) module which models the changes in behavior of consumers and producers caused by policy measures. It takes into account the influence of measures on transport possibilities, costs and calculates the demand for passenger and freight transport for each mode.

The model estimates transport demand, modal shifts, vehicle stock renewal and scrapage decisions, the emissions of air pollutants and the welfare level for different policies. Among the policies that can be evaluated by TREMOVE model are road pricing, public transport pricing, emission standards, subsidies for cleaner cars.

Recent studies have contributed to the development of an enhanced and extended version of this model. The new model, TREMOVE 2, covers also rail, air and shipping and the model deals with a larger set of pollutants and covers all European countries along with Switzerland, Norway, Czech Republic, Hungary, Poland and Slovenia.

TREMOVE consist of 21 parallel country models. Each country model consists of three inter-linked core modules: a transport demand module, a vehicle turnover module, and an emission and fuel consumption module. In TREMOVE 2, welfare cost module and a life cycle emissions module are also added.

The mechanism of the model is depicted in Figure 2.2. The transport demand module determines the traffic demand. Using speed and load data from the transport demand module, and usage and stock structure data from the vehicle stock turnover module, the fuel consumption and emissions module calculates fuel consumption and other external costs like emission amounts. The welfare module assesses the transport policy taking all the factors into account.

TREMOVE has been developed to compute the effects of various types of policy measures on the main reasons of transport emissions. The main purpose of the model is to compute the effect of policy measures on emissions and the welfare costs of these policies.

The scope and level of detail of the TREMOVE model enable the simulation of policies on different levels, such as, pricing policies, technology-related policies, alternative fuel and fuel quality policies, and transport management policies. TREMOVE is an

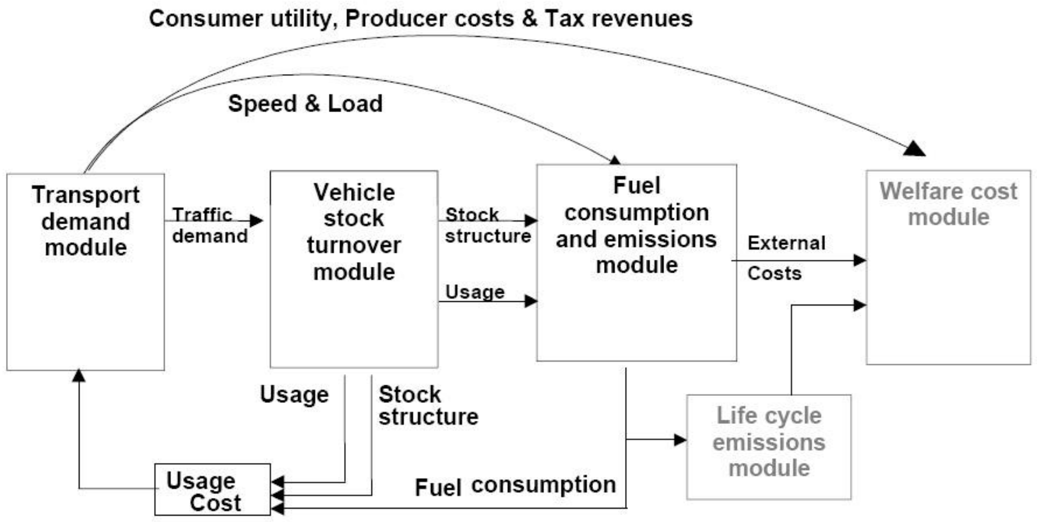


Figure 2.2: The mechanism of Tremove Model

integrated simulation model. The model simulates the changes in volume of transport, model choice and vehicle choice relative to a transport and emissions baseline in a reasonable way. The equations in the transport demand module are specifically designed to analyze how policy changes affect changes in behavior relative to the baseline transport projections. This model is used to simulate the effects of various policy measures in the context of CAFE (Clean Air for Europe) and other programs.

SCENES Model in TREMOVE

The SCENES model represents a comprehensive range of behavioral economic responses at a detailed segmented level as mode, route, destination and length of trip. The model incorporates all travel on all modes for all EU and much of the rest of Europe. It has separate passenger and freight demand modules. Transport model has 4 stages. Detailed physical networks were established for each mode. There are 11 freight modes and 6 Passenger modes. The SCENES model has a feedback loop for highway congestion on road. It uses 1995 data for calibration and validation and can make forecasts up to 2020 based on constant costs.

Passenger and freight demand were designed separately. Passenger demand is represented as a demand matrix which is based on national travel survey derived trip rates, population in 20 socio-economic groups per zone, 10 trip purpose categories, costs of transport by mode and country and some calibration parameters. Freight demand is also represented as a demand matrix which is based on 15 EU Input-Output tables.

Network supply model is based on travel time, monetary cost and distance. Travel times include congestion from passengers and freight. Monetary cost is vehicle operating cost for cars and tariff for other modes.

In TREMOVE, the SCENES model is used to provide a spatially detailed 1995 database from which aggregated data is extracted. It is also used for the purpose of providing a 2020 Baseline Scenario dataset of transport demand and costs. TREMOVE model uses the output of the SCENES. In order to transfer demand volumes per year SCENES zoning system is matched to TREMOVE metropolitan, other urban, non-urban zones by country and SCENES purpose, mode and vehicle categories were matched to TREMOVE , and some exogenous data were introduced.

In TREMOVE, within the metropolitan and other urban area only one type of road is present. In the non-urban regions, motorways and other roads are modeled separately and trips are split into long and short distances. The SCENES origin-destination matrices can identify long and short distance trips. The classification of the links of the SCENES network into different road categories can identify the share of traffic on motorways and other roads.

SCENES describes transport over a complete day, while TREMOVE explicitly separates peak and off-peak periods. The division of the peak from the off-peak traffic is based on the trip purpose profile of trips by time of day from national UK travel survey data. The peak period is supposed to last 6 hours, while off-peak period takes 18 hours.

The speed on a road type in TREMOVE (metropolitan, other urban, non-urban motorways and other non-urban roads) is a weighted average over SCENES links. The speed of transit modes is also drawn from the SCENES model results. Value of time is estimated from the values used in SCENES plus additional information used to weight value of waiting time.

SUMMA Model

SUMMA (SUstainable Mobility, policy Measures and Assessment) has been designed by RAND Europe for European Commission Directorate General for Energy and Transport to support policymakers by providing them with a consistent framework for making trade-offs, among the economic, environmental and social components of sustainability. SUMMA has the objectives of defining sustainable transport and indicators, determining the scope of sustainability problems in transportation and assessing various policy measures. For details see [25].

In SUMMA there are two types of indicators, system indicators and outcome indicators. Defined as a proxy for what takes place inside the system, system indicators are very crucial in monitoring the system and calculating the outcome indicators. Some of the system indicators are given in the Table 2.5.

Percentage of people with work location outside household
Percentage of population owning a car
Disposable income distribution
Regional distribution of industries
Percentage of population living in urban areas
Mean distance to closest public transport stop
Fuel/energy usage per 100 km
Emission of air pollutants by transport mean
Space per passenger on public transit
Vehicle fleet mix by mode
Fixed and variable costs by mode per passenger
Numbers of vehicles that can be operated per km per day
Price of infrastructure use (tolls, parking fees, etc.)
Emissions of air pollutants by industries related to transport
Number of vehicles produced by mode per year

Table 2.5: SUMMA system indicators

The outcome indicators are used for describing changes in the outcomes of interests. The outcomes of interest are the impacts of the transportation that the policymakers are interested in. SUMMA selected the outcomes of interest to cover the three dimensions of sustainability. Table 2.6 summarizes the outcomes of interest by category.

Economic	Social	Environmental
Accessibility	Affordability	Resource use
Transport operation cost	Safety and security	Direct ecological intrusion
Productivity / Efficiency	Fitness and health	Emissions to air
Costs to economy	Livability and amenity	Emissions to soil and water
Benefits to economy	Equity	Noise
	Social cohesion	Waste

Table 2.6: SUMMA outcomes of interest

Fast Simple Model

Ideally, a model to represent the transport system would be able to model all policy measures and provide the outcomes of interest with sufficient detail and accuracy. Additionally the model would cover all of Europe and be fast, simple and accurate enough to be able to support policy makers in their decision making process.

The EXPEDITE model is a system that calculates the impact of transport policies on transport demand for the whole of Europe. This process is fast enough to develop a policy assessment instrument that can be used by policy makers. SUMMA developed a new model using the EXPEDITE model as the basis, for quantifying the impacts of transport policies. The model is called the Fast Simple Model (FSM). It is a computer tool that enables the calculation of the impacts of various policy measures and policy packages.

The mechanism of FSM is illustrated in Figure 2.3. Demand Response Module generates forecasts of demand for passenger and freight transport. Taking the demand data, Impact Assessment Module estimates the environmental, economic, and social impacts of the transport demand. The indicator values calculated are used in Policy Assessment Module that produces an aggregate measure of the sustainability of the policies.

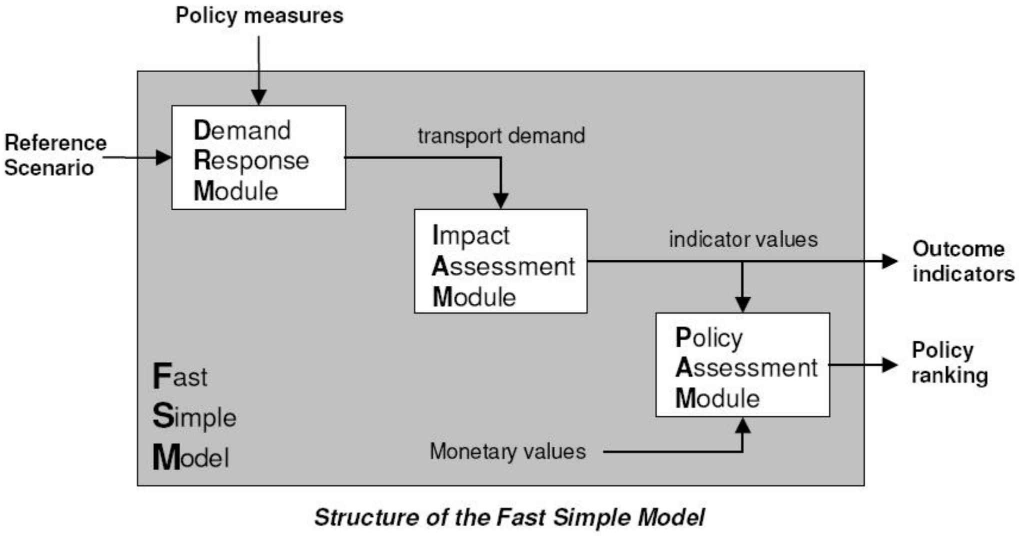


Figure 2.3: The mechanism of Fast Simple Model

The Demand Response Module calculates the demand for both passenger and freight transport. For passenger transport it calculates the number of trips made and the number of kilometers. For freight transport, the transport volumes are calculated in tonnes and ton-kilometers. For each of the modes different vehicle type shares are calculated.

The FSM is a meta-model. A meta-model can be defined as a simple aggregate model that approximates more complex and disaggregate behavior. Based on calculations with more detailed transport models for a representative set of countries, a model is estimated that represents transport in the whole of Europe based on calculations with more detailed transport models. Since it is not a network model, FSM has been supplemented with a set of regional and city level models.

The EXPEDITE meta-model that establishes the base of the DRM, generates transport demand by mode, but not by vehicle type. It is not possible to calculate environmental impacts of transport demand accurately without vehicle type information. The Vehicle Stock Model (VSM) disaggregates the transport demand by mode to demands by vehicle type. It is based on the TREMOVE model which is explained above. The VSM calculates different vehicle type shares for each mode in 1995 as well as in 2020. These shares are used to disaggregate the transport activities by vehicle type.

2.2.2 Analytical Approaches

There are several performance indicators of sustainable urban transportation systems, some of which are described above. But the question is how to quantify and analyze them. In the literature some suitable analytical techniques were mentioned, which can be useful to understand the relationship between land use and travel demand.

