Urban Transportation Planning for Air Quality Management - The Role of Social and Economic Costs in Welfare Maximization of Mobility Choice: A Case Study in Delhi, India

Karolin Kokaz
Harvard University
Division of Engineering and Applied Sciences
Pierce Hall 119
29 Oxford Street
Cambridge, MA 02138 USA
Phone: (617) 495-9293
Fax: (617) 496-1457
E-mail: kkokaz@fas.harvard.edu

Peter Rogers
Harvard University
Division of Engineering and Applied Sciences
Pierce Hall 116
29 Oxford Street
Cambridge, MA 02138 USA
Phone: (617) 495-2025
Fax: (617) 496-1457
E-mail: rogers@deas.harvard.edu

Abstract

The recent economic expansion along with the population growth experienced in developing countries has had a big impact on the development of large cities like Delhi, India. Accompanied by Delhi's rapid spatial growth over the last 25 years, urban sprawl has been contributing to increased travel. The vehicle fleet projected at current growth rates will result in more than 13 million vehicles in Delhi in 2020. Planning and managing such a rapidly growing transport sector will be a big challenge. Choices made now will have impacts lasting well into the middle of this century. With such rapid transport growth rates, automobile emissions have become the fastest increasing source of urban air pollution. In India most urban areas, including Delhi, already have major air pollution problems that could be greatly exacerbated if growth of the transport sector is managed unwisely. The transport plans designed to meet such large increases in travel demand will have to emphasize the movement of people not vehicles for a sustainable transportation system. Therefore, the mathematical model developed here estimates the optimal transportation mix to meet this projected *passenger km demand*, while satisfying environmental goals, reducing congestion levels, improving system and fuel efficiencies through exploiting a variety of policy options at the minimum overall cost or maximum welfare from transport. The results suggest that buses will continue to satisfy most of passenger transport in the coming decades, so planning done in accordance with improving bus operations is crucial.

INTRODUCTION

India is the world's seventh largest country in areal extent with 2.2% of global land and the world's second most populous country with more than 1 billion population. With a rapid economic expansion and population growth and a high rate of urbanization, planning and managing transportation systems has become a serious challenge. The total number of vehicles in India increased by more than 11 times from 1970 to 1990, approaching 21 million vehicles. The number of vehicles per 1000 people has increased from 3.4 to 25.31 in the same period, with previously given estimates of reaching 43 vehicles per 1000 people in 2000 (1). The number of registered vehicles has maintained its increasing trend with a growth from 25.2 millions in 1993 to 33.85 millions in 1996, 37.23 millions in 1997 and to an estimated vehicle fleet of over 50 million vehicles in 2001 (2).

This accelerated growth of the transportation sector in India will have the greatest impact on large cities where development is occurring in a fast and imperfect form. India is claimed to have 1% of world's vehicles (3) and most of these vehicles are located in urban centers. Automobile emissions are the most rapidly growing source of urban air pollution in most of these developing cities. These emissions contribute to a disproportionate amount of exposures and therefore result in very high health damages. Hence it is much more cost-effective to control vehicular emissions rather than industrial emissions in urban areas (4). This paper, therefore, focuses on urban transportation planning for air quality management at a macro level with Delhi as the case study.

Delhi has the largest vehicle population in the country with close to 3 million vehicles in 2000. The number of vehicles has grown very rapidly in the past 3 decades, the fleet has become 15 times bigger in this time period. The total number of vehicles per 1000 people in 1998 was 238. This number is estimated to reach 305 vehicles per 1000 people in 2005 (5). As the number of motor vehicles kept increasing the number of trips and distances traveled per trip have also increased with motorized passenger trips rising and cutting into bicycles' share of passenger trips. The transportation system is very inefficient with mostly personal vehicles - cars and two wheelers - that have mainly single occupancies (6).

Cities in developing countries usually allocate 10-15% of their total land area for roads compared to 15-30% in cities in industrialized countries (20-25% in European cities). Delhi has 23% of its land area as roads. Although Delhi has one of the highest per capita road lengths and lowest number of vehicles per unit road length when compared with large cities around the world due to its large road network, it is still the most congested city in India (7). Delhi has the highest road length in India (26,379km of total length in 1998/1999), and its roads, if modern traffic management is applied, could accommodate 2-3 times the existing number of vehicles (5). In international comparisons of urban population density versus per capita length of urban roads (8), Delhi remains an outlier. Therefore, in order to reduce traffic congestion in Delhi, the use of well-designed traffic management control options are essential, and they will provide Delhi with a relatively quick and easy reduction in congestion levels.

In this study of urban transport, which is one part of a project on transportation and environment at Harvard University, two different methodologies, simulation and optimization, are used to model the future vehicle fleet growth and the resulting vehicular air pollution in Delhi. The results from these applications will also be later linked to a GIS for Delhi for a visual representation and the evaluation of the effects of land use changes on air quality.

WAYS TO FIGHT AGAINST VEHICULAR AIR POLLUTION AND DEVELOP AN EFFICIENT TRANSPORTATION SYSTEM

Transport planning is very important in the continued growth of the economy of a country. It should be carried out very carefully because there are many options to choose from and compare, the investments are very large, projects are very long lasting, and once committed to one there is no easy way of going back. A good transport plan should, after going through the steps of travel surveys and data collection, consider all the alternatives, transport management strategies, and policies for transport development that can be used in meeting the forecasted demands.

There are two major ways of reducing adverse environmental impacts of the transportation sector: reducing the emissions per kilometer driven and reducing the amount of travel (vehicle km traveled - VKT). There are many different ways of achieving both of these objectives.

Emission factors (g/km) are affected by a variety of parameters: fuel efficiency, traffic flow, speed, driver behavior, temperature, fuel characteristics, age, and maintenance levels of the vehicles. There are numerous ways of reducing these emissions per kilometer driven: emission standards for new vehicles, emission control devices, improving fuel quality, decreasing vehicle retirement ages, improving maintenance standards, using clean fuels and better engine design technologies (alternative fuel vehicles, new and clean vehicle technologies), flextime working hours, and managing the existing street space to maximize available capacity.

There are also various ways of enforcing the reduction of VKT: traffic demand and supply management options which include vehicle ownership and use controls, encouraging ridesharing, telecommuting, building roads, improving public transit, providing park and ride facilities, pricing options (road pricing, parking pricing, vehicle fees, fuel taxes), area licensing, land use management, change of modal split, road segmentation for buses, bicycles, and other vehicles. Other options such as increased quality of pedestrian environment in suburban zones has been found to decrease vehicle miles traveled.

All these measures should be considered carefully because of the interactions they have among each other and while improving one they can worsen the effects of another. For example increasing vehicle prices will decrease vehicle registrations (i.e. the number of vehicles) but also will increase the vehicle life which will increase emissions per kilometer driven. Increasing fuel prices on the other hand will result in a win-win situation because it will decrease vehicle use and will also increase fuel efficiency because people would want to buy more fuel efficient vehicles. Also, benefits obtained by some control options could be in the short run only. For example, half of the time saved from improvements in speed has been found to be used for further travel. Finally, “new capacity attracts new demand”, increased highway capacity has shown to have resulted in readjustments of settlement patterns and an increased dependence on motor vehicles (9).

People want access to timely, convenient, comfortable, and dependable mobility at an affordable price. Transport plans should keep that in consideration and also should emphasize the movement of people not vehicles. This is the only way to achieve both satisfaction and increased quality of life with the least environmental and economic damage.

DELHI’S TRANSPORTATION SYSTEM CHARACTERISTICS

Compared with other big cities in the world, Delhi has less automobile usage, no subway or light rail passenger transport, and much more bus passenger transport and non-motorized vehicle usage (mainly walking and bicycling). Turnover period of vehicles in Delhi is about 20 years compared to 6-8 years in developed countries and in Delhi vehicles also lag behind European standards (Delhi just introduced Euro 2 norms in April 2000 for all new cars and Euro 1 for all heavy duty vehicles).

