Emerging Social Dilemmas in Managing Transportation-Related Carbon Footprint in Optimal Urban Infrastructure Development

LOUKAS DIMITRIOU
Dept. of Transportation Planning and Engineering
National Technical University of Athens
5, Iroon Polytechniou, 15773, Athens
GREECE
lucdimit@central.ntua.gr

ANTONY STATHOPOULOS
Dept. of Transportation Planning and Engineering
National Technical University of Athens
5, Iroon Polytechniou, 15773, Athens
GREECE
a.stath@transport.ntua.gr

Abstract: - Urban areas are facing an enormous pressure for mobility opportunities, a phenomenon closely related to economic activity and urban welfare growth. The development of urban transportation networks is a vital component in the performance of metropolitan complexes, where multiple policies can be employed and multiple objectives is urged to be met. In this paper, a policy-driven approach will be presented for providing optimal investment plans for future network expansions, by taking into account the management of carbon footprint related to the vehicle emissions on urban networks. In particular, optimal network design and pricing decisions will be attempted to be inquired in order multiple social, economical and environmental targets to be simultaneously optimized. Under this framework, multiple social dilemmas are able to be revealed, while quantitative results can support decisions related to the sustainable urban development. The methodological approach presented here is based on an advanced formulation of a complex, non-convex, multi-level, vector optimization programming problem, while the solution sets are composed of the Pareto Front, estimated by suitably hybridized evolutionary algorithms. Insights are provided by applying the proposed framework into a part of a realistic network, for alternative problem setups.

Key-Words: Sustainable urban development, optimal transportation planning, vector optimization, distance-based genetic algorithms

1 Introduction
Following the traditional paradigm of the optimal design of future transportation infrastructure development plans, investments are allocated based on criteria expressing the prudence of the public or private authorities for the performance of the designed system. The performance criteria used for most of such studies, endeavors to optimize economic (or economic related) metrics of the investments. Nevertheless, contemporary society’s requirements are moving towards a sustainable development pattern, especially since for some time now environmental conditions have been identified that determines attractiveness and thus future opportunities [1]. Concentrating to metropolitan areas, the development plans are focusing to ameliorate negative externalities of the requirements for increased mobility, a phenomenon closely related to urban welfare growth. One of the most evident negative environmental externality of urban transportation is air pollution. Since traffic emissions are closely related to congestion phenomenon a net of policies and initiatives should be suitably combined for remedy negativities, spanning to infrastructure provision, road pricing and/or other traffic management strategies. The theoretical foundations of optimal traffic networks design and management strategies are mainly depended on classical and neoclassical economic ideas. Nevertheless, the implementation of
such ideas have been come against the problem emerging when monetary costs are only considered in development plans as well as to complexity of identifying optimal management plans in realistic networks, as have been exposed in various paradoxes that emerges in investigating investment or pricing strategies. For example the paradox of the increment of the total social cost (as reflected by total travel time) by the provision of additional transportation infrastructure and the similar case of the increment of congestion-related traffic emissions in special cases of improvement of travel times by capacity improvements [2]. Also, the paradox of the increment of traffic emissions by reducing total travel time moving from user-optimal towards system-optimal traffic network conditions through network pricing [3], demonstrates the complex and the conflicting nature of alternative network design and management strategies. The difficulty of identifying optimal strategies is significantly increased when considering the determination of joint choices for all available alternative policies, or when dealing with multiple interrelations as those emerging in realistic urban networks. 

This paper aims to provide a comprehensive framework for identifying optimal network strategies encompassing joint decisions of both network development (investments) and management policies (pricing) for a realistic case of an urban highway, as well as in exposing the social dilemmas emerging in such circumstances. Moreover, instead of determine a unique optimal strategy a non-linear, non-convex, multi-level, multi-objective optimization problem is formulated incorporating conflicting (economical, social, and environmental) network objectives, able to provide a Pareto-Optimal set of policies. The solution algorithm for addressing the above described optimization problem is based on hybrid game-theoretic evolutionary tactics implemented in genetic algorithms. The proposed formulation and solution approach is able to capture optimal tradeoffs among contradicting objectives, providing valuable information for meta-analysis aiming to a final network management plan.

On the next section of the paper, the description of the problem of the multi-objective sustainable joint network design and pricing problem will be provided. Then the formulation of the problem as a multi-level optimization problem is presented, while the description of the solution evolutionary algorithm follows. Results from the implementation of the proposed framework on a part of a realistic network from the city of Athens will be provided, while the final section concludes.