Descriptive statistics, exploratory and graphical methods can help to understand the structure of the transportation system. Statistical mapping allows interpretation about geographical patterns. Spatial statistics assist in determining whether geographical patterns are systematic or random.

Travel preference functions can be used to understand transportation network users' behavior. A travel preference function is an aggregate of the travel behavioral response by a zonal grouping given a particular opportunity surface surrounding those travelers. The estimation of a raw preference function is determined in the following five steps: First, destination zones are ranked in order of increasing distance from the origin zone. Second, the cumulative number of jobs is calculated at an increasing distance from the origin zone, and these are expressed as a proportion of the metropolitan total. Third, from the O-D data, the number of jobs with destinations at increasing distance from the origin zone is set out. The O-D flows are expressed at the fourth step as a proportion by destination of the total zonal trips productions. Finally, at the last step the proportions are plotted as a graph.

Regression analysis is used in transportation engineering and planning to forecast trip generation, to study speed and concentration of trip flows, and to assess the effects of transportation infrastructure in land prices, among other applications [4].

2.2.3 A General Optimization Model

In [34] and [33] a general optimization model that incorporates emission factors per vehicle kilometer is used. The optimization model is used for the transportation planning in the assessment and evaluation processes proposed.

The objective function of the model is minimizing the total cost, which includes capital cost, and operational and maintenance cost of the vehicles that should be added during the planning horizon, and the operational and maintenance cost of the existing vehicles for the passenger transportation. The number of vehicles and the kilometers traveled by vehicle modes are the two variables of the model. Parameters of the model are the discounted capital cost of a vehicle, discounted salvage value of a vehicle and operating cost of a vehicle.

The model has four different kinds of constraints. Travel demand constraint includes two subtypes; one for transport services supply, one for total travel services. Vehicle capacity constraint ensures the total vehicle-kilometer service provided by any type of vehicle does not exceed its maximum vehicle-kilometer capacity of the total stock of that type of vehicle. Vehicle stock constraint guarantees total number of vehicles added to the transport system does not exceed the maximum limit on the number of vehicles. Emission constraint has also two subtypes; annual emission constraint and total emission constraints.

2.2.4 Emission Pricing for Sustainability

Nagurney introduces the term emission pricing which can be defined basically as the toll pricing scheme that guarantees the network to be sustainable in that the environmental quality standard will be met and that the traffic flow pattern will be in equilibrium [21].

In the simple pricing model for sustainability, the objective function is identical to that in the classical traffic network equilibrium models. The constraints remain the same, with an additional one that serves as the environmental quality constraint. Two types of policies are proposed for emission pricing: Link pricing which is introducing tolls in links and path pricing that introduces tolls for paths. Different formulations of emission pricing model are provided for alternative situations with different assumptions including Models for elastic demand networks. Nagurney also proposes solution methods for the proposed models (See [21] for details). An emission constraint, which ensures that emission amounts do not exceed specific levels, is added to the model.

2.2.5 Emission Permits

Tradable pollution permits are a free-market solution to the pollution problems. In literature it is shown that pollution permits can be traded to satisfy environmental standards with the quantity of pollution fixed by the total number of permits. Nagurney considers users of a transportation network, as firms that have to pay for emission permits [22, 23] .

According to formulation, the network user on a path is also subject to the payment of the price or cost of emissions besides the user travel cost. The emission payment for traveling on a path is equal to the sum of marginal cost of emission abatement times the emission factor on all the links on the path. In this framework, it is transportation authorities' responsibility to inform the travelers of the license prices and the corresponding payments required.

Equilibrium conditions for the model consist of systems of equalities and inequalities which must hold for the path flows, the marginal costs of emission abatement, the licenses, and the license price. At the equilibrium point, a traveler on any of the network arcs, is subjected to the payment of the true cost of his emissions while traveling on the path. Nagurney provides a variational inequality formulation of pollution permit system traffic network equilibrium; See [21, 22, 23] for details.

2.3 Mathematical Background for the Study

In the subsequent chapters, we discuss bilevel programming especially in the context of toll optimization. For ease of reading, we review both subjects in this section.

2.3.1 Bilevel Programming

Bilevel programming is a branch of hierarchical mathematical optimization. In this programming method, the model has two levels; the upper level and the lower level. The model seeks to maximize or minimize the upper level objective function while simultaneously optimizing the lower level problem. Bilevel programming is the adequate framework for modeling asymmetric games that has a “leader” who integrates the optimal reaction of a rational “follower” to his decisions within the optimization process; see [7] for details. The mathematical model expresses the general formulation of a bilevel programming problem:

$$
\begin{aligned}
\min_{x,y} \quad & F(x,y), \\
\text{s.t} \quad & G(x,y) \leq 0, \\
& \min_{y} f(x,y), \\
& \text{s.t} \;\; g(x,y) \leq 0,
\end{aligned}
\tag{2.1}
$$

where $x \in R^n$ is the upper level variable and $y \in R^n$ is the lower level variable. The functions F and f are the upper-level and lower-level objective functions respectively. Similarly, the functions G and g are the upper-level and lower-level constraints respectively.

The bilevel programming structure is suitable for many real-world problems that have a hierarchical relationship between two decision levels. Among the fields that the concept can be applied are management (facility location, environmental regulation, credit allocation, energy policy, hazardous materials), economic planning (social and agricultural policies, electric power pricing, oil production), engineering (optimal design, structures and shape), chemistry, environmental sciences, and optimal control. In these cases the upper level may represent decision-makers who set policies that lead to some reaction within a particular market or group of system users. The reaction of the market or system users constitutes the lower level of the system under study.

A sustainable urban transportation model may also have a two level structure. The government, transportation system manager or another responsible institution determines pricing schemes, traffic flow control measures, policies to reach some objectives including the minimization of congestion or emission. According to determined price levels and other variables, drivers aim to maximize their utilities, which mostly include the monetary and time cost of the route chosen. Therefore bilevel programming is a suitable structure for modeling sustainability in transportation networks.

Despite the fact that a wide range of applications fit the bilevel programming framework, real-life implementations of the concepts are scarce. The main reason is the lack of efficient algorithms for dealing with large-scale problems. Bilevel programming problems are NP-Hard problems. Even the simplest instance, the linear bilevel programming problem was shown to be NP-hard [14]. Therefore in the literature global optimization techniques such as implicit enumeration, cutting planes or meta heuristics have been proposed for its solution; see [12, 14]. Despite the problem being NP-Hard, some specific cases enable us to solve the problem in polynomial time. Many researchers proposed several optimality conditions for bilevel programming problems.

Some of these conditions are used in various solution methods and algorithms. Among the proposed methods are descent methods, penalty function methods and trust region methods.

2.3.2 Toll Optimization Problem

Road pricing is a widely used instrument in dealing with negative externalities of transportation systems, such as congestion and pollution. It is common to use congestion fees, namely toll pricing, to reduce the congestion. One of the targets of toll optimization models is to alleviate the congestion effects [16, 5]. Marcotte et al. provide an extensive literature survey on bilevel programming approach to toll optimization problems [20]. Labbe et al.[16] and Brotocorne et al. [5] propose different bilevel programming formulations the problems.

In toll optimization problems, the upper level problem usually has the objective of maximizing revenue earned from introduced tolls, where the lower level problem reflects the decisions of rational network users. A rational user is assumed to choose the route in that he can minimize his or her cost of travel. The lower level problem can be deemed as a reformulation of the classic traffic assignment problem.

The traffic assignment problem concerns the selection of the routes between origins and destinations through links that have associated travel costs in a transportation network. The solution of the problem is obtained when a stable pattern of travelers' choice is reached. This is called the user equilibrium. It is based on the Wardrop's first principle (1952) which states that the travel times in all of the used routes are equal and less than those, which would be incurred by a single vehicle on any unused route.

There are two different formulations of the traffic assignment problem. Path formulation incorporates predetermined routes having specific order of links. Network users then choose which route to use. In multicommodity formulation the modeling structure is based on the numbers of users that are headed to each destination on each link. In this study only the multicommodity formulation is covered.

Consider a transportation network defined by a set of nodes N, and a set of arcs A. A link of the network is denoted by subscript $a \in A$ and a tuple $(i, j) \in A$ with $i, j \in N$. For some of the links in A, there are associated toll prices. Other arcs are only subject to the travel cost. It is assumed that travel demand between each origin-destination pair is fixed, and the travelers choose the shortest path, namely the least costly route, according to the applied travel cost function. The model that we use in our numerical study incorporates the widely used standard travel cost function introduced by Bureau of Public Roads (BPR, 1964),

$$c_a(f_a) = \alpha_a + \beta_a(\frac{f_a}{C_a})^4, \tag{2.2}$$

where α_a is the free flow travel cost of the link a, f_a is the traffic flow in the link, β_a is a link parameter, and C_a is the designed capacity of the link. These parameters are usually determined by analyzing the historical data or from tables in Highway Capacity Manual [30].

Let K be the set of origin-destination pairs. For each $k \in K$ we denote the origin by $o(k)$ and the destination by $d(k)$. Then the demand associated with each origin destination pair $k \in K$ is defined by

$$d_i(k) = \begin{cases} n^k, & \text{if } \ i = o(k), \\ -n^k, & \text{if } \ i = d(k), \\ 0, & \text{otherwise,} \end{cases}$$

where n_k is the total demand of origin-destination pair $k \in K$. The following table includes the notation used in the model.

f_a	:	Traffic flow in link a
x_a^k	:	Total number of origin-destination pair k users in link a
$c_a(f_a)$	:	Travel cost function of link a
T_a	:	Toll price in link a
T_a^{max}	:	Upper bound for toll price in link a

Table 2.7: Notation for the toll optimization problem

Based on the notation given above the toll optimization problem can be formulated as

$$\max_{T,x} \sum_{a \in \bar{A}} T_a f_a, \tag{2.3}$$

$$\text{s.t} \quad T_a \leq T_a^{max}, \qquad \forall a \in \bar{A}, \tag{2.4}$$

$$T_a \geq 0, \qquad \forall a \in \bar{A}, \tag{2.5}$$

$$T_a = 0, \qquad \forall a \in A - \bar{A}, \tag{2.6}$$

$$\min_{x} \sum_{a \in A} \int_0^{f_a} c_a(y)dy + \sum_{a \in \bar{A}} T_a f_a, \tag{2.7}$$

$$\text{s.t} \quad \sum_{j:(i,j) \in A} x_{(i,j)}^k - \sum_{j:(i,j) \in A} x_{(j,i)}^k = d_i^k, \forall k \in K, \forall i \in N, \tag{2.8}$$

$$f_a = \sum_{k \in K} x_a^k, \qquad \forall a \in A, \tag{2.9}$$

$$x_a^k \geq 0, \qquad \forall k \in K, \forall a \in A, \tag{2.10}$$

where $\bar{A} \subseteq A$ denotes the arcs that are subject to tolling. In case $\bar{A} \notin \emptyset$ and $\bar{A} \neq A$ the problem is also referred to as second best toll pricing with fixed demands [18]. The objective (2.3) and the constraints (2.4),(2.5) and (2.6) constitute the upper level problem. The upper level objective (2.3) is total profit maximization. The assumption that any toll price T_a cannot exceed a predetermined value T_a^{max} is given by (2.4). The lower level objective (2.7) with constraints (2.8), (2.9) and (2.10) constitute the lower level problem. The lower level objective function (2.7) reflects the decisions of the network users based on minimizing the total travel cost. The constraints (2.8) and (2.9) constitute demand and conservation of flow constraints, respectively. The constraints (2.10) ensure the non-negativity of the flows on the links.

As mentioned before the bilevel problems are usually reduced to one level by some reformulations. The bilevel structure of the problem can be induced to one level by substituting the lower level problem with its optimality conditions. Many researchers have studied different formulations of bilevel problems [8].

CHAPTER 3

A SUSTAINABLE URBAN TRANSPORTATION MODEL

In this chapter we first discuss the role of mathematical programming in sustainable urban transportation. After a brief review of emission modeling, emission functions are derived through a multi-step process. Then these determined emission functions are incorporated into proposed models to assess sustainability in transportation.