Although there is a large rail network of 120km in Delhi, almost all passenger transport demand is met by road. Delhi has two ring roads and one ring railroad. Five railroads and nine roads, of which five are national highways, intersect in Delhi leading to large amounts of congestion in the city. There is no traffic segregation and lane discipline, and all motor vehicles as well as bicycles, tricycles, handcarts, bullock carts, animals, and pedestrians share the same road space. All this chaos results in about 10,000 accidents per year which causes about 2,000 deaths and 10,000 injuries.

The public transport system is inadequate with only buses and poorly planned routes. There is yet no subway or light rail transport system (LRTS). Increasing incomes and economic activities together with the inefficient public transport system has led to an increase in cars and two wheelers. The older and poorly maintained vehicle stock has contributed to the air pollution problem in Delhi. In 1995, Delhi was named to be one of the top ten most polluted cities in the world and the fourth most polluted city in the world in terms of particulate matter (10). Particle levels in Delhi consistently remain 3 to 5 times the national standards. Maximum levels of PM10 in a residential area in Delhi (Ashok Vihar) have reached 10 times the standards in October 2000 (11). Particulate pollution was reported to kill 1 person per hour in 1995 (12). The annual average ambient total suspended particulates concentration was around 400µg/m^3 in Delhi in 2000. On the other hand, SO_2 and NO_x values tend to stay below the ambient standards and the 2000 annual average ambient concentrations of SO_2 and NO_x were 18µg/m^3 and 40µg/m^3 respectively. Also, about 14% of CO_2 emissions come from the transportation sector in India with an increasing trend (13). An average car in India weighs about 800kg and emits 5 times its weight of CO_2 in one year. The rapidly growing, yet inefficient and inadequate, transportation sector in urban cities of India could have large impacts on greenhouse gases emissions in the future.

In light of the problems faced by the Delhi government in planning and managing the extremely fast growing transport sector, many actions has already been taken to curb air pollution from motor vehicles and develop a sustainable transportation sector. Leaded gasoline was phased out in September 1998 and catalysts were mandated on all new cars in October 1998. Delhi has introduced Euro II standards for all new cars in April 2000 and Euro I for all new light duty and heavy duty vehicles. Sulfur content of diesel and gasoline were reduced to 0.05% by weight in April 2000. Tighter motorcycle standards with mandatory use of catalysts were introduced in 2000. New retirement ages for vehicles were set up by successive rulings of the Supreme Court - after year 2000 the retirement age for cars was 25 years, for two wheelers 15 years, for autorickshaws 10 years, for taxis 10 years, for buses 8 years, and for trucks 12 years. The Delhi government banned the registration of diesel taxis in the capital starting January 2000 to control toxic particulate pollution in the capital. The use of alternative fuels and especially CNG buses are being pushed. The entire city buses (Delhi Transport Corporation (DTC) and Private) were to be steadily converted to CNG by September 30, 2001, but the deadline has been extended once more to March 31, 2002. The results of the implementation of such decisions are rather uncertain. Delhi Metro Rail Corporation is working on a large project for the implementation of Delhi's mass rapid transport system (MRTS) which in its first phase plans to build 11km of subway and 41km of surface and elevated rail by 2005 in order to reduce congestion, air pollution, and accidents and save fuel and space (14). The full system is planned to be finished by 2021 with 34.5km of subway, 35.5km elevated and 111km surface rail, and 17.5km of dedicated busway with a total system length of 198.5km. On the traffic demand management side, the Supreme Court has limited the monthly number of car registration to 1500 (previously 4000 vehicles per month were being sold). Finally, goods vehicles are restricted during the day within the city limits (December 1997).

Delhi, which has experienced a massive growth in small-scale industries in the last 15 years, has been directed by the Supreme Court to relocate its 114 highly polluting stone crushers outside the city boundaries (15). Though how effectively this policy has been implemented is questionable.

There is also a huge need for institutional and regulatory reform in Delhi. Multiple institutions are responsible for urban transport planning in Delhi. It is not clear which organization is responsible for doing what and many approvals need to be taken to be able to run and implement a project. There is a lack of coordination and poor enforcement. It would be better to have one overseeing body responsible for organizing and coordinating these many institutions to run more effectively and efficiently. Some of these organizations are private organizations and they do not share their data. There is a small amount of publicly available data with very little explanation about how they have been gathered or calculated, therefore with questionable credibility. All these make models which are very data intensive, such as the ones being implemented here, easy to develop, but hard to calibrate. The following discussion is based upon the results of model runs using the best available data set.

METHODOLOGY AND RESULTS

Simulation versus Optimization

Usually planners make simulations of one or more options to evaluate their cost effectiveness and to make comparisons. Using optimization requires less of the repetitive work involved in running many simulations, and it is an integrated way of looking at an extensive list of control options.

The motor vehicle fleet in Delhi is represented in our simulation model by 6 different types: cars/jeeps/station wagons (categorized as cars), two wheelers, three wheelers (autorickshaws), taxis, buses, and trucks. Other modes of transport include bicycles, tricycles, light rail and subway. Walking is not entered as a transport choice in the models mentioned in this paper but calculations for this mode are made outside the model to check that this demand will be met.

Walking trips made up 32% of the total trips in 1994 in Delhi (16). This accounted for about 7 million trips per day and totaled approximately 4.4 billion-passenger km (bpkm) (about 5% of the total PKM traveled in 1994). As motorization continued over the years in Delhi, walking trips were somewhat reduced. By 2000, roughly 4.4 million people out of 13.8 million people met their travel needs by walking; about 2.7 bpkm which was a little over 3% of total PKM traveled.

A spreadsheet simulation model, which is a vehicular air pollution information system for Delhi (VAPIS - 17, 18), using current growth rates of vehicles, retirement age prerequisites, strict emissions standards, fuel efficiency and fuel quality requirements, projects the number of vehicles, average vehicle fuel efficiencies (km/lt), average vehicle emission factors (g/km), age distribution of vehicles in each year, vehicle kilometers traveled by each mode in each year, fuel consumption, and emissions of pollutants (CO, NO_x, HC, Pb, TSP, PM10, SO_2, CO_2). In addition to Delhi being under Euro II standards for all new cars (2000), the model assumes that Euro III and Euro IV standards will be enforced for all new vehicles by 2005 and 2015 respectively. The corresponding fuel qualities for sulfur content of gasoline and diesel are also required to comply with the Euro norms accordingly. Essential technological improvements in vehicle engine designs and fuel qualities are assumed to be accomplished to meet the mandatory emissions standards and fuel efficiencies. The aim is to investigate technology advancement’s impact (through emissions standards, fuel efficiency, and fuel quality requirements) on air pollution from mobile sources.

The spreadsheet reports that the vehicle fleet which was close to 3 millions, mostly dominated by cars and two wheelers, in 2000 will reach about 13.5 million vehicles in 2020, approximately a 4.7 times increase in 20 years. Although the fleet becomes younger and cleaner, the emissions and fuel consumption of such a large network also ends up being very high. Total emissions and fuel consumption increase by 3 times. If necessary land use and traffic management options are not implemented then with so many vehicles on roads speeds will reduce drastically and traffic congestion will become an immense problem which will result in increased delay time in traffic, fuel wasted and more vehicular emissions (18).

The ideal thing to do would be to make an optimization model to maximize the net benefits which would include traffic delay time savings, health damages avoided, and fuel savings minus the costs of vehicular air pollution reduction. However, it is very hard to quantify exactly some of these benefits so instead the model considers two different approaches. In one of them, the mathematical model minimizes total costs (fuel costs, vehicle costs and their operations and maintenance costs (OM), infrastructure costs, and traffic control options costs) subject to a variety of constraints and an accounting equation on the health damages and value of time. The outcome of these social costs can then be analyzed and if the user is unhappy with the results the constraints can be changed and the model can be run again until satisfactory results are obtained. The second approach to including best estimates of social costs in the decision making process is to have them in the objective function for minimization. So the model will minimize all direct system costs together with health costs and value of time spent in traffic. Therefore, while meeting travel demand with the least possible cost, the model will also try to keep speeds high and emissions low to minimize the social costs.

A third approach utilized for using the optimization framework to aid urban transportation planning is the general equilibrium analysis of the maximization of producers’ and consumers’ surplus for maximizing the welfare from the transport sector in Delhi (19, 20, 21). (See Figure 4.) This general equilibrium model makes use of cross price elasticities and income elasticities for different modes of transport to define demand and supply functions for them, and both prices and incomes are endogenous to the model (9, 22, 23). Therefore, the solution of the model will verify both the position of the demand curve (as demand functions will shift when incomes change in time) and the point on the demand curve. Linear downward sloping demand curves are assumed and maximization of the producers’ and consumers’ surplus is carried out to achieve a representation for maximizing welfare from the future transportation system of Delhi in order to determine the vehicle fleet composition to attain this goal.

The optimization model contains 10 transport modes (cars, two wheelers, autorickshaws, taxis, buses, trucks, light rail, subway, bicycle, tricycle - again calculating remaining travel for walking outside the model) with nine different engine technologies and fuel types (gasoline, diesel, ethanol, methanol, natural gas (CNG), liquefied petroleum gas (LPG), electric, hybrid electric, hydrogen fuel cells).

The model constraints include emissions limits for air quality improvements and reduction of health impacts, improvement of system and fuel efficiencies, a budget constraint for government spending on infrastructure investments and public transportation, and most importantly the travel demand constraint which states the future passenger km demand that needs to be met by the transportation system. Also the calculation of number of vehicles in each year, age distribution of the vehicles, vehicle km traveled by mode, average emissions factors and fuel efficiencies, fuel consumption, emissions and concentrations, speeds, value of time, energy use and emissions per passenger km, costs per passenger km for each mode, million tons of carbon emissions, and average toxicity of the emissions are carried out through defined equations in the model.

The traffic control options included in the optimization model are: 1. Advanced and clean vehicle technologies and alternative fuels, as mentioned previously, to meet transport demand, 2. Emissions standards, fuel quality, and fuel efficiency requirements (2% annual fuel efficiency improvements, Euro II - 2000, Euro III - 2005, Euro IV - 2015 emissions standards and corresponding fuel quality requirements -

0.015% gasoline sulfur content and 0.035% diesel sulfur content under Euro III and 0.005% gasoline and diesel sulfur content under Euro IV), 3. Investments in rail infrastructure, 4. Simple traffic management options such as arranging traffic direction according to flows, putting traffic signals and policemen to arrange traffic, and synchronization of traffic lights, all in order to increase fuel efficiencies and reduce emissions through increasing traffic flow speeds, 5. Building inspection and maintenance stations for vehicle testing, 6. Increasing the parking cost for cars by 10% (from around Rs20/day to Rs22/day), 7. Ridesharing - increase car and taxi occupancy by 7%, 8. Telecommuting - for a 10% reduction in passenger km demand, 9. Fuel taxes: increasing gasoline prices by 5% and diesel fuel prices by 10%, 10. Fuel subsidies: reduce alternative fuel prices by government subsidies - methanol, ethanol, and LPG by 5%; electricity and CNG by 10%, hydrogen fuel by 20%, hybrid by 5% for electricity use. (See Figure 1 for the model structure.)

In summary, the mathematical model developed here will generate the optimal transportation mix for Delhi to meet its future passenger km demand, environmental goals and other constraints through a variety of policy options at the minimum economic and social cost or in other cases at maximum welfare benefits. A very important idea used in this model is that vehicle growth rates are not predetermined, but instead left for the model to allocate. The current version of the optimization model has 2,250 to 3350 equations and 3250 to 4350 variables, depending on the case, with nonlinearity in both the objective function and constraints. The model can be solved using different NLP (non linear programming) solvers present in GAMS' (General Algebraic Modeling Systems) latest version (24).

Optimization Model Structure - Analysis of Different Cases

These models are very data intensive and the outcome will be as good as the data set used in their preparation. Although the best available data set is formed in order to be used in these models, as with all models there are assumptions made both in terms of some of the data and the relationships formulated. Data assumptions are such as averages in occupancy levels and VKM driven for each vehicle mode, attainment of specified retirement ages, emissions factors, fuel qualities, fuel efficiencies, cost estimates for future technologies (vehicle and their OM costs, fuel costs), projections of population growth and future PKM demand, and effects of different control options. Relationships created include going from emissions to concentrations, calculating health impacts, estimating speeds based on vehicle and population growth, and use of speeds, trip times, wages, and passengers traveling for the calculation of value of time spent in traffic (VoT).

The optimization model has been run for various cases including:

- *minimizing total costs or maximizing welfare (for two different sets of pkm demand in the future)*[1]
  - with or without the social costs (value of time and health costs) in the objective function
  - with all the traffic control options listed or with only the first three control options for vehicle technologies, emissions, fuels, and rail infrastructure
  - with or without a limited government budget spending for the transport sector (mainly for public transportation and infrastructure investments)
  - with limited number of buses for some of the previous cases

The following sets are defined in the model: *p:* different pollutants, *v:* different vehicle types, *f:* different fuel types, *t:* different years from 2000 to 2020 with 5 year intervals, and *a:* age of the vehicles. Some of the many different outputs the model provides include: average emissions factors (p,v,f,t), average fuel efficiencies (v,f,t), emissions (p,v,t), average toxicity of total emissions, concentrations (p,t),

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[1] One set of PKM demand assumes a 5% increase per year starting from 2000 to 2020 based on TERI estimates (6) - *SET 1* - and the other set uses the equivalent PKM traveled for passengers, excluding the trucks, from the spreadsheet results - *SET 2* - for the transport demand constraint in the optimization model.

fuel consumption (f,v,t), total system fuel costs and health damages (economic costs of health impacts, premature deaths due to air pollution, life years lost, disability adjusted life years (DALYs)), million tons of carbon emissions (t), number of vehicles (v,a,f,t), modal choice (VKT and PKM by vehicle), vehicle costs and their OM costs (v,t), average speeds, value of time, energy use - emissions - and costs per PKM, rail infrastructure investments, costs breakdown at optimal solution, shadow prices on constraints (budget, vehicle upper/lower bounds, emissions limits, PKM demand), and tradeoff curves for costs/emissions/PKM demand.

Discussion of Model Results

The optimization model was run for more than 60 cases for a combination of the objectives defined in the previous section. The following 10 cases are chosen for cross comparison in more details:

- *Case 1:* Minimizing total costs without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 1 PKM demand
- *Case 2:* Case 1 with SET 2 PKM demand
- *Case 3:* Case 2 with social costs
- *Case 4:* Case 2 with all the traffic control options
- *Case 5:* Maximizing welfare without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 2 PKM demand
- *Case 6:* Case 5 with an aggregate demand and supply curve for total motor vehicles
- *Case 7:* Case 1with limited number of buses (35,000)
- *Case 8:* Case 2 with limited number of buses (50,000)
- *Case 9:* Case 5 with limited number of buses (50,000)
- *Case 10:* The spreadsheet simulation

Some of the model outputs for these cases are shown in Tables 1 and 2.

Analyzing the results for Case 1 shows that the increase in passenger transport demand is being met almost solely by gradually increasing the number of buses in accordance with the growing demand. All the other modes of transport basically remain at their lowest utilization limits. By the year of 2020 more than 80% of the PKM demand is satisfied by public transport buses. This supports the large reduction in emissions along with the use of clean and alternative fuel vehicles such as gasoline and CNG cars, LPG and ethanol two wheelers, LPG autorickshaws, CNG taxis, and hybrid buses and trucks. The resulting annual value of time spent in traffic (VoT) and fuel costs from this transport system amount to $2.39 billion and $2.32 billion respectively, and the health costs are about $1.26 billion in 2020.