3.1 Role of Mathematical Programming

Mathematical programming models are used to minimize or maximize an objective function while satisfying certain constraints. Many real life or theoretical problems can easily be modeled and solved by using different mathematical programming tools.

To model a transportation problem consistent with the real nature of transportation networks, traffic flows should be modeled properly. Therefore, mathematical programming models are used in many conventional transportation problems. As an important example traffic assignment problem is a widely known application of mathematical programming in transportation.

Using mathematical programming techniques in sustainable urban transportation is crucial. To be able to build a sustainable transportation model, indicators of sustainability should be determined and analyzed carefully. The main indicators of sustainability in transportation networks are the level of congestion and the total amount of emission. The congestion levels can easily be derived from traffic flow and designed capacities of the links. But emission cannot be measured easily. To incorporate emission effects of congestion into the model properly, the real relationship between traffic flow and total emission must be specified analytically. In this section we give the details of the conducted study for expressing total emission in terms of traffic flow.

3.1.1 Emission Functions vs. Emission Factors

Emission modeling is a wide research area. In one of the early studies, Guensler and Sperling showed that vehicle emissions are highly dependent on the vehicle speed in [13]. Many researchers studied the relation between transport emissions and vehicle types, speeds, driving styles, weather or several other factors. Emission factors are usually determined as average values per vehicle kilometer for each vehicle category. In the literature several mathematical models and simulation tools using emission factors are proposed to minimize the emission [31, 25]. The emission factors determined by several institutions give reasonable approximations of real emission values in relatively less congested networks. But in the case of considerable congestion, emission amounts of the vehicles highly fluctuate because of the engine start and stop emissions. Therefore, especially in highly congested networks, using emission factors does not reflect the real values. From a sustainability point of view to deal with the emissions, the effect of congestion on the emission amounts should be known. An emission function with respect to traffic flow may easily reflect the real amounts of congestion emissions.

In this study we propose emission functions instead of emission factors. We performed a two-stage study to express the total emission function in terms of traffic flow. In the first stage we expressed emission in terms of speed by using emission-speed data provided by several institutions. Then by the help of traffic flow-speed studies, we determined the mathematical relationship between traffic flow and speed. Plugging obtained function into emission-speed relation enabled us to have a general function of pollutant emissions with respect to traffic flow.

3.1.2 Emission Function Determination

Among several institutions that perform emission-speed relationship studies is California Air Resources Board. They provide emission amounts per mile versus vehicle speed data tables [6]. Tables are based on the average emission factors by speed. These tables establish the basis of our study. Using Lab Fit we derived the approximated function for emission - speed relation. Lab Fit is a curve fitting software that performs nonlinear regression; for details see [17]. Unregistered version provides necessary data handling for our study. General relation between NOx emission of a pollutant and vehicle speed is depicted in Figure 3.1. We conducted the same study for some of other pollutants. The results are very similar. Figure 3.2 depicts the emission - vehicle relation for CO_2. We continued the study with NOx emission-speed relation. It is demonstrated that the amount of emission emitted by a vehicle highly depends on the cruising speed. Both low and high speeds result in higher emissions. In the case of congestion since the average speed of vehicles decreases significantly, the total emissions of a vehicle increase considerably.

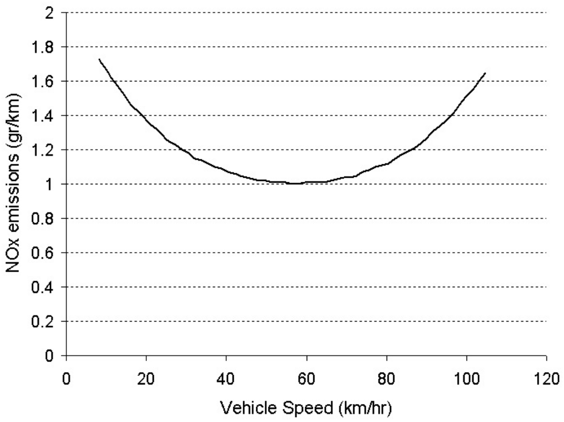


Figure 3.1: Vehicle NOx emission amounts with respect to vehicle speed

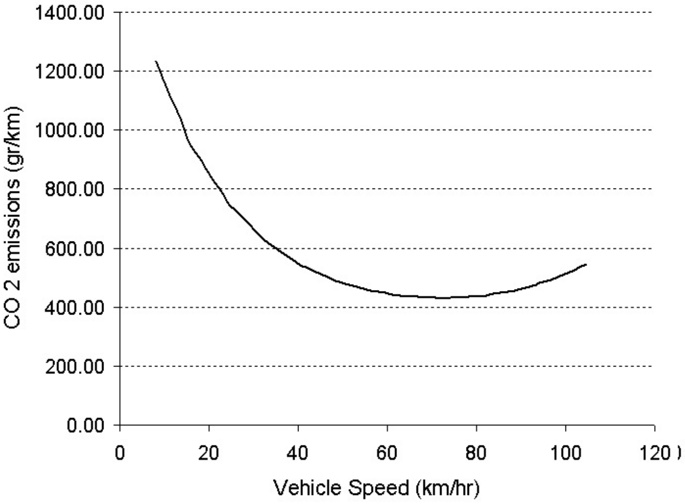


Figure 3.2: Vehicle CO_2 emission amounts with respect to vehicle speed

On the other hand many previous studies prove that there is a direct relationship between vehicle speed and traffic flow in the link. Akçelik performed extensive studies on this subject; for details see [1, 2]. According to several studies in literature general vehicle speed-traffic flow relationship can be demonstrated as in Figure 3.3. The average vehicle speed remains almost constant until the capacity is near 70 percent. After a sudden decrease in vehicle speed the capacity reaches the designed level. Then average vehicle speed continues to decrease slowly as traffic flow increases.

Combining determined vehicle speed-traffic flow and emission-vehicle speed functions we expressed total emissions in terms of traffic flow. The resulting function of

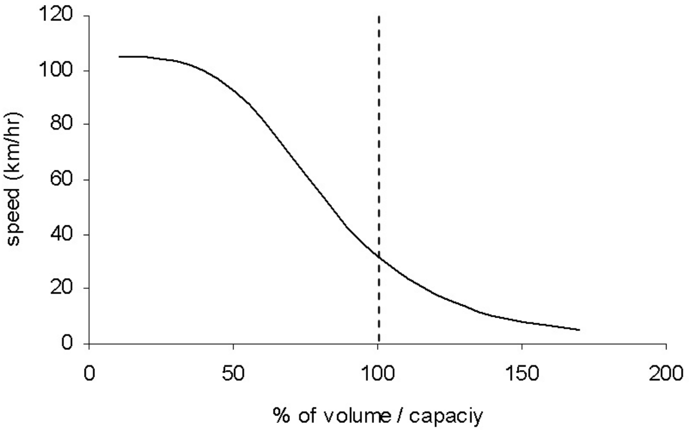


Figure 3.3: Average vehicle speed with respect to traffic flow

total Nitrogen Oxides (NOx) emissions in terms of traffic flow shows nearly exponential behavior as shown in Figure 3.4.

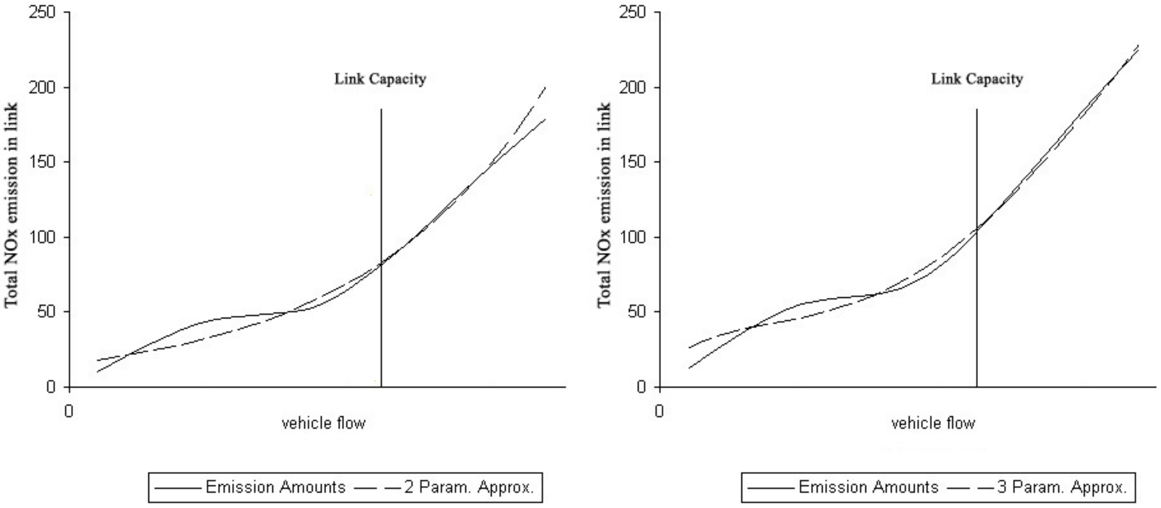


Figure 3.4: Total emission in a link with respect to traffic flow

It can be seen from the figure that after traffic flow reaches the designed capacity level, the total amount of emissions starts to increase exponentially. This is an expected result because when a road's capacity is reached and congestion occurs, vehicles are unable to cruise without stopping, and hence the resulting stop and go pattern decreases the average vehicle speed and increases the total emissions significantly. Since both the number of vehicles in the traffic and the amount of emission each vehicle produce increase, the total emission in a link as depicted in Figure 3.4, increases exponentially.

Emission of any pollutant mainly depends on the vehicle speed. We conducted the same study for some of other pollutants. Total emissions of pollutants showed very similar behavior. Therefore emission function of a pollutant t with respect to traffic flow in link a can be defined as follows

$$E_a^p(f_a) = A(p, C_a) l_a e^{B(p,C_a) f_a}, \tag{3.1}$$

where f_a is the traffic flow in link a, l_a is the length of link a, $A(p, C_a)$, and $B(p, C_a)$ values are the parameters of the function that depend on the pollutant type and designed capacity of the link. These parameters are determined by the fitting software that uses the emission factor tables for the corresponding pollutant. Determining the functions for main pollutant types, enables us to construct the basis of the model.

The previous function is the best fitting two parameter function for the emission flow relationship. It is also possible get a better fit by using a three or more parameter function. The following function is the three parameter function that yields a better fit.

$$E_a^p(f_a) = \lambda(p, C_a) {f_a}^{\gamma(p,C_a) f_a} + \phi(p, C_a) ln(f_a), \tag{3.2}$$

where $\lambda(p, C_a)$,$\gamma(p, C_a)$, and $\phi(p, C_a)$ are the parameters that depend on the pollutant type and designed capacity of the link.

It is obvious that three parameter version of the emission functions gives a better fit. But for the use in mathematical programming models two parameter version is preferred because of the convex structure of the function. Especially if the objective function of the model is non-convex it becomes relatively hard to solve and the solution effort usually results in local optimum instead of global optimum. Therefore in our computational results section we used emission function (3.1).

3.2 Bilevel Programming Model

A sustainable transportation model should be consistent with the real nature of the transportation networks. In most of the cases transportation networks can be modeled as leader-follower games. Network managers use some instruments to manage the demand or for some other purposes while network users consider only their total travel costs. This structure can be modeled by bilevel programming tools which are described in the previous sections. Emission functions are inserted in toll optimization models, which have bilevel structure, as an application. The modifications on the model are described in detail.