Case 1 has used the PKM demand given by Set 1, which assumed about a 5% per year growth in travel demand (6). This is rather a more conservative growth estimate compared to the annual growth of travel demand which is stated to be around 9.5% in Padam and Singh, 2001 (2). Case 2 utilizes the Set 2 PKM demand that necessitates a higher PKM travel than SET 1 estimated through using the spreadsheet simulation (18). This being still lower than the annual 9.5% increase, corresponds to a slower initial growth rate followed by about a 7.6% annual growth rate in travel demand. As a result, Case 2 simply becomes Case 1's parallel only with the higher PKM demand that needs to be met. Similar results to Case 1 can also be observed from Case 2's outcome where most of the additional travel demand is carried out by buses. But in 2020 buses reach their limit of 85% of PKM travel and supplementary bicycles and tricycles are utilized to meet the left over demand. Case 2 has slightly more motor vehicles and therefore a little lower speeds. This together with more passengers on roads due to increased travel demand results in higher VoT and health costs compared to Case 1.

Comparing Case 2 and Case 3, the addition of social costs in the objective function in Case 3 results in no change in the total number of motor vehicles in the fleet and its composition. However, in

Case 3 a light rail network replaces more than half of the bicycles present in Case 2 since a much larger passenger group can be served with a small light rail network eliminating many bicycles from roads. Also, cleaner vehicle technologies are used in Case 3 to reduce emissions and therefore health costs/impacts further: gasoline and CNG cars, LPG and CNG two wheelers, CNG and electric autorickshaws, CNG taxis, and hybrid buses and trucks. The outcome is that Case 3 has lower health costs/impacts and VoT. The total costs of the system for the model period of 20 years is slightly higher in Case 3 from the utilization of more expensive and cleaner vehicle technologies and the construction of the light rail network.

Comparing Case 2 to Case 4, where we have all the traffic control options present in the model, the total number of vehicles are less in 2020; the reduction coming from having fewer buses, bicycles, and tricycles due to a lower PKM demand resulting from the additional ride sharing and telecommuting options in Case 4. Somewhat fewer vehicles on roads lead to a little higher speeds and therefore lower VoT in Case 4. Also vehicular emissions and therefore resulting concentrations and health impacts are lower in Case 4.

Case 5 is similar to Case 2 except that here maximization of welfare from transport replaces the minimization of total costs equation in the objective function. Total cost of the suggested transportation system by the model is calculated with a separate equation. This formulation results in more vehicles in Case 5 that maximize people’s welfare from transportation but also have much higher system costs (close to 80% higher). Most important modes of transport are cars, taxis, and buses which increase in number to meet the growing travel demand. Since there are more vehicles on the same road network, VoT is higher in this case than in Case 2. However, since emissions limits still need to be met a mix of different alternative fuel vehicles and clean vehicle technologies are used by each mode of transport, which keeps health costs at a lower level than Case 2.

Case 6 uses the same approach of welfare maximization as in Case 5 but this time instead of having individual demand and supply curves for each transport mode there is one demand and supply curve for the total number of vehicles and passenger transport. This results in a switch to the utilization of high occupancy transport modes such as buses, light rail, and subway. The reason for this switch might be because these modes lie on the lower right hand side of the demand function where the cost per PKM is very low for a large quantity of PKM travel that these modes can satisfy. By using more of these transport modes the solution moves southeast towards the down right side on the demand curve and this increases the consumers’ and producers’ surplus area which in turn results in higher welfare values. In this case, all of the increase in travel demand is being met by increasing the number of buses, light rail, and subway; and all the other modes of transport remain at their lower limits. Consequently, Case 6 has lower total number of vehicles and this yields a decrease in VoT compared to Case 5. Only in this case, since some of the travel demand is met through zero emission light rail and subway and low emissions per PKM transport mode of buses, to reduce system costs a wider mix of vehicle fuel and technologies including more traditional ones are used which results in higher emissions (still meeting the requirements) and therefore higher health costs in Case 6 compared to Case 5.

One of the general outcomes observed in Cases 1 through 6 is that the system requires a lot of buses to meet the passenger transport demand (Figure 2 - example of Case 1). This implies that buses are the most cost effective and environmentally friendly form of transport for moving people. Therefore, a very well planned public transport system, with dedicated bus lanes and bus priorities, is essential for developing a sustainable transportation system.

It will be very hard to build a transportation system with the number of buses suggested by the previous optimization runs. Therefore, to investigate which other modes of transport will become competitive and also to make comparisons with the spreadsheet simulation results in Case 10, Cases 7, 8, and 9 are run with a limit on the total number of buses (about half the number suggested by the model output). So, Case 7 is Case 1 with a limit on buses of 35,000. What happens is first light rail then autorickshaws, bicycles, and tricycles are utilized up to their limit and then many more two wheelers come into the system to meet the demand of about 35,000 buses that are removed from the system. The total number of motor vehicles alone is more than 2.3 times that in Case 1 and this results in a much higher VoT in Case 7. Emissions limits need to be met in this case too but because there are more vehicles on roads, the result is higher vehicular emissions which also produce higher health costs/impacts in Case 7 compared to Case 1.

Case 8 is formulated such that it is Case 2 with a restriction of having at most 50,000 buses, half the amount in Case 2 outcomes, in order to observe how the transport system will change and compensate for the 50,000 buses removed from the system. In this case, first light rail and subway, then bicycles, tricycles, and autorickshaws, and finally two wheelers and taxis increase in number and reach their maximum limits in the model by 2020 to meet the left over demand from the 50,000 buses that are removed from the system. The total number of vehicles in this case is much higher and therefore speeds go down and VoT reaches about $17 billion in 2020. There are still emissions limits that need to be met and there are so many more vehicles on roads, therefore more of clean vehicle technologies must be used. The vehicle fleet composes of gasoline and CNG cars, ethanol and CNG two wheelers, electric, hybrid, and CNG autorickshaws, CNG taxis, electric and hybrid buses, and hybrid, LPG, and ethanol trucks. Case 9 is Case 5 with a limit on buses of 50,000. Cars, taxis, and tricycles are welfare maximizing transport modes and their numbers increase to compensate for the reduction in buses. Also, some light rail and subway is used to meet travel demand. Compared to Case 5, more vehicles are required to meet the demand in this case and therefore speeds go down accompanied by a large increase in the VoT and consequently about $14 billion is lost in time spent in traffic in 2020. A mix of advanced vehicle technologies are used to reduce emissions in this case, but still the result is higher health costs compared to Case 5. Case 9 has lower total number of vehicles than Case 8, most of the two wheelers, autorickshaws, light rail, subway, and bicycles in Case 8 are replaced by cars, taxis, and tricycles in Case 9. Therefore, VoT and health costs are also lower in Case 9 (See Figure 6).

The vehicle fleet composition in Case 8, comes closer to the vehicle fleet from the spreadsheet simulation, which can be seen as Case 10 in the last column of Table 2. There are more cars in Case 10 and the total number of motor vehicles is higher as well. Therefore, the VoT in 2020 in Case 10 is also very high (about $16.5 billion). The spreadsheet simulation model projected the current situation into the future and therefore the vehicle fleet was gasoline and diesel based, although much cleaner due to the emissions standards, fuel efficiencies, and fuel quality requirements. Since a variety of alternative fuel vehicles and clean vehicle technologies were available to choose from in the optimization model runs, there are much larger emissions and higher health costs in Case 10 compared to outcomes from the optimization cases.