Road pricing is a demand management instrument, which is suitable to use for sustainability purposes. Toll prices can be used as disincentives that discourage network users to use more congested links or links with more total emissions. Therefore, the structure of toll optimization models is proper for a sustainable urban transportation model. To formulate a model focused on sustainability, we can easily modify the toll optimization problem, defined in the previous section, by modifying the upper level problem. Besides some additional constraints, an objective function of minimizing total emission instead of maximizing profit is introduced. Using the notation and structure of toll optimization problem and previously described emission functions, the sustainable urban transportation model (SUTM) takes the following form:

$$
\begin{aligned}
&\min_{T,x} \sum_{a\in A}\sum_{p\in P} E_a^p(f_a), && && (3.3)\\
&\text{s.t}\;\; T_a \le T_a^{max}, && \forall a \in \bar{A}, && (3.4)\\
&\qquad T_a \ge 0, && \forall a \in \bar{A}, && (3.5)\\
&\qquad T_a = 0, && \forall a \in A-\bar{A}, && (3.6)\\
&\min_{y} \sum_{a\in A}\int_0^{f_a} c_a(y)dy + \sum_{a\in\bar{A}} T_a f_a, && , && (3.7)\\
&\text{s.t}\;\; \sum_{j:(i,j)\in A} x_{(i,j)}^k - \sum_{j:(i,j)\in A} x_{(j,i)}^k = d_i^k \forall k \in K, \forall i \in N, && && (3.8)\\
&\qquad f_a = \sum_{k\in K} x_a^k, && \forall a \in A, && (3.9)\\
&\qquad x_a^k, \ge 0 && \forall k \in K, \forall a \in A. && (3.10)
\end{aligned}
$$

where P is the set of pollutants. In the upper level problem (3.3-3.6) leader's objective function (3.3) is to minimize the total emission. In the lower level problem (3.7-3.10) objective function (3.7), which reflects the network users' decisions, is to minimize the travel costs. Constraint sets (3.8) and (3.9) are demand and conservation of flow constraints respectively. The constraints (3.10) ensures the non-negativity of the flows on the links. Lower level problem is a modified version of classic traffic assignment problem reflecting the traffic equilibrium.

3.3 Extensions for Different Policies

The sustainable urban transportation model provided above can be modified to incorporate different policy measures for sustainability. Among the various policies are district pricing, capacity enhancement and emission dispersion which are described below. All the proposed models in this section, are applied to the testing network in the computational results chapter. The results are analyzed and interpreted in detail below.

3.3.1 District Pricing

In case of high congestion in some sections of the network, instead of applying a toll for each a subset of links, area tolling schemes can be applied. In other words for predetermined areas all incoming arcs to the area or all outgoing arcs from the area can be subject to toll pricing as demonstrated in Figure 3.5 which will be described in Chapter 4 in detail.

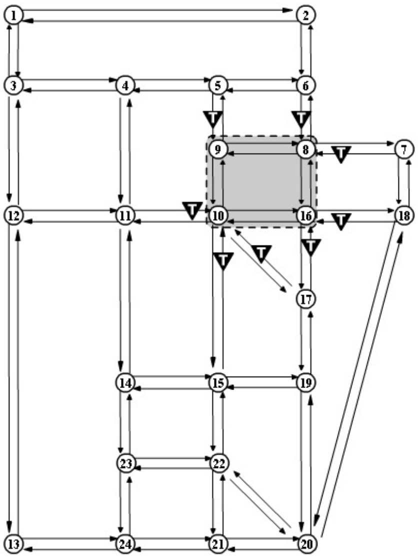


Figure 3.5: A possible example of district pricing

An example of district pricing is still being applied in London. A congestion toll is charged to a motor vehicle within the designated 21 square kilometers area of central London during the hours 7 am - 6.30 pm in weekdays. Transport for London, which operates the Central London Congestion Charge toll scheme reports that after a year it is stable and successful. The results encourage London administratives to expand the toll zone; for details see [29].

Being a common way of dealing congestion, district pricing approach can also be applied to transportation networks for sustainability purposes like alleviating the emissions in specific districts of the transportation network. To incorporate district pricing policy into previously defined sustainable urban transportation model, simply the corresponding constraints are introduced for only on the tolled links.

3.3.2 Capacity Enhancement

Instead of introducing toll prices for selected links network managers can also decide to increase the capacities of some determined links which leads to the capacity enhancement problem. This problem is concerned with the modifications of a transportation network by introducing new links or improving existing ones to reach some objectives. Introduction of new links can be formulated by the discrete capacity enhancement problem which is very hard to solve. Capacity extensions of existing links can be formulated by the continuous capacity enhancement problem.

There are some costs associated with the enhancement of link capacities. Defined as the capital investment and operating cost function $K(EC)$ is in the following form;

$$K(EC) = \sum_{a \in A} k_a EC_a^2, \tag{3.11}$$

where EC_a is the capacity enhancement in link a and k_a is the unit capital and operating cost for link a. This convex cost function is incorporated into the model as a budget constraint.

On the other hand total emission amounts and travel costs are also affected by the capacity enhancement. Corresponding functions take the following forms:

$$E_a^p(f_a, EC_a) = A(p, C_a + EC_a) l_a e^{B(p, C_a + EC_a) f_a}, \tag{3.12}$$

$$c_a(f_a, EC_a) = \alpha_a + \beta_a \left(\frac{f_a}{C_a + EC_a} \right)^4. \tag{3.13}$$

where $A(p, C_a + EC_a)$ and $B(p, C_a + EC_a)$ reflect the change in the function parameters with the enhancement of the capacities. Above is derived a total emission amounts function with respect to traffic flow. The parameters of this function depend on pollutant type and designed capacity of the link. Therefore enhancing the capacity of the link affect the parameters. According to the fitting studies for different capacities there is an almost linear relationship between capacity of the link and these parameters. So the effect of capacity enhancement on these parameters can be expressed mathematically as follows:

$$A(p, C_a + EC_a) = A(p, C_a) + \delta_A EC_a, \tag{3.14}$$

$$B(p, C_a + EC_a) = B(p, C_a) + \delta_B EC_a, , \tag{3.15}$$

where δ_A and δ_B values are determined by data fitting. Plugging these functions into model, we get:

$$\min_{T,x} \quad \sum_{a\in A}\sum_{p\in P} E_a^p(f_a, EC_a), \tag{3.16}$$

$$\text{s.t} \quad \sum_{a\in \bar{A}} k_a EC_a^2 \leq B, \tag{3.17}$$

$$EC_a \leq UC_a, \qquad \forall a \in \bar{A}, \tag{3.18}$$

$$EC_a \geq 0, \qquad \forall a \in \bar{A}, \tag{3.19}$$

$$\min_{y} \sum_a \int_0^{f_a} c_a(y, EC_a)dy, \tag{3.20}$$

$$\text{s.t} \quad \sum_{j:(i,j)\in A} x_{(i,j)}^k - \sum_{j:(i,j)\in A} x_{(j,i)}^k = d_i^k, \forall k \in K, \forall i \in N, \tag{3.21}$$

$$f_a = \sum_{k\in K} x_a^k, \qquad \forall a \in A, \tag{3.22}$$

$$x_a^k \geq 0, \qquad \forall k \in K, \forall a \in A, \tag{3.23}$$

where UC_a is defined as maximum capacity enhancement in link a, and B is the total budget allocated for capacity enhancement. Notice here that $\bar{A} \subseteq A$ denotes the arcs that are subject to capacity enhancement.

This capacity enhancement problem with the objective of minimizing total emission can be used for sustainability purposes. It determines the optimum capacity enhancements for candidate links to alleviate total emission amounts while satisfying the budget constraint for enhancement.

3.3.3 Emission Dispersion

According to the government or municipality, which is the natural manager of the urban transportation network, the emission accumulations in specific areas of the transportation network are also important as well as the emission produced by the flow on a link. Traffic flows with reasonable levels emission in highly dense parts of the network may sum up to excessive amounts of emission which is an undesirable situation. Especially for residential and commercial areas there may be some predetermined emission limits. Therefore besides minimizing the total emission amounts, the dispersion of the emission throughout the network may also be an objective form sustainability point of view. Concerning this issue the upper level objective function of previously described mathematical programming models can be modified as following:

$$\min_{T,x} \sum_{a \in A} \sum_{p \in P} max \left\{ (E_a^p(f_a) - el_a^p), 0 \right\}, \tag{3.24}$$

where el_a^p is the desired level of emission in link a. The function (3.24) penalizes the amount of emission that exceed the desired levels. el_a^p values should be determined by the network managers according to land use characteristics. The following function can be used the determine these values.

$$el_a^p = \mu_d AE \qquad \forall a \in d, \forall d \in D, \forall p \in P, \tag{3.25}$$

where μ_d is the coefficient that depends on district of the link, AE is the average emission on the network, and D is the set of districts.

After implementing the defined objective function, the modified version of the sustainable urban transportation model takes the following form:

$$\min_{T,x} \sum_{a \in A} \sum_{p \in P} max \left\{ (E_a^p(f_a) - el_a^p), 0 \right\}, \tag{3.26}$$

$$\text{s.t} \quad T_a \leq T_a^{max} \qquad \forall a \in \bar{A}, \tag{3.27}$$

$$T_a \geq 0 \qquad \forall a \in \bar{A}, \tag{3.28}$$

$$T_a = 0, \qquad \forall a \in A - \bar{A}, \tag{3.29}$$

$$\min_{y} \sum_{a} \int_0^{f_a} c_a(y)dy + \sum_{a \in \bar{A}} T_a f_a, \tag{3.30}$$

$$\text{s.t} \quad \sum_{j:(i,j) \in A} x_{(i,j)}^k - \sum_{j:(i,j) \in A} x_{(j,i)}^k = d_i^k, \forall k \in K, \forall i \in N, \tag{3.31}$$

$$f_a = \sum_{k \in D} x_a^k \qquad a \in A, \tag{3.32}$$

$$x_a^k \geq 0, \qquad \forall k \in K, \forall a \in A. \tag{3.33}$$

The objective function (3.26) is the only modification to the previously proposed sustainable urban transportation model. Other constraints are same with the SUTM model. Introducing (3.26) as the objective function will enable the model to determine the optimal toll prices to disperse the total emission.

CHAPTER 4

COMPUTATIONAL RESULTS AND ANALYSIS

The models proposed above are in the form of Mathematical Problems with Equilibrium Constraints, (MPEC). The solution to this kind of problems requires specialized software and solver. The GAMS/NLPEC solver, solves MPEC models by reformulating the complementarity constraints as nonlinear programs (NLP); for details see [24]. The resulting sequence of NLP models are solved by existing NLP solvers after being parameterized by a scalar . The solutions are used to recover an MPEC solution.

GAMS/NLPEC is an effective tool for solving MPEC models. It provides several ways of reformulation strategies. NLPEC solver has an open architecture. The model reformulations are written out as GAMS source codes for solution via an NLP solver to enable the source to be viewed and modified. In this thesis study in computational results and analysis we used the GAMS/NLPEC solver in modeling and solution process with default options and reformulation strategies.

4.1 Characteristics of the Testing Network

The proposed models are applied on Sioux Falls network. Sioux Falls is widely used medium-sized testing network problem consisting of 24 nodes, 76 arcs and 23 destinations (528 O-D pairs) with asymmetric arc costs. GAMS provides a toll optimization model (*tollmpec.gms*) based on this testing network [11]. Demand characteristics of the testing network is depicted in the Figure 4.1. It can be seen that for some sections of the network for some of the nodes there is respectively higher demand.

To evaluate the effects of using emission functions and different modifications for the sake of sustainability, we modified the original *tollmpec.gms* file according to formulations given in the previous section and solved corresponding models including the original toll optimization model on the Sioux Falls network. A shortened version of the GAMS code is provided in Appendix C. The results and contributions of each model are demonstrated and analyzed below.

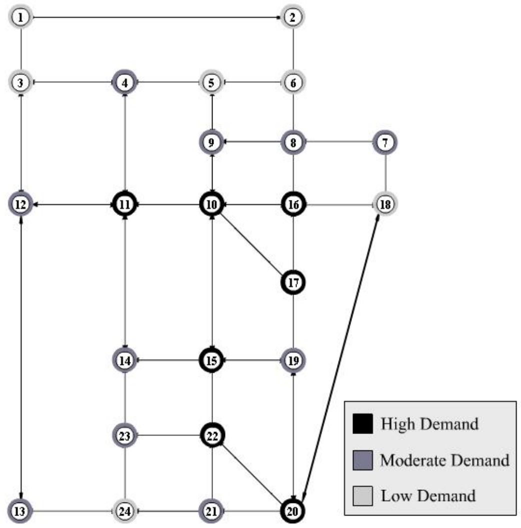


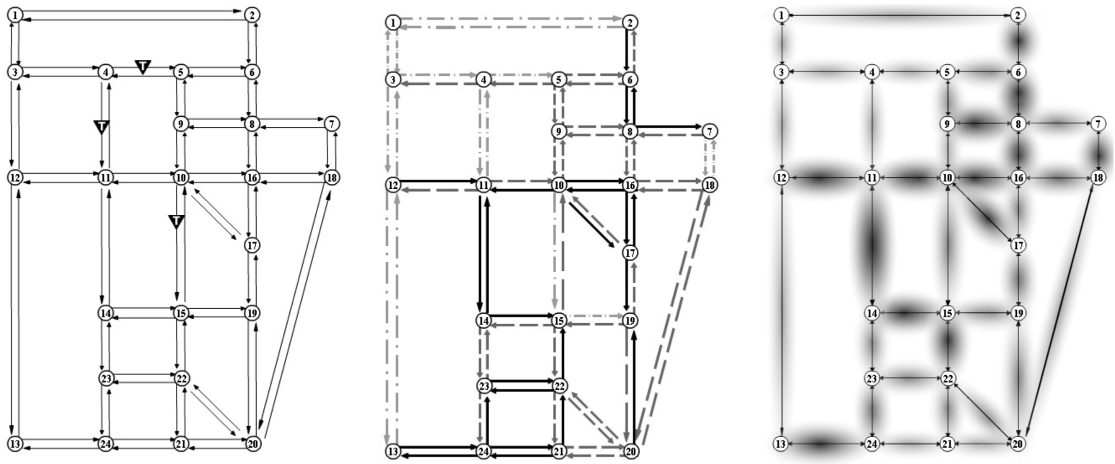
Figure 4.1: Demand characteristics of Sioux Falls network

Despite the total emission functions are defined as the sum of all pollutants in the previous chapters, we only included the pollutant of NOx for the computations in this chapter. The objective functions of the models are assumed to be minimizing the total emission of NOx.

The graphical illustrations in the following sections depicting the results of the various models were prepared in three steps: First the corresponding models are solved. The results of the models are transferred into Microsoft Excel software. In the excel files we prepared, traffic flows and emission amounts of each arc are divided in to three groups as no congestion (reasonable emission), moderate congestion (moderate emission) and high congestion (highest emission) for traffic flow (total emission) respectively. Then this information for each model is transfered into Macromedia Flash software that draws the corresponding graphs according to the results. Appendix B provides more information on visualization process.

4.2 Original Toll Optimization Problem

To have a base result for comparison, we solved the original toll optimization problem on the Sioux Falls network provided by GAMS library incorporating our emission functions to measure the resulting emissions. The results are depicted in Figure 4.2. It demonstrates the tolled arcs, the traffic flow of the links and the corresponding emission amounts calculated according to proposed emission function. Upper level objective is maximizing the profit with three tolled links. These links are (4,5), (4,11), (10,15) in Figure 4.2(a). The user decides which route to use only according to travel cost functions. It is assumed that emission amounts in the links are not taken into account by the network users. Therefore if a link has the least cost, it is not important for the user whether it is congested and polluted or not. As a consequence congestion occur in some links of the network. Congestion graph, Figure 4.2(c), demonstrates the congestion levels for each link. The darker and more solid the line, the more congestion on the link. The emission amounts are depicted in Figure 4.2(c). In this emission graph, the darker the ellipses on the arcs, the more the emission amounts on the corresponding road.



(a) Tolled arcs (b) Traffic flows (c) Emission amounts

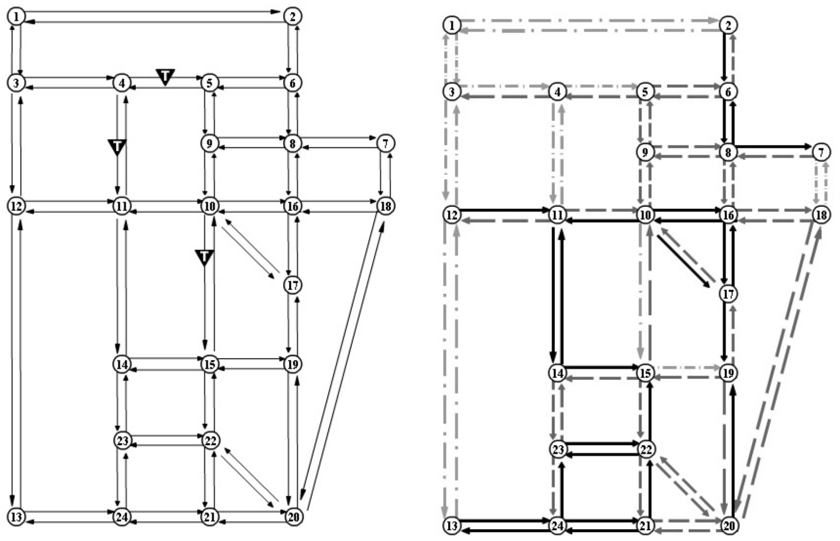
Figure 4.2: Solution diagram of original toll optimization model

4.3 Sustainable Urban Transportation Model

We applied the sustainable urban transportation model with minimizing the total emissions as objective function (3.3) with the same number of tolls in the same links. We also applied SUTM with eight tolls to demonstrate the effect of tolls.

With 3 Tolled arcs

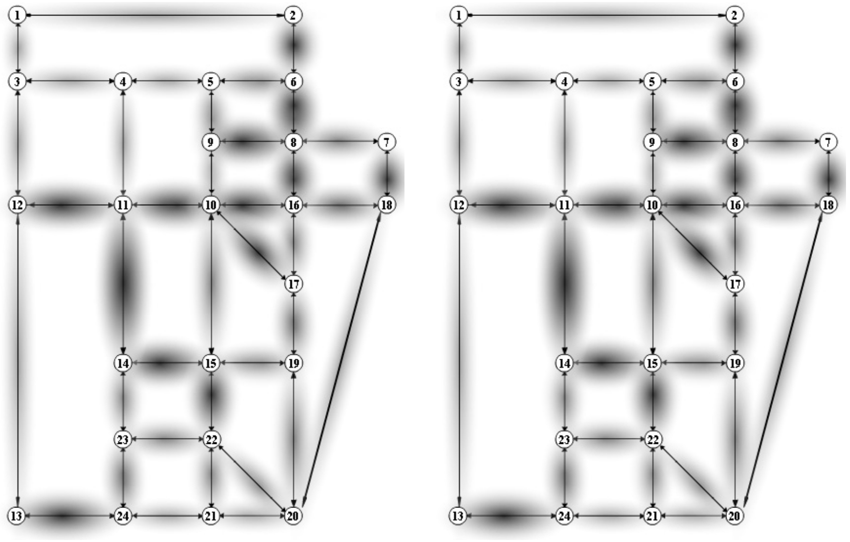
The resulting traffic flow and total emission graphs depicted in figures 4.3 and 4.4 show almost no difference with the original tollmpec results. This is an expected result because emission is still not a concern for network users. In the upper level objective functions of the network managers is to minimize total emission. The main instrument for network managers to reach this goal is toll pricing. In this instance the number of tolls which is the main means of alleviating congestion and emission is not enough to be able to manage the demand effectively. Therefore, the number of tolls in the network should be increased. On the other hand the lower and upper bounds of the tolls, which are determined by network managers, also affect the efficiency of demand management.



(a) Tolled arcs

(b) Traffic flows

Figure 4.3: Solution diagram of SUTM with 3 tolls



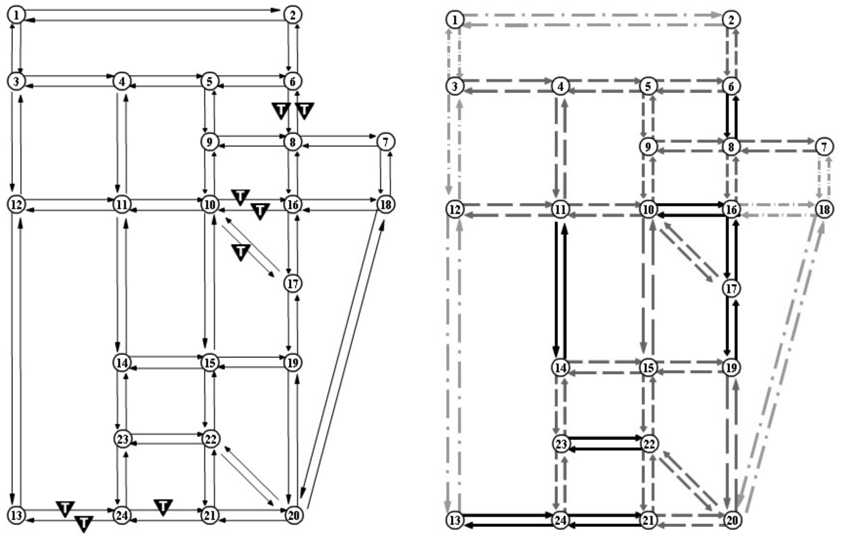
(a) Emission amounts of SUTM with 3 tolls

(b) Emission amounts of original problem

Figure 4.4: Emission graph of SUTM with 3 tolls compared to original model

With 8 Tolled arcs

Since in the previous model the number of tolls is not enough to affect the utilities of the network users significantly, we introduced a total number of 8 tolls on the links that are relatively more congested according to the original tollmpec solution. Introducing tolls more than 8, is also possible for modeling purposes but it is not easily applicable in real life. Therefore the number of tolls is chosen as 8 which is approximately 10 percent of total number of arcs. The tolls are introduced in the arcs (6,8), (8,6), (10,16), (10,17), (13,24), (16,10), (24,13), (24,21) as depicted in Figure 4.5(a). The resulting traffic flow and total emission graphs, Figure 4.5(b) and Figure 4.6(a), demonstrate a significant decrease in total amount of emission in the network. It is also demonstrated that introducing necessary number of tolls in the congested arcs enables the network managers to determine toll prices to alleviate the congestion hence the total emission in these arcs. A comparison of total emission graphs of original toll optimization model and sustainable urban transportation model with 8 tolls is depicted in Figure 4.6. In the original problem calculated total emission is 8439.806. By using SUTM with 8 tolls the emission amount is 7306.26. The total reductions is about 13.5%.



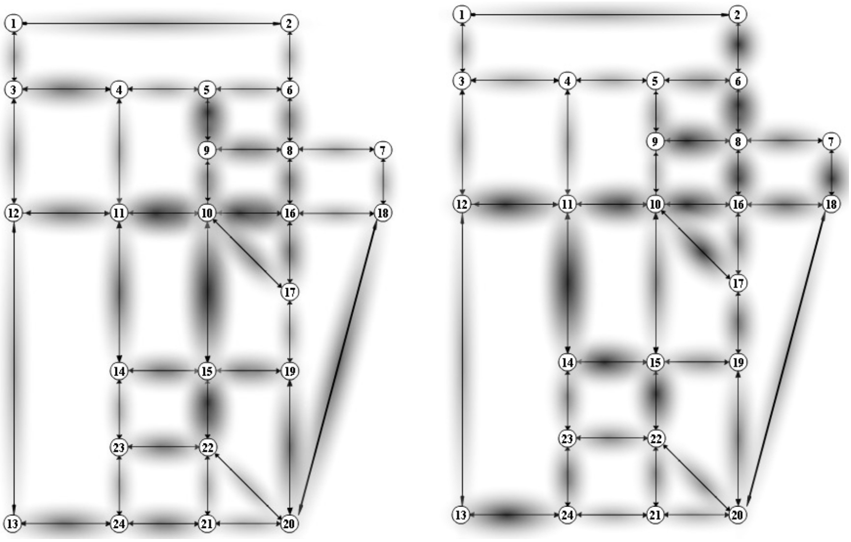
(a) Tolled arcs

(b) Traffic flows

Figure 4.5: Solution diagram of SUTM with 8 tolls

4.4 Capacity Enhancement Problem

Instead of introducing tolls we can increase the capacities of congested arcs. This leads us to the capacity enhancement problem. Among the described formulations in previous chapter, the continuous capacity enhancement formulation is used in this study. The arcs subject to capacity enhancement are the same as the previous instance. These are given in Figure 4.7(a) as (6,8), (8,6), (10,16), (10,17), (13,24), (16,10), (24,13), (24,21). The traffic flow and total emission flow graphs are depicted in Figure 4.7(b) and Figure 4.8(a). It can be realized that capacity enhancement is an effective tool