There are a great number of bicycles and tricycles and also a large subway and light rail network in Case 8. The spreadsheet simulation has not modeled the subway and light rail network, and the assumption is that Delhi Metro Rail Corporation’s plans for 2021 is what will happen in the future which will provide a 146.5 km of light rail network and 34.5 km of subway network. So the subway and LRTS for Cases 8 and 10 will be similar as well. Also, in the spreadsheet case, future transport demand is not projected but current trends are followed into the future producing 354 bpkm traveled. This does not include about 37 bpkm for subway and light rail transport and at least 5bpkm for current levels of bicycle and tricycle travel that may also be supplied by these modes, though how they would affect the distribution of other transport modes has not been laid out in the simulation model.

Although PKM traveled and energy use increase over time, PKM driven increases more leading to a decrease in the energy use per PKM (Figure 3). In the optimization runs due to the emissions limits in the model, cleaner vehicles enter the fleet and emissions per PKM also decrease. When Cases 1 through 9 and Case 10 are examined for emissions and energy use of the transport system, the results for the optimization runs provide a much more efficient system than the spreadsheet simulation case. The CO_2 emissions per PKM of the overall vehicle fleet drops from around 100g/PKM in 2000 to about 23 to 41g/PKM in 2020 in the optimization cases compared to 92g/PKM in 2020 for Case 10. Energy use of the total transport system ranges from 0.23 to 0.37 MJ/PKM in 2020 in Cases 1 through 9, compared to 0.54MJ/PKM in Case 10. Buses are very efficient in terms of moving people with the lowest emissions and energy use per PKM and also the cheapest motorized form of transport in terms of costs per PKM including annualized vehicle costs, annual OM costs, fuel costs, taxes, and traffic control options cost (in year 2000 these statistics for buses were: 0.29 cents/PKM, 0.22MJ/PKM, and 30gCO_2/PKM).

CONCLUSIONS AND RECOMMENDATIONS

Projection of the vehicle fleet at current growth rates will result in more than 13 million vehicles, mostly cars and two wheelers, for a population of close to 22 million people by the year of 2020. Buses satisfy a very large amount of the transport demand despite the fact that their numbers are small. So measures directed to facilitate their operation are essential. Although technological improvements are necessary, the effects of traffic congestion and reduced speeds on emissions and fuel consumption from vehicles are even higher. Costs of congestion in terms of increased health impacts, fuel wasted, and delay time in traffic are very high. Appropriate measures should be taken to reduce these adverse effects of reduced speeds and to increase the efficiency of the transport system.

Running a simulation model is a good way of investigating specific policies and control options. Nevertheless, optimization involves less repetitive work and is able to consider a list of options at the same time and produces the most cost-effective combination.

The results of the optimization runs suggest a transportation system dominated by buses. Although buses are less than 4% of total motor vehicles they will satisfy more than 80% of the PKM demand in 2020. When buses are limited many more vehicles in all the other modes are required to meet the transport demand. Since there are emissions limits that need to be met, cleaner and more expensive vehicle technologies are required for these vehicles. In these limited bus cases, an extensive light rail network becomes also essential (similar to the one planned by the Government of India (GoI) and Government of National Capital Territory Delhi (GNCTD) through the company of Delhi Metro Rail Corporation building Delhi’s MRTS by 2021) with also some subway utilization in the increased PKM demand cases to meet the remaining transport demand.

In all the optimization cases, cleaner vehicles need to be adopted due to emissions reduction requirements included in this model. Competitive vehicle technologies in cost minimizing cases turn out to be: CNG taxis, hybrid buses and trucks, electric, LPG, and CNG autorickshaws, gasoline and CNG cars, and ethanol, LPG, and CNG two wheelers. A mixture of different alternative fuel vehicles and clean vehicle technologies are used in the welfare maximizing cases still maintaining widely the choice of CNG for taxis and hybrid for buses and trucks.

Among the various cases analyzed, the addition of all the traffic control options to any case results in lower total motor vehicles, higher speeds, and lower health costs and value of time spent in traffic (VoT). The addition of social costs in the objective function results in some cases with the use of more light rail, less bicycles, and lower VoT, and in almost all the cases in the use of cleaner vehicle technologies and consequently lower health costs. Maximizing welfare compared to minimizing total costs generally results in larger total number of motor vehicles, mainly more cars and taxis but fewer buses, higher transportation system costs and higher VoT. (See Figure 5.)

The very rapid growth observed in the transportation sector in most of the developing countries has made the planning and managing of these systems very difficult. But since the development is at a rather early stage all available options need to be considered very carefully with also learning from mistakes and success stories from other more developed countries. The key is trying to move people efficiently and as a start some simple traffic management options can attain a relatively quick and easy reduction of the congestion in Delhi. Also, the large increase in the number of buses suggested by these models speaks the need for a transport system with dedicated bus lanes and bus priorities, maybe such as the case in Curitiba, Brazil.

The transportation and environment project at Harvard University also includes models for future land use planning, GIS models for data handling and visual representations, and use of satellite remote sensing for ground level PM2.5 monitoring. All these models, including the simulation and optimization models, will be linked together to form a complete decision support system. These models in the hands of the policy makers could become a great tool for urban transport planning.

ACKNOWLEDGEMENT

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LIST OF TABLES AND FIGURES

FIGURE 1 Optimization model structure.