(a) Emission amounts of SUTM with 8 tolls

(b) Emission amounts of original problem

Figure 4.6: Emission graph of SUTM with 8 tolls compared to original model

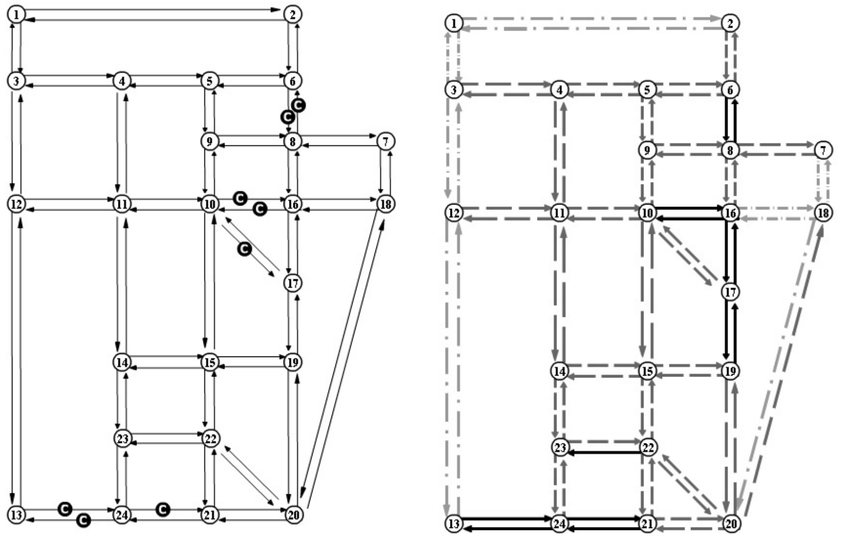
for decreasing congestion and total emission. Especially total emission graph shows significant decreases of total emission when compared to original tollmpec solution as illustrated in Figure 4.8. Total emission is calculated as 6055.761 which is reduced 28% compared to the original results. It is an expected result since the increasing capacities of congested arcs decreases the congestion hence the total emission in this link significantly. The capacity enhancement for each arc are given in Table 4.1. Determined capacity enhancement in link 16 and 30 is 0, which means there is no capacity enhancement. Capacities of other links are enhanced by different values.

Arc	Original Capacity	Enhancement
16	4.899	0
19	4.899	1.597
29	5.1335	2.268
30	4.9935	0
39	5.0913	1.92
48	5.1335	2.158
74	5.0913	1.251
75	4.885	1.548

Table 4.1: Capacity enhancement

4.5 Application of District Pricing

The results of the original tollmpec problem give several managerial insights about the network characteristics. From the figures it can be realized that there is a significant



(a) Arcs subject to capacity enhancement

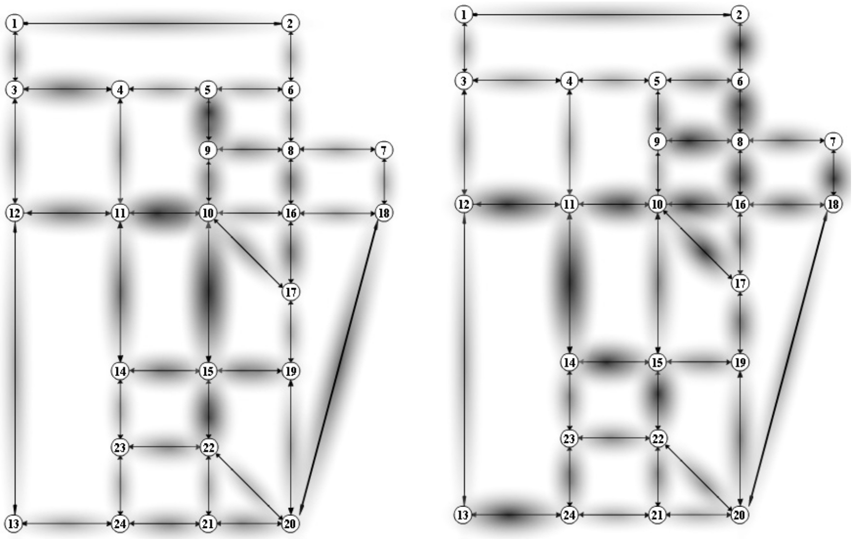
(b) Traffic flows

Figure 4.7: Solution diagram of the capacity enhancement problem

emission accumulation in and around the district consisting of nodes 8-9-10-16. From sustainability point of view sometimes avoiding emission accumulation can be the objective instead of minimizing the total emission. Concerning this issue to make this transportation system more sustainable we must disperse the traffic flow in this area. To alleviate the congestion hence the emission in and around this district a single toll price can be applied to the incoming arcs of the district as in Figure 4.9. In the figure arcs (5,9), (6,8), (7,8), (11,10), (15,10), (17,10), (17,16), and (18,16) are tolled. The traffic flow and total emission graphs depicted in Figures 4.9 and 4.10 show the congestion and emission alleviation effects of district pricing. Since the utilities of users' are affected by the introduction of tolls, the congestion and the total emission are dispersed from the tolled district to the links in the neighborhood according to travel costs. In the original problem calculated emission amount within the district is 1273.131, but district pricing policy enabled to reduce emission to 1101.132. The reduction is about 14%.

4.6 Application of Emission Dispersion

So far the models have the objective of minimizing the total emission. As mentioned in the previous section, from sustainability point of view sometimes the dispersion of the total emission is more important than the total amount. Instead of avoiding emission accumulation in a specific area, the objective may be minimizing emission accumu-



(a) Emission amounts of Capacity Enhancement

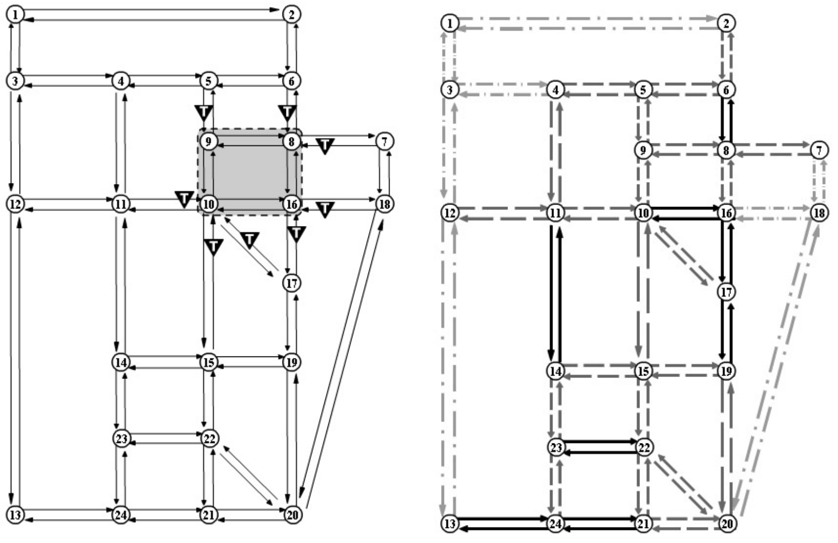
(b) Emission amounts of original problem

Figure 4.8: Emission graph of the capacity enhancement problem compared to original model

lations everywhere in the network. To modify the models concerning this issue we can simply change the objective function. The modified objective function is provided in previous chapter in (3.24). We applied this objective function to the model with eight tolls (Figure 4.11). The emission level coefficients given in (3.25) for the districts residential, commercial, industrial, and non-urban are taken as 0.6, 0.8, 1.2, 1.4 respectively. The traffic flow and total emission graphs depicted in figures 4.8(b) and 4.12(a). Figure 4.12 demonstrates the dispersion effect of the model on total emission. When compared with the graph depicting the original tollpec solution, it is obvious that the total emission is minimized and emission accumulations are avoided. In the original problem the dispersion measure is calculated to be 2671.497, but with emission dispersion policy the measure is 2119.697. The reduction is about 21%.

4.7 Numerical Results and Analysis

Numerical results of the previously mentioned models are summarized in Table 4.2. Detailed tables, including traffic flow and total emission amounts for each arc, are provided in Appendix A. *Average Traffic Flow in a link* is almost same for all the models. Slight differences arise from route changes. A network user using three links in his or her route may use another route consisting of two links. This means that all the improvements in total emission or dispersion amounts are achieved without making



(a) Tolled arcs and district

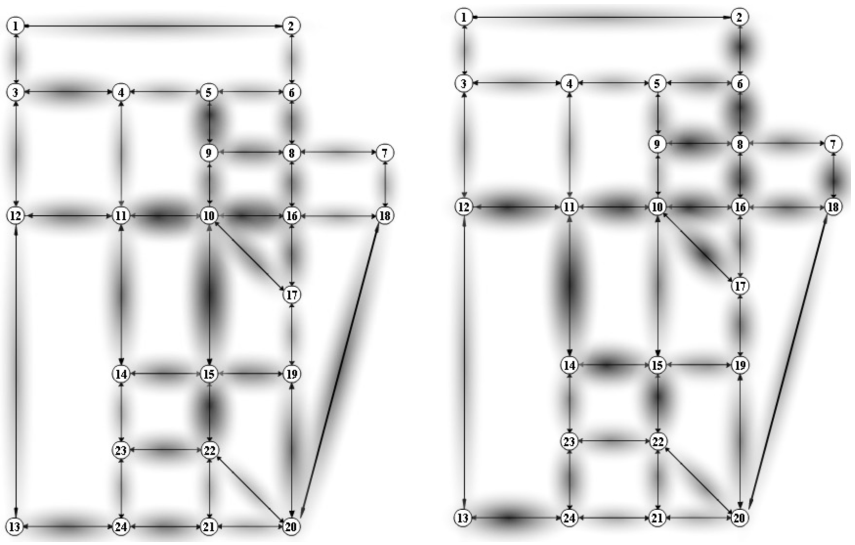
(b) Traffic flows

Figure 4.9: Solution diagram of the model exploiting district pricing

network users to use much longer routes.

The main difference among the models arise in *Total Emission.* As mentioned above the SUTM with three tolls give slightly better result than original tollmpec problem because of the number of tolls. But increasing the number of tolls and using district pricing resulted in a significant decrease in total emission besides the dispersion of the emission from the tolled district. The best result is given by the capacity enhancement problem formulation. This is an expected result since the extra capacities reduce the congestion hence the emission. This implies that capacity enhancement is an effective way of congestion and emission reduction.

Dispersion is a measure of emission dispersion throughout the network. If a network manager wants the prevent the accumulation of emission in specific areas, the model with the objective of minimizing emission dispersion can be used. The results given in the table also validate this suggestion. If the capacity enhancement model is not taken into account, the model with the objective function of minimizing emission dispersion gives the minimum dispersion measure as expected.