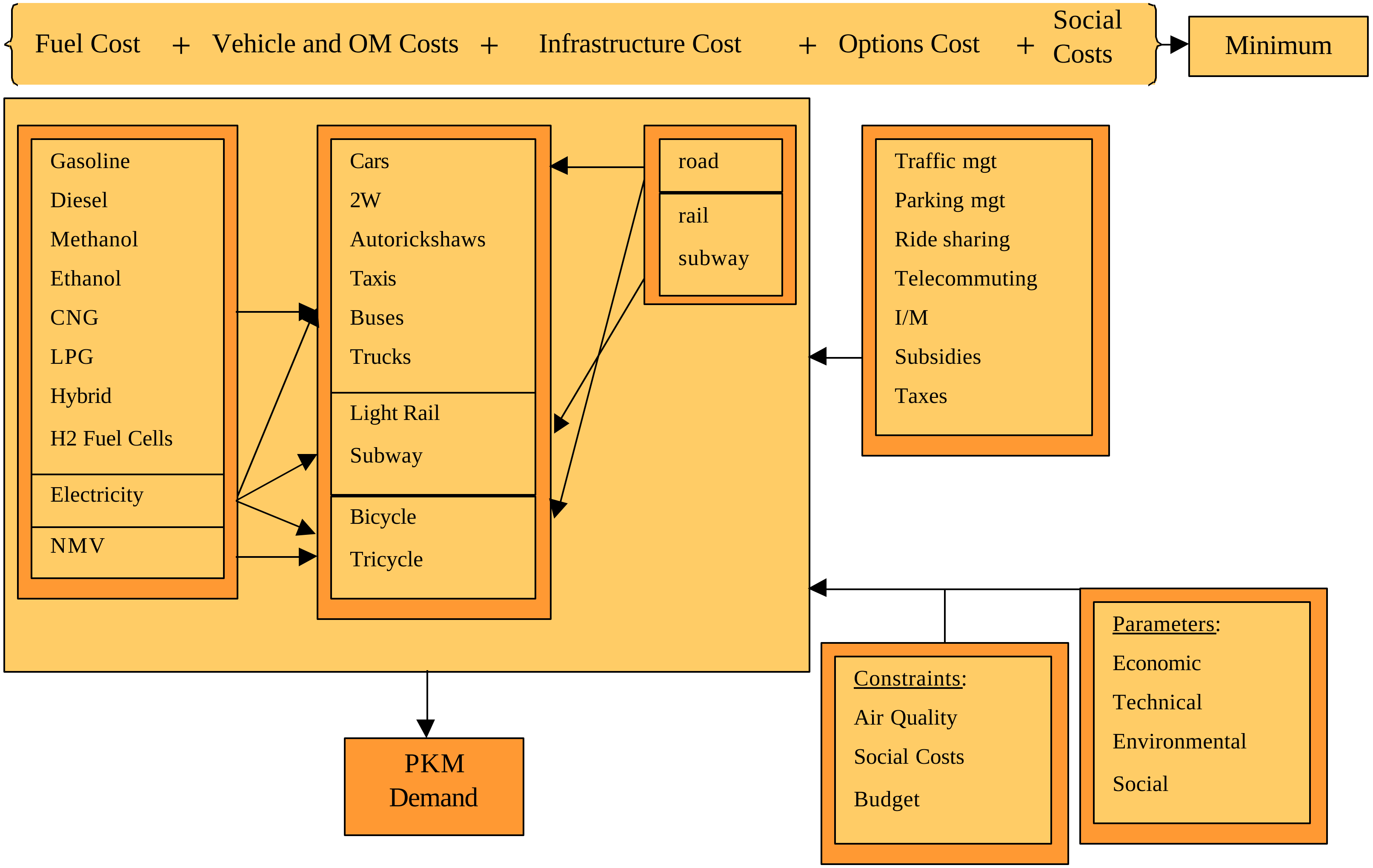


TABLE 1 Comparison of Model Output for the Cases without a Limit on the Number of Buses

	2020	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
total motor vehicles		2,619,781	2,652,206	2,652,206	2,641,187	3,734,383	2,648,425
cars		1,267,537	1,267,537	1,267,537	1,267,537	2,242,478	1,267,537
two wheelers		1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
autorickshaws		25,000	25,000	25,000	25,000	25,000	25,000
taxis		11,600	11,600	11,600	11,600	128,000	11,600
buses		71,210	103,635	103,635	92,615	94,470	99,853
trucks		244,435	244,435	244,435	244,435	244,435	244,435
subway		-	-	-	-	-	78
light rail		-	-	101	-	-	289
bicycle		2,200,000	4,597,534	2,200,000	2,200,000	2,200,000	2,200,000
tricycle		60,000	210,000	210,000	166,493	82,812	60,000
value of time	*million $*	2,392	3,099	2,746	2,673	3,914	2,673
health costs	*million $*	1,257	1,940	1,335	1,763	1,357	2,048
fuel costs	*million $*	2,317	2,865	2,637	2,574	2,740	3,162
GWC	*million $*	42	55	45	53	45	58
DALYs		288,095	444,827	306,117	404,171	311,138	469,515
PMD		2,846	4,390	3,024	3,990	3,073	4,633
LYL		105,300	162,437	111,875	147,617	113,684	171,425
MTC		2.12	2.75	2.24	2.67	2.27	2.89
PM10 conc	*micrograms/m3*	13.40	20.70	14.24	18.80	14.47	21.85
SO2 conc	*micrograms/m3*	0.18	0.18	0.18	0.18	0.17	0.17
TSP emissions	*tons/yr*	2,085	3,892	2,240	3,310	2,285	4,294
SO2 emissions	*tons/yr*	267	265	312	271	112	143
PKM	*bpkm*	251	341	341	309	341	341
Passengers	*million pass/day*	10.13	14.13	11.74	11.28	13.39	11.33
Total Costs	*billion $*	9.82	10.01	10.06	9.89	17.88	15.02

Case 1: Minimizing total costs without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 1 PKM demand

Case 2: Case 1 with SET 2 PKM demand

Case 3: Case 2 with social costs

Case 4: Case 2 with all the traffic control options

Case 5: Maximizing welfare without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 2 PKM demand

Case 6: Case 5 with an aggregate demand and supply curve for total motor vehicles

MTC: million tons of carbon emissions.

bpkm: billion passenger km.

PMD: premature deaths due to air pollution resulting from vehicular emissions.

GWC: global warming costs.

LYL: life years lost due to air pollution resulting from vehicular emissions.

DALYs: disability adjusted life years due to air pollution resulting from vehicular emissions.

TABLE 2 Comparison of Model Output for the Cases with a Limit on the Number of Buses and the Spreadsheet Case

	2020	Case 7	Case 8	Case 9	Case 10
total motor vehicles		6,066,004	12,186,843	8,165,821	13,556,004
cars		1,267,537	1,286,409	6,580,560	5,831,141
two wheelers		4,229,432	10,200,000	1,000,000	7,044,943
autorickshaws		278,000	278,000	25,000	121,510
taxis		11,600	128,000	265,826	98,284
buses		35,000	50,000	50,000	53,569
trucks		244,435	244,435	244,435	406,557
subway		-	175	89	
light rail		667	667	108	
bicycle		13,000,000	13,000,000	2,200,000	
tricycle		210,000	210,000	702,382	
value of time	*million $*	8,742	17,179	14,364	16,537
health costs	*million $*	1,546	1,900	1,536	2,919
fuel costs	*million $*	2,723	3,699	6,661	7,453
GWC	*million $*	59	59	58	176
DALYs		354,582	435,695	352,308	670,180
PMD		3,501	4,300	3,478	6,614
LYL		129,526	159,106	128,687	244,728
MTC		2.93	2.94	2.90	8.80
PM10 conc	*micrograms/m3*	16.50	20.27	16.39	31.20
SO2 conc	*micrograms/m3*	0.17	0.17	0.16	0.18
TSP emissions	*tons/year*	2,717	3,753	2,692	9,563
SO2 emissions	*tons/year*	151	245	56	256
PKM	*bpkm*	251	341	341	359
Passengers	*million pass/day*	24.51	33.20	22.73	24.51
Total Costs (PDV)	*billion $*	11.61	13.99	41.30	66.17

Case 7: Minimizing total costs without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 1 PKM demand with limited number of buses (35,000)

Case 8: Case 7 with SET 2 PKM demand with limited number of buses (50,000)

Case 9: Maximizing welfare without social costs with only the first three control options for vehicle technologies, fuels, and rail infrastructure with SET 2 PKM demand with limited number of buses (50,000)

Case 10: The spreadsheet simulation

MTC: million tons of carbon emissions.

bpkm: billion passenger km.

PMD: premature deaths due to air pollution resulting from vehicular emissions.

GWC: global warming costs.

LYL: life years lost due to air pollution resulting from vehicular emissions.

DALYs: disability adjusted life years due to air pollution resulting from vehicular emissions.

FIGURE 2 VKT & PKM breakdown by travel mode for Case 1.

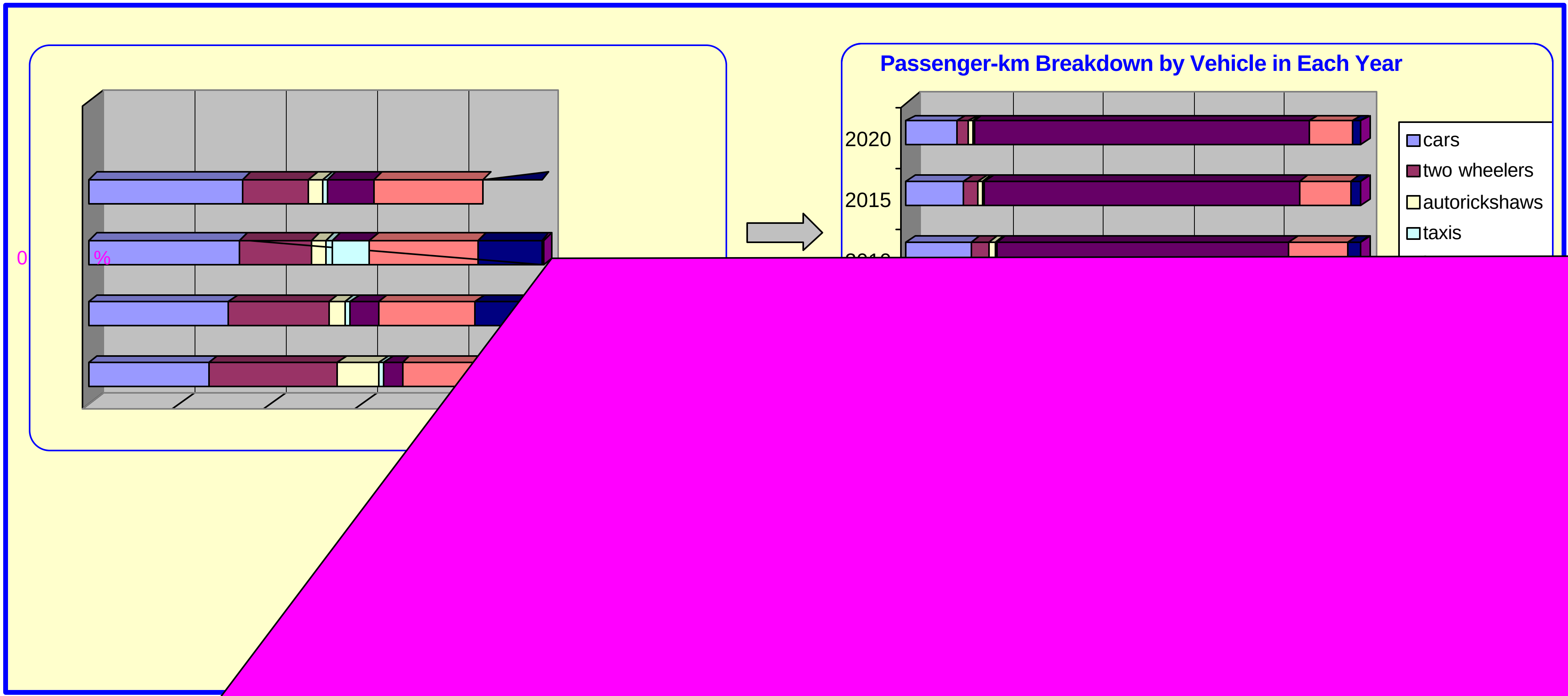
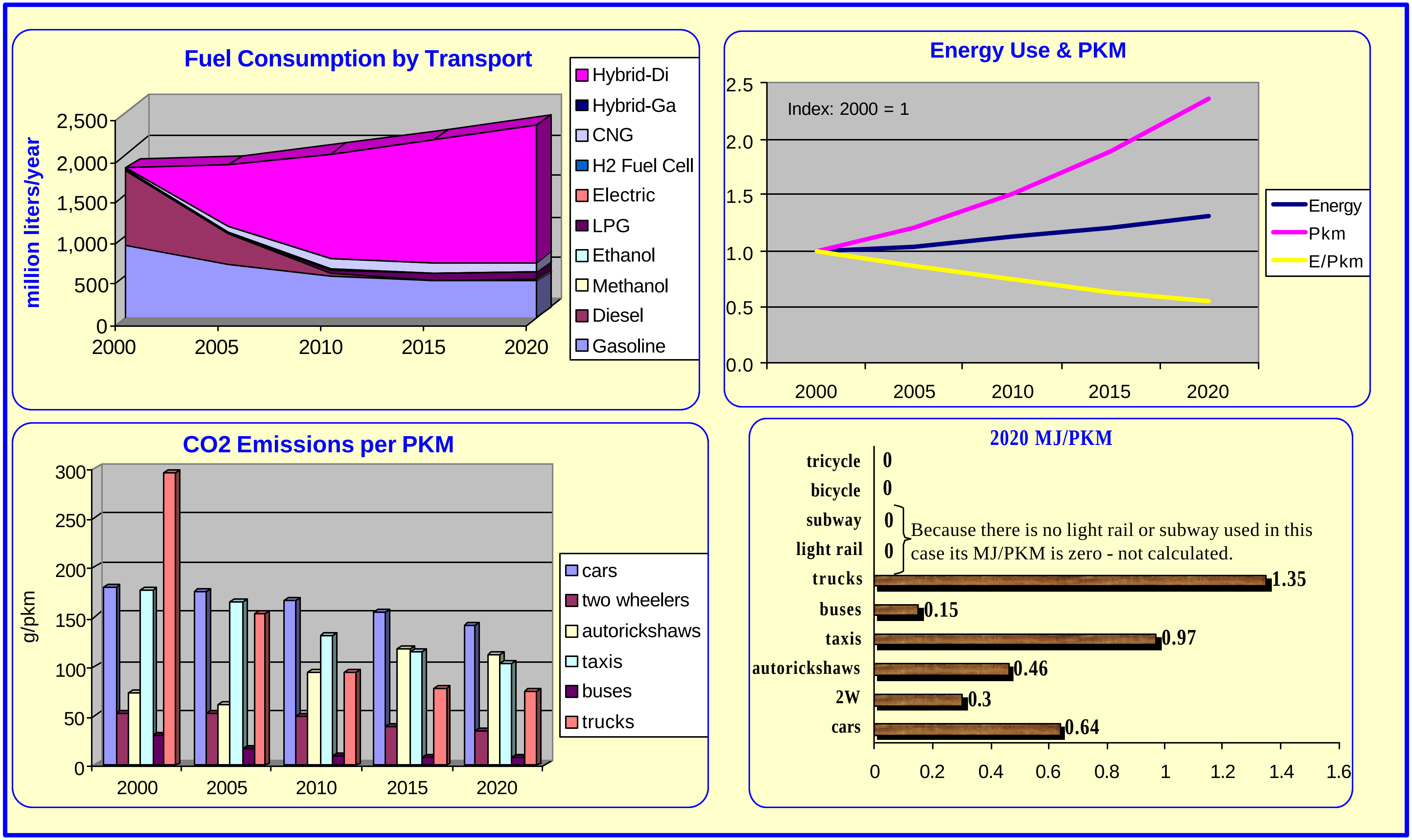


FIGURE 3 Fuel consumption by mode & energy use and CO_2 emissions per PKM for Case 1.



Fuel Consumption by Transport

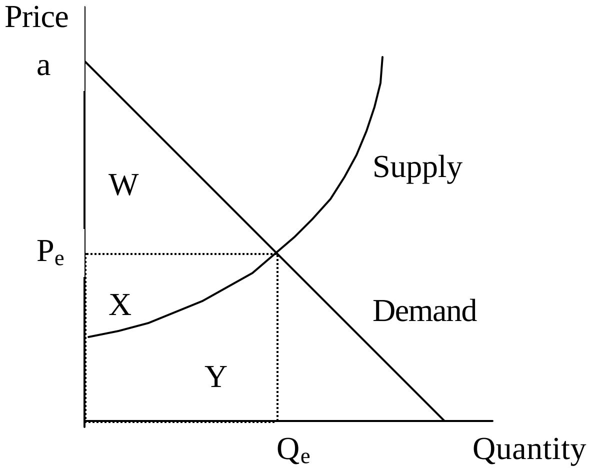
Energy Use & PKM

CO2 Emissions per PKM

2020 MJ/PKM

Because there is no light rail or subway used in this case its MJ/PKM is zero - not calculated.

FIGURE 4 Demand and Supply relationships for welfare maximization.