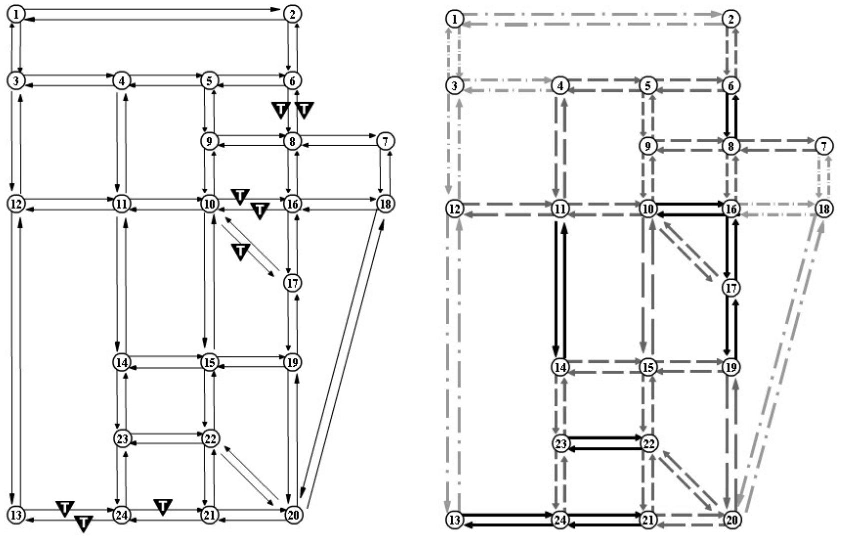
(a) Emission amounts of District Pricing

(b) Emission amounts of original problem

Figure 4.10: Emission graph of the model exploiting district pricing compared to original model

Model	Avg. Traffic Flow	Total Emission	Dispersion
Original Problem	12.98	8439.806	2671.497
SUTM w/ 3 tolls	12.97	8326.029	2609.112
SUTM w/ 8 tolls	12.92	7306.26	2136.315
SUTM of capacity enhancement	12.9	6055.761	1639.031
SUTM of district pricing	12.87	7325.201	2156.155
SUTM of emission dispersion	12.87	7336.288	2119.697

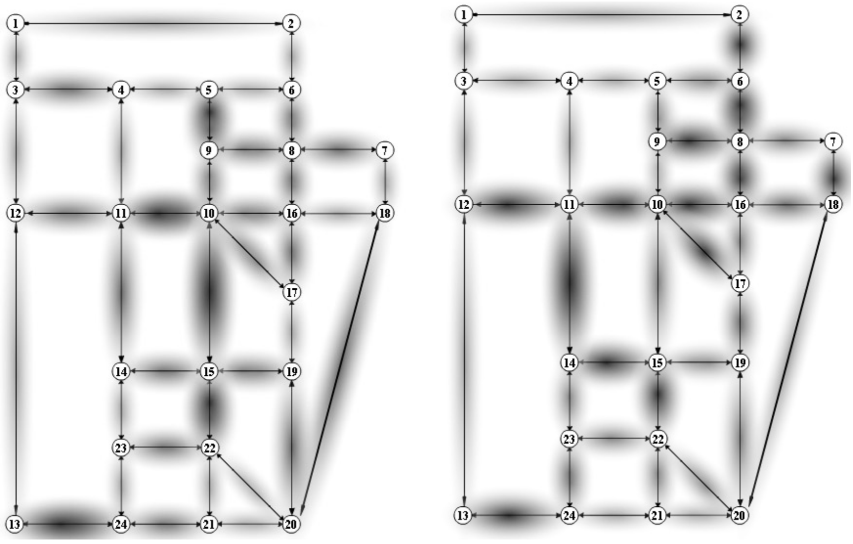
Table 4.2: Summary of numerical results



(a) Tolled arcs and district

(b) Traffic flows

Figure 4.11: Solution diagram of the model of emission dispersion



(a) Emission amounts of Emission Dispersion

(b) Emission amounts of original problem

Figure 4.12: Emission graph of the model of emission dispersion compared to original model

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH

In this study, focusing on the emerging topic of sustainable urban transportation, we conducted a wide literature survey. Mathematical and quantitative studies were examined. Concerning the lack of optimization models for sustainability, we investigated the means of using mathematical programming tools in the context of sustainable urban transportation. Suitable infrastructure for modeling sustainability in transportation networks is determined as bilevel programming. Requirements for a sustainable urban transportation model were discussed.

The exact relationship between traffic flow and vehicle emissions should be studied in detail and expressed analytically to build a model for sustainability of transportation networks. We performed a two stage study to express vehicle emissions in terms of traffic flow. The exponential behavior of the proposed emission functions reflected the real effect of congestion on air pollution. We have incorporated the emission functions in different mathematical programming models that we proposed for sustainable urban transportation.

The extensions to the models are provided for different kinds of transportation policies such as toll pricing, district pricing and capacity enhancement. It is shown that determining optimal parameters for these policies is possible by using the proposed models.

It is demonstrated that by using some demand management instruments and mathematical programming tools, it is possible to affect the users' utilities and to make transportation systems more sustainable. The proposed models determine the optimal toll pricing schemes to decrease total emission amounts. District pricing resulted in significant congestion and emission decrease in and around the districts. Introducing emission dispersion into proposed models enabled model to prevent emission accumulations throughout the transportation network.

Computational results and comparisonal analysis have shown that using more realistic emission functions instead of emission factors enables used mathematical models to have the ability of determining the optimal toll pricing policy for sustainability.

For future research the proposed mathematical models can be extended to include all urban transport modes. The emission functions should also be analyzed and expressed analytically for each transport mode and for each vehicle category. Besides the emission indicator, some of the other measurable indicators of sustainable urban transportation could also be incorporated into the model. In this study demand is assumed to be fixed, but in real life this is not the case. Applied tolls or capacity enhancement policies affect the travel demand. Therefore the proposed models should be modified to incorporate dynamic demand. This kind of a model requires extensive data but it provides a more suitable analysis tool for network managers.

Appendix A

RESULTS OF COMPUTATIONAL STUDY

This appendix invloves the results for the following models discussed in Chapter 4:

- Original tollmpec model
- SUTM with 3 tolls
- SUTM with 8 tolls
- Capacity enhancement
- District pricing
- Emission dispersion

ARC	FLOW	EMISSION	ARC	FLOW	EMISSION
1	10.353	77.896	39	15.341	410.873
2	8.452	44.037	40	11.425	137.24
3	5.602	60.557	41	11.439	172.206
4	12.333	221.218	42	9.047	70.531
5	13.203	58.561	43	23.766	212.94
6	7.407	35.787	44	9.264	93.687
7	17.424	75.439	45	15.373	69.32
8	19.014	91.627	46	17.375	128.9
9	10.23	22.863	47	9.318	95.113
10	0	8.4	48	12.021	202.701
11	18.097	41.899	49	12.64	96.435
12	5.797	28.384	50	21.494	76.278
13	14.893	113.839	51	8.91	135.736
14	7.582	58.494	52	12.216	85.63
15	9.418	78.253	53	11.568	71.435
16	15.369	207.072	54	18.36	39.899
17	14.295	76.69	55	19.993	68.773
18	20.025	44.09	56	26.876	133.011
19	14.241	150.952	57	19.913	102.43
20	15.96	101.772	58	9.133	36.121
21	8.163	137.662	59	8.357	58.131
22	9.955	113.657	60	23.71	110.003
23	19.138	206.249	61	10.462	104.794
24	9.335	191.115	62	7.923	77.214
25	20.152	89.335	63	8.603	77.848
26	25.569	152.726	64	7.655	71.636
27	21.306	279.39	65	10.669	55.528
28	13.362	91.224	66	11.065	93.055
29	13.31	290.822	67	21.065	216.082
30	10.921	238.362	68	7.81	62.347
31	3.74	23.937	69	9.057	35.363
32	19.619	220.607	70	10.346	101.447
33	8.517	91.192	71	9.535	80.849
34	13.111	220.068	72	11.631	109.052
35	10.568	49.997	73	8.664	31.677
36	12.256	259.801	74	12.224	171.666
37	16.985	55.351	75	12.408	135.562
38	13.868	46.923	76	10.437	52.044

Table A.1: Numerical results of original tollmpec problem

ARC	FLOW	EMISSION	ARC	FLOW	EMISSION
1	9.977	76.357	39	15.072	381.065
2	8.489	44.135	40	11.4	136.284
3	5.511	60.264	41	11.327	166.894
4	11.957	199.086	42	9.056	70.699
5	12.955	57.696	43	23.89	215.568
6	8.048	37.692	44	9.314	95.007
7	16.746	72.433	45	15.661	71.063
8	18.879	90.632	46	17.527	131.673
9	11.083	24.416	47	9.3	94.621
10	0	8.4	48	12.007	201.927
11	18.175	42.151	49	12.645	96.561
12	5.983	29.901	50	21.478	76.193
13	15.432	122.764	51	8.91	135.736
14	7.491	57.018	52	12.199	85.233
15	9.366	77.113	53	11.465	69.404
16	15.307	203.506	54	18.49	40.211
17	14.245	76.029	55	20.019	68.897
18	20.077	44.229	56	26.771	132.178
19	14.225	150.311	57	20.026	103.431
20	15.832	99.578	58	9.146	36.257
21	8.109	135.587	59	8.344	57.914
22	9.901	111.976	60	23.725	110.101
23	19.14	206.309	61	10.389	102.684
24	9.216	184.834	62	7.893	76.569
25	20.741	94.7	63	8.533	76.335
26	25.556	152.528	64	7.615	70.843
27	21.249	277.168	65	10.559	53.845
28	14.1	98.141	66	11.078	93.408
29	13.31	290.822	67	20.94	212.342
30	10.783	229.348	68	7.81	62.347
31	3.74	23.937	69	9.052	35.309
32	19.45	215.453	70	10.352	101.636
33	8.546	91.934	71	9.507	80.212
34	12.961	211.008	72	11.536	106.171
35	10.38	49.438	73	8.684	31.852
36	12.048	245.098	74	12.208	170.907
37	16.544	54.073	75	12.308	131.794
38	13.68	46.459	76	10.318	50.335

Table A.2: Numerical results of SUTM with 3 Tolls

ARC	FLOW	EMISSION	ARC	FLOW	EMISSION
1	6.184	62.452	39	10.783	114.663
2	10.152	48.765	40	10.93	119.499
3	6.192	62.479	41	9.806	109.041
4	6.517	43.411	42	8.905	67.77
5	10.144	48.741	43	26.382	275.869
6	17.242	79.371	44	9.778	108.183
7	12.853	57.344	45	20.466	107.423
8	17.328	79.926	46	18.725	155.722
9	21.301	53.624	47	9.191	91.771
10	6.06	45.838	48	11.748	187.793
11	21.333	53.757	49	12.432	90.968
12	8.809	65.969	50	19.077	64.561
13	18.216	181.263	51	8.91	135.736
14	6.525	43.51	52	12.417	90.605
15	8.807	65.936	53	10.162	48.178
16	14.112	145.634	54	18.419	40.041
17	14.129	74.554	55	19.031	64.354
18	18.42	40.043	56	22.328	101.248
19	14.119	145.892	57	20.502	107.754
20	14.13	74.564	58	10.147	47.986
21	7.991	131.185	59	9.413	78.136
22	9.19	91.751	60	22.28	100.96
23	18.25	182.128	61	9.435	78.607
24	7.998	131.417	62	6.91	58.153
25	24.298	134.676	63	7.7	60.456
26	24.339	135.215	64	6.884	57.734
27	19.102	205.206	65	8.739	32.35
28	26.271	327.437	66	10.838	87.33
29	11.81	191.059	67	18.772	156.743
30	8.91	135.736	68	7.7	60.456
31	6.114	46.534	69	8.768	32.609
32	19.093	204.956	70	10.303	100.243
33	9.147	108.793	71	8.997	69.541
34	10.867	117.379	72	10.378	76.781
35	12.759	57.021	73	7.532	23.072
36	9.128	108.22	74	10.67	111.093
37	15.29	50.597	75	10.784	86.012
38	15.177	50.295	76	7.699	24.178

Table A.3: Numerical results of SUTM with 8 Tolls

ARC	FLOW	EMISSION	ARC	FLOW	EMISSION
1	5.677	60.798	39	14.381	50.13
2	11.343	52.378	40	9.708	84.861
3	7.415	66.663	41	9.535	101.04
4	5.457	32.262	42	8.9	67.679
5	9.605	47.191	43	23.24	202.13
6	17.389	80.327	44	9.641	104.09
7	13.562	59.836	45	18.285	89.053
8	17.367	80.181	46	18.156	143.78
9	20.706	51.224	47	9	87.006
10	5.29	36.948	48	14.816	50.409
11	20.897	51.982	49	11.973	79.996
12	8.376	58.45	50	19.22	65.202
13	17.5	163.97	51	8.878	134.52
14	7.195	52.482	52	11.977	80.092
15	9.195	73.508	53	10.235	49.178
16	13.174	45.333	54	17.465	37.814
17	13.615	68.318	55	19.053	64.451
18	16.309	35.28	56	23.315	107.42
19	15.73	49.654	57	18.366	89.669
20	12.459	56.129	58	10.207	48.799
21	5.676	68.599	59	8.959	68.812
22	8.602	77.818	60	24.303	113.98
23	16.872	150.17	61	9.012	69.833
24	6.678	90.81	62	7.044	60.381
25	23.943	130.02	63	7.7	60.456
26	24.317	134.92	64	8.085	80.808
27	18.571	190.49	65	10.184	48.474
28	22.527	226.02	66	11.227	97.387
29	15.378	50.519	67	18.895	159.46
30	8.91	45.333	68	7.7	60.456
31	5.077	34.807	69	9.023	35.022
32	18.825	197.4	70	10.349	101.55
33	8.878	100.89	71	8.799	65.791
34	9.703	84.745	72	9.928	67.686
35	11.846	53.984	73	9.174	36.542
36	8.915	101.93	74	12.702	49.008
37	15.921	52.316	75	13.429	49.571
38	14.242	47.862	76	8.652	31.567

Table A.4: Numerical results of capacity enhancement policy

ARC	FLOW	EMISSION
1	6.09	62.142
2	10.05	48.468
3	6.09	62.142
4	6.426	42.317
5	10.05	48.468
6	16.604	75.379
7	12.03	54.583
8	16.604	75.379
9	21.004	52.412
10	5.72	41.672
11	21.004	52.412
12	8.807	65.946
13	17.923	173.98
14	6.426	42.317
15	8.807	65.946
16	14.017	141.809
17	14.053	73.587
18	18.343	39.857
19	14.017	141.809
20	14.053	73.587
21	7.99	131.135
22	9.165	91.107
23	17.923	173.98
24	7.99	131.135
25	24.013	130.926
26	24.013	130.926
27	19.163	206.948
28	25.555	305.024
29	11.926	197.398
30	8.91	135.736
31	5.72	41.672
32	19.163	206.948
33	8.911	101.838
34	10.624	109.658
35	12.03	54.583
36	8.911	101.838
37	14.437	48.361
38	14.437	48.361
39	11.728	149.412
40	10.624	109.658
41	9.826	109.626
42	9.184	73.271
43	25.555	254.187
44	9.826	109.626
45	20.157	104.604
46	19.235	167.247
47	9.165	91.107
48	11.926	197.398
49	12.441	91.208
50	19.212	65.164
51	8.91	135.736
52	12.441	91.208
53	10.169	48.282
54	18.343	39.857
55	19.212	65.164
56	22.539	102.541
57	20.157	104.604
58	10.169	48.282
59	9.44	78.721
60	22.539	102.541
61	9.44	78.721
62	7.18	62.713
63	7.7	60.456
64	7.18	62.713
65	8.749	32.439
66	11.089	93.689
67	19.235	167.247
68	7.7	60.456
69	8.749	32.439
70	10.373	102.217
71	9.184	73.271
72	10.373	76.663
73	8.339	28.924
74	11.728	149.412
75	11.089	93.689
76	8.339	28.924

Table A.5: Numerical results of district pricing policy

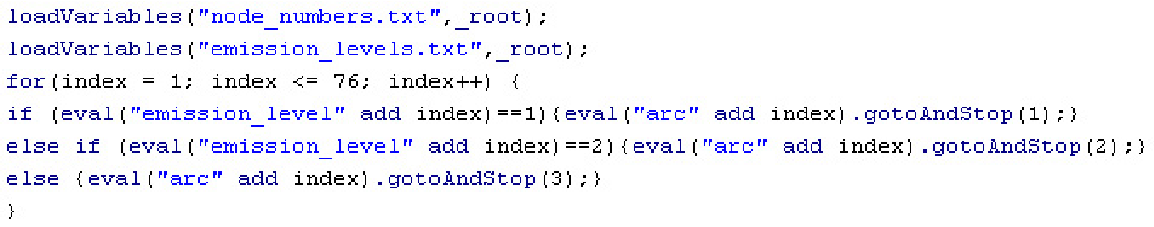
ARC	FLOW	EMISSION	ARC	FLOW	EMISSION
1	6.146	62.327	39	11.844	154.332
2	10.113	48.653	40	10.819	115.836
3	6.153	62.352	41	9.836	109.932
4	6.417	42.21	42	9.218	73.986
5	10.106	48.63	43	26.115	268.696
6	16.602	75.364	44	9.838	110.005
7	12.015	54.531	45	21.075	113.199
8	16.59	75.291	46	19.306	168.921
9	20.956	52.216	47	9.198	91.961
10	5.68	41.21	48	10.858	146.363
11	20.95	52.194	49	12.742	99.212
12	8.805	65.909	50	18.152	60.57
13	17.811	171.283	51	8.91	135.736
14	6.425	42.301	52	12.729	98.866
15	8.81	65.992	53	10.211	48.851
16	14.071	143.963	54	18.019	39.091
17	14.209	75.571	55	18.091	60.313
18	17.996	39.038	56	21.803	98.11
19	14.083	144.454	57	21.105	113.493
20	14.186	75.281	58	10.199	48.681
21	8.114	135.761	59	9.776	86.499
22	9.188	91.706	60	21.764	97.882
23	17.801	171.043	61	9.794	86.927
24	8.093	134.989	62	7.11	61.498
25	24.278	134.404	63	7.7	60.456
26	24.248	134.001	64	7.089	61.134
27	19.177	207.365	65	8.85	33.368
28	26.077	321.2	66	11.105	94.124
29	10.942	149.841	67	19.317	169.182
30	8.91	135.736	68	7.7	60.456
31	5.674	41.136	69	8.836	33.234
32	19.192	207.792	70	10.385	102.571
33	8.891	101.264	71	9.222	74.066
34	10.813	115.634	72	10.382	76.857
35	12.019	54.545	73	8.445	29.791
36	8.893	101.322	74	11.85	154.605
37	14.534	48.609	75	11.099	93.943
38	14.54	48.626	76	8.445	29.795

Table A.6: Numerical results of emission dispersion policy

Appendix B

VISUALIZATION OF RESULTS

The results of the corresponding models are visualized through a two step study. First, resulting emission and traffic flow values are transferred into MS Excel software and classified according to the levels. Then determined levels are used as an input to the Macromedia Flash file which we created for graph drawing. Macromedia Flash file includes two different kinds of objects, arcs and nodes, and 100 instances of these objects (24 nodes and 76 arcs). The code in the first frame of the first layer of the file, which is provided below in Figure B.1, uses a text file as an input for emission levels or traffic flows. Then the corresponding graph is drawn according to these values. An arc object consists of three frames that demonstrates the emission or congestion level of the arc.



```
loadVariables("node_numbers.txt",_root);
loadVariables("emission_levels.txt",_root);
for(index = 1; index <= 76; index++) {
if (eval("emission_level" add index)==1){eval("arc" add index).gotoAndStop(1);}
else if (eval("emission_level" add index)==2){eval("arc" add index).gotoAndStop(2);}
else {eval("arc" add index).gotoAndStop(3);}
}
```

Figure B.1: The code in Flash file

Appendix C

GAMS CODE

The following code is a modification of the original GAMS code tollmpec.gms. All the necessary variables and constraints for total emission and emission dispersion calculations are also included. These calculations are performed in all the models. Different models have different objectives like minimizing total emission or emission dispersion. The model provided below has 2611 variables and 2607 equations.

Variables x1,x2,...,x1748, *traffic flow variables
x1749,x1750,...,x2300, *distance variables
x2301,x2302,...,x2376, *traffic flows in arcs
x2377,x2378,x2379, *toll prices
ems1,ems2,...,ems76, *emission values in arcs
el1,el2,...,el76, *desired emission levels
z1,z2,...,z76, * dummy variables for absolute value constraints
objvar, *original objective function
emission, *total emission
avems, *average emission
absems, *emission dispersion

Positive Variables x1,x2,...,x1748, x1749,x1750,...,x2300, x2301,x2302,...,x2376, x2377,x2378,x2379, ems1,ems2,...,ems76, el1,el2,...,el76, z1,z2,...,z76;

Equations e1,e2,...,e1748, *complementarity constraints
e1749,e1759,...,e2376, *conversation of flow constraints
ee1,ee2,...,ee76, *calculation of emission in arcs
eel1,eel2,...,eel76, *calculation of desired emission levels
ez1,ez2,...,ez76, *calculation of z values
of, *objective function

```
te, *total emission calculation
ep, *emission dispersion calculation

e1.. 0.9*POWER(0.0386097404653246*x2301,4) - x1749 =G= -6;
e2.. 0.9*POWER(0.0386097404653246*x2301,4) - x1750 + x1773 =G= -6;
...
e1748.. 0.3*POWER(0.196908535985035*x2376,4) - x2300 =G= -2;

e1749.. x1 + x24 - x94 =G= 0.11;
e1750.. x2 + x25 - x48 =G= 0.11;
...
e2300.. - x896 - x1517 + x1702 + x1725 + x1748 =G= 0.77;

e2301.. - x1 - x2 - x3 - x4 - x5 - x6 - x7 - x8 - x9 - x10 - x11 - x12 - x13 - x14 -
x15 - x16 - x17 - x18 - x19 - x20 - x21 - x22 - x23 + x2301 =E= 0;
e2302.. - x24 - x25 - x26 - x27 - x28 - x29 - x30 - x31 - x32 - x33 - x34 - x35 - x36 -
x37 - x38 - x39 - x40 - x41 - x42 - x43 - x44 - x45 - x46 + x2302 =E= 0;
...
e2376.. - x1726 - x1727 - x1728 - x1729 - x1730 - x1731 - x1732 - x1733 - x1734 - x1735
- x1736 - x1737 - x1738 - x1739 - x1740 - x1741 - x1742 - x1743 - x1744 - x1745 - x1746
- x1747 - x1748 + x2376 =E= 0;

ee1.. -6*25*exp(1.5*0.0386097404653246*x2301)+ems1=E= 0;
ee2.. -4*25*exp(1.5*0.0427286516973957*x2302)+ems2=E= 0;
...
ee76.. -2*25*exp(1.5*0.196908535985035*x2376)+ems76=E= 0;

eel1.. el1-1.4*avems=E=0;
eel2.. el2-1.4*avems=E=0;
...
eel76.. el76-1.2*avems=E=0;

ez1.. ems1-el1=L=z1;
ez2.. ems2-el2=L=z2;
```

```
...
ez76.. ems76-el76=L=z76;

of.. x2377*x2309 + x2378*x2310 x2379*x2328+ objvar =E= 0;

te.. ems1+ems2+ems3+ems4+ems5+ems6+ems7+ems8+ems9+ems10+ems11
+ems12+ems13+ems14+ems15+ems16+ems17+ems18+ems19+ems20+ems21
+ems22+ems23+ems24+ems25+ems26+ems27+ems28+ems29+ems30+ems31
+ems32+ems33+ems34+ems35+ems36+ems37+ems38+ems39+ems40+ems41
+ems42+ems43+ems44+ems45+ems46+ems47+ems48+ems49+ems50+ems51
+ems52+ems53+ems54+ems55+ems56+ems57+ems58+ems59+ems60+ems61
+ems62+ems63+ems64+ems65+ems66+ems67+ems68+ems69+ems70+ems71
+ems72+ems73+ems74+ems75+ems76)/76-totems =E= 0;

ep.. z1+z2+z3+z4+z5+z6+z7+z8+z9+z10+z11+z12+z13+z14+z15+z16+z17
+z18+z19+z20+z21+z22+z23+z24+z25+z26+z27+z28+z29+z30+z31+z32+z33
+z34+z35+z36+z37+z38+z39+z40+z41+z42+z43+z44+z45+z46+z47+z48+z49
+z50+z51+z52+z53+z54+z55+z56+z57+z58+z59+z60+z61+z62+z63+z64+z65
+z66+z67+z68+z69+z70+z71+z72+z73+z74+z75+z76-absems =E= 0;

* set non default bounds and levels
....

Model m / e1.x1,e2.x2,..., e2376.x2376, *definition of orthogonality relationship
ee1,ee2,...,ee76, eel1,eel2,...,eel76, ez1,ez2,...,ez76, of, te, ep /;

Solve m using MPEC minimizing objvar;
display objvar.l;
display totems.l;
display absems.l;
```

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