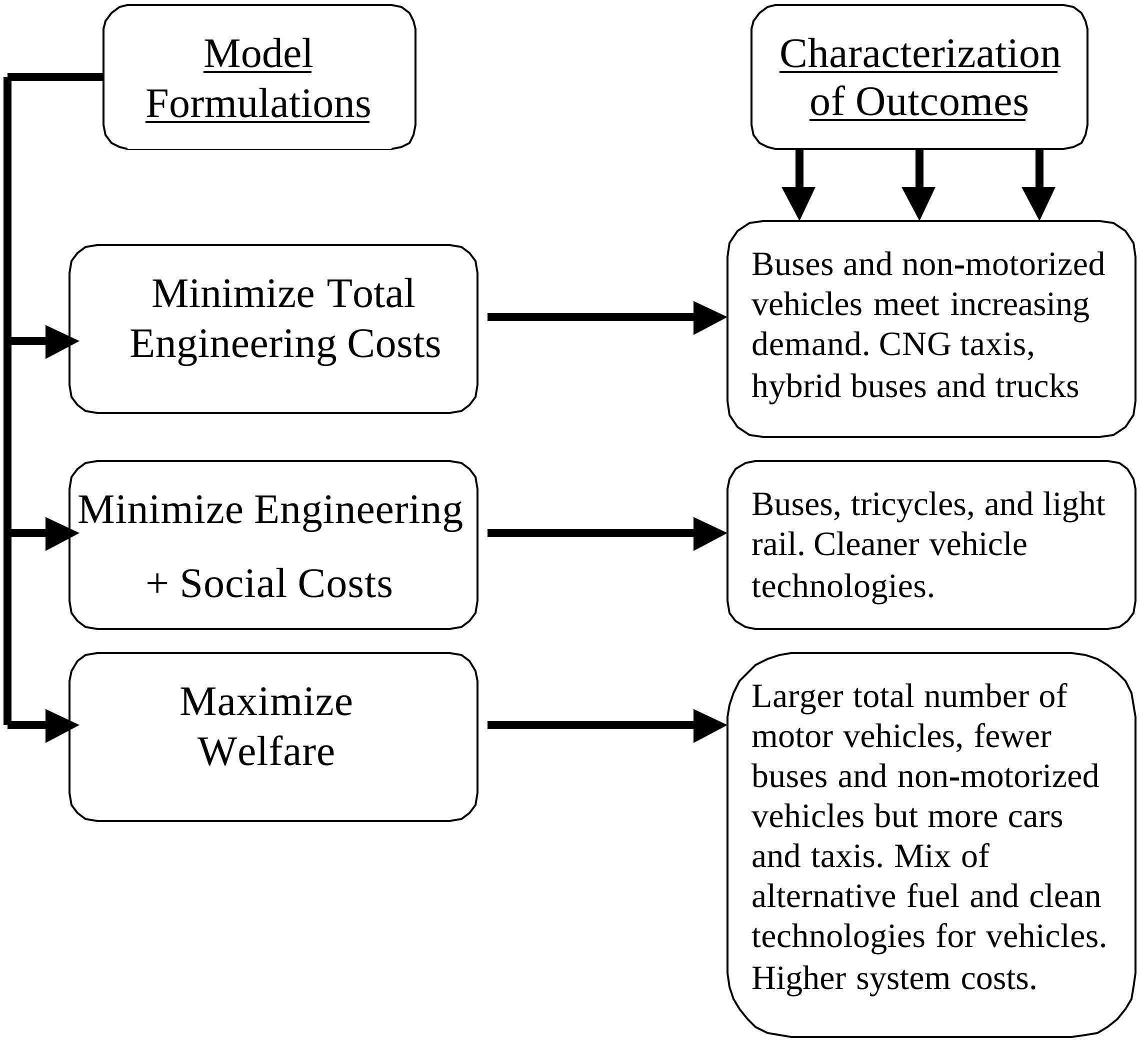


Price: cost/pkm (v,t)

Quantity: pkm (v,t)

Welfare = Area under the Demand Function
- Area under the Supply Function
= Consumers’ surplus (W)
+ Producers’ surplus (X)

FIGURE 5 Main model formulations and their general outcomes.

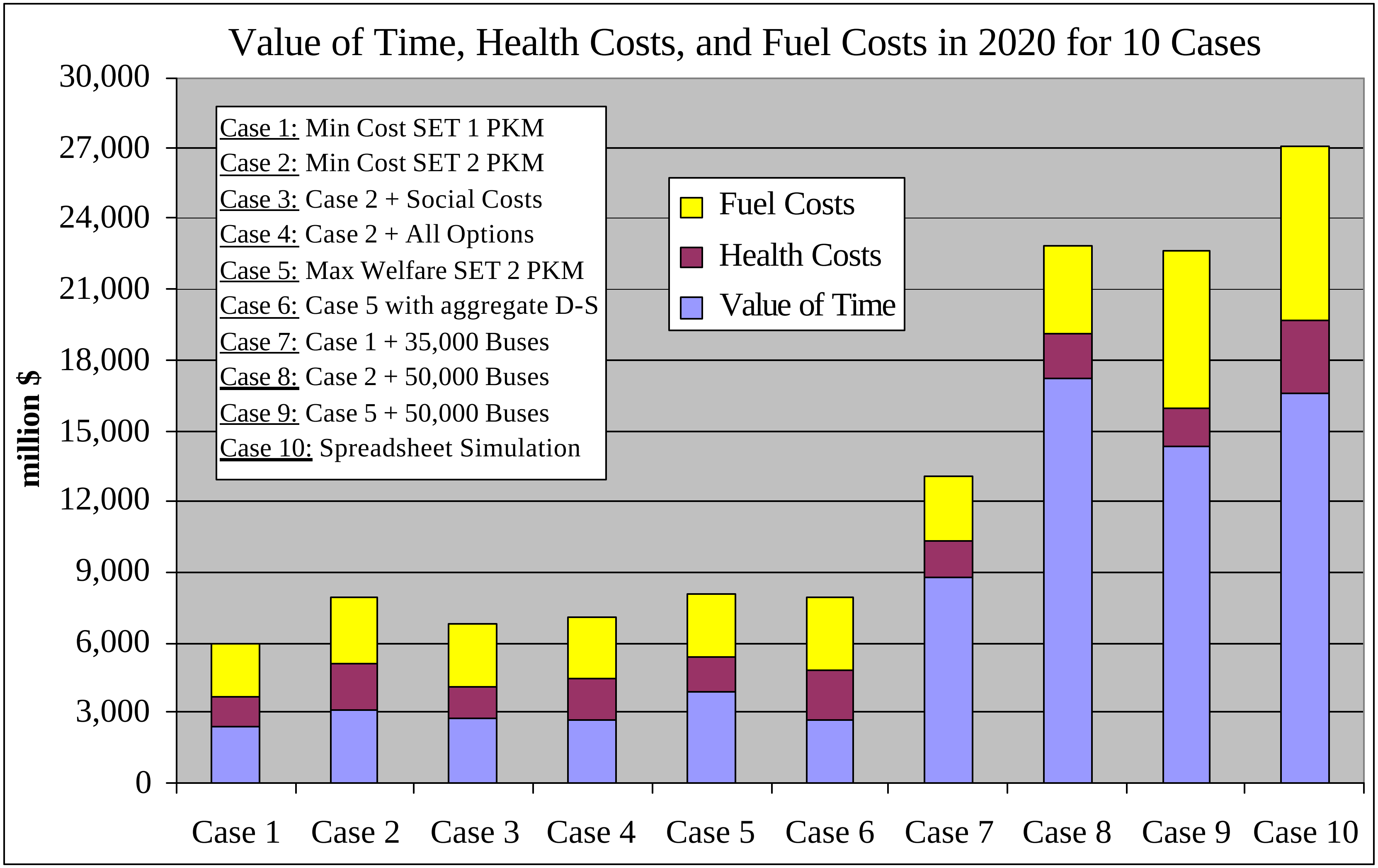


Buses and non-motorized vehicles meet increasing demand. CNG taxis, hybrid buses and trucks

Buses, tricycles, and light rail. Cleaner vehicle technologies.

Larger total number of motor vehicles, fewer buses and non-motorized vehicles but more cars and taxis. Mix of alternative fuel and clean technologies for vehicles. Higher system costs.

FIGURE 6 Costs of Transportation in 2020 for the 10 Cases.



SET 1: 5% annual growth rate in travel demand over base year 2000. SET 2: Spreadsheet simulation equivalent travel demands.