2 Problem Formulation

Environmental prudence on the performance of urban networks has been mainly investigated in works related to network pricing strategies [4], while an comprehensive investigation of alternative pricing strategies can be found in [3]. Less attention has been paid on the problem of optimal network investment allocation (usually termed as Network Design Problems) with respect to the emission performance. Nagurney [5] has been pointed out several valuable insights regarding the effects of capacity improvements in total network emissions. No effort has been made to the more realistic situation of the determination of optimal strategies by considering joint network design and pricing decisions aiming to take into account the environmental (in terms of emissions) effects.

The problem of the simultaneous determination of optimal design and pricing strategies for urban networks, despite its considerable policy implications, has received little attention ([6], [7], [8], [9], [10], [11], [12]). These studies actually concerns simplified networks, using assumptions that considerably departs from realistic situations. In an evolutionary approach has been presented for the joint design and pricing of realistic urban highways, considering alternative pricing strategies, solving a mixed-integer, non-linear, non-convex optimization problem, while important results have been presented regarding the efficiency of alternative pricing strategies to network performance. Here a number of extensions are introduced for taking into account the emissions produced in the network with respect to alternative planning strategies, revealing the multiple social choice issues raised in such urban planning cases. At first, a multi-objective problem is formulated for identifying optimal tradeoffs among conflicting social, economic and environmental objectives. The formulation aims to model a multi-level Stackelberg game among a single network authority (responsible for the investments decisions and pricing policies) and the network users. Also, at the level of network users, a joint model of trip (re-)distribution and stochastic traffic assignment has been utilized for capturing location selection and route choices non-cooperative game among multi-class network users, triggered by the network schema. The formulation will be presented in the following section.

3 Expanding a Network Design and Pricing Game to Incorporate Environmental Considerations
The processes of road network design and pricing (with or without emission control considerations) are typically considered as two-stage Stackelberg game with perfect information among alternative players. These games recognize the principal players, which are the system designer/operator (here termed as network authority) and the system users, and they can be generally solved as bi-level programming problems. Such a type of formulation is commonly met in the literature when considering separately the Network Design Problem - NDP [13] and the Toll Design Problem - TDP [14]. At the upper level, the system operator (the ‘leader’), taking into account a number of constraints, integrates within the design and pricing tactics the non-cooperative responses of users of different classes (the ‘followers’). In this paper, ‘leader’ stands for the system authority (government) who controls location-specific investments in network expansions and the level of toll rates imposed on highway access points. It is assumed that the set (number and location) of the highway links has already been identified before the problem is formulated and solved. This assumption typically holds for a realistic network design process that takes place in an urban environment, as in the present case. Therefore, the problem seeks to estimate the spatially differentiated toll charges and/or the number of link lanes from the designer/operator point of view, so that the tolled highway, which competes with free alternative roads, will attract such a portion of multi-class users that optimizes network performance. Since in this paper an attempt is made to deal with the situation where significant alterations on the network conditions are endeavored, the users responses should involve the joint non-cooperative decisions in the residential location selection and route choice behavior. The relationship among land use and transportation infrastructure has been investigated as a network equilibrium problem where network users are competing for choosing residential location with respect to network conditions as determined by route choices, while joint trip distribution and traffic assignment models have been proposed for capturing such interactions. In these responses have been investigating for the case of the determination of optimal road tolls on urban highways aiming to maximize social welfare. Also, a bi-level formulation has been proposed for capturing network users location decisions and transportation infrastructure. Here the combined trip-distribution and traffic assignment problem is preferred to be modeled by adopting an elastic demand route choice model. In particular, multiple user classes are engaged in a stochastic route choice process (leading to network conditions termed as stochastic user equilibrium-SUE) where the network performance determines the demand levels on all locations. Formally, consider a network \( G(N, A) \) composed of a set of \( N \) nodes and \( A \) links, which connect the origin zone \( r \) with destination zone \( s \), and \( q_m^w \) be the demand of the users of class \( m \) for moving between the O-D pair \( r - s \). In this context, each class \( m \) corresponds to a particular user group having an assumed common value of travel time (VOTT), which may reflect similar socio-economic and travel characteristics. As it is typically adopted in the literature, this study assumes that, for each user group, travelers share the same discrete VOTT probability distributions. It is noted that other user group definitions may be additionally adopted, according to the nature of each application, such as the type of vehicle (private car and truck) in relation to the damage causing to the pavement condition. Also, consider the link travel time function \( t_a(x_a) \) (in minutes) as being positive and monotonically increasing with traffic flow \( x_a \) at each link \( a \in A \). Here, the complete form of the bi-level optimization framework, for the design and pricing of a private highway that constitutes part of the network is expressed in the upper-level problem as a vector optimization problem:

\[
\min R = [R_1, R_2, R_3] = \\
\sum a \sum \left[ E_{s}(x_{s}) + E_{s}(x_{w}) - \sum a E_{a} \left( p_{a}, f_{a}, \sum a E_{a} \right) \right] \quad (1)
\]

subject to

\[
w_a \in \{0,1,\ldots, \ell\}, \quad \forall a \in \bar{A} \quad (2)
\]

\[
p_{\min} \leq p_a \leq p_{\max}, \quad \forall a \in \bar{A} \quad (3)
\]

\[
\sum \left( V_a \left( p_a, f_a \right) \right) \leq B, \quad \forall a \in \bar{A} \quad (4)
\]

\[
x_a \left( p_a, f_a \right) \leq L, \quad \forall a \in \bar{A} \quad (5)
\]

\[
\sum_{r} D_{w}^{r} \left( S_{w}^{r} \right) \geq k \sum_{r} D_{w}^{r} \left( S_{w}^{r} \right) \quad (6)
\]

while the SUE link flow conditions are estimated at the lower-level problem:

\[
\min Z(x,q) = \sum_{r} VOT_{w} \delta_{w}^{r} \left( x_{s} \right) x_{s} - \sum_{r} VOT_{w} \delta_{w}^{r} \int t_{a} \left( w \right) dw +
\]

\[
\]
expresses the followed by users of group $a$ denotes vector of the scalars. A vehicle traversing a network's link are estimated assumption, CO2 emissions (in g/km) of each representative of the car use over a study area [3], carbon pollutants has been preferred as being concentrated to the CO2 emissions. Although other estimation of the carbon footprint here is final term component of the objective vector provides the economic performance of alternative strategies. This objective is composite function of the investment monetary expenditures $V_a$ for capacity provision at highway link $a \in A$ minus the revenues collected by the toll stations (here operational of enterprising benefits are omitted). Here toll charges, $P_a$, are imposed only on the entry volume $I_a$ of users. At this entry-based toll pricing scheme, revenues depend on the selection of the entry point, and index $a$ refers to the highway access (entry) link $a \in A$, with capacity $q_a$, whose entry node is used by travelers to access the highway, where $\hat{A}$ is the set of highway links. Finally, the third component of the objective function vector stands for the aggregate network emissions, produced in all network links. The estimation of the carbon footprint here is concentrated to the CO2 emissions. Although other carbon pollutants has been preferred as being representative of the car use over a study area [3], here CO2 has been preferred for the reasons explained in the introductory section. Under this assumption, CO2 emissions (in g/km) of each vehicle traversing a network’s link are estimated based on the following formula:

$$e_a(x_a) = \omega_1 + \omega_2/s(x_a) + \omega_3s(x_a)^2$$

(8)

where $s(x_a)$ is the average speed (in km/h) of link $a$ that is estimated subject to the link loading $x_a$ and $\omega_1, \omega_2, \omega_3$, scalars.

Moving to the constraints set, scalar $w_a$ is an integer decision variable which determines the number of lane additions in link $a \in A$, up to a physical threshold $\ell$, as shown in relationship (2).

The scalars $P_{\min}$ and $P_{\max}$ in relationship (3) denotes the minimum and maximum allowable toll charges, which are controlled by the government. The budgetary restrictions are represented in inequality (4), where $B$ is the total available highway construction budget.

Relationship (5) introduces the regulatory control of the government on the minimum required level of service (mobility target) in the set of constraints, where $L$ is the maximum allowable flow-to-capacity ($x_a/y_a$) ratio for each highway link $a \in A$. This operational target is used to ensure a desired balance between infrastructure supply and highway utilization rate that enhances mobility, in terms of reducing travel times between the various O-D pairs, after the new network configuration. It should be noted here that the simultaneous consideration of budget and level-of-service requirements in the set of constraints may result in an unfeasible solution. This possibility stresses the need for careful selection of the bound of each problem constraint. Finally, due to the nature of the problem of the joint design and pricing problem with elastic demand an additional welfare constraint is added in inequality (6), related to the total social welfare conditions. Namely, the minimization of total travel time could be obtained by setting an infinite (or extremely high) toll rate and thus the reduction of total travel time could be attributed to residential location alterations outside the study area. So this constraint assures that total demand will not be decreased below a rate $k$.

At the lower-level problem, $Z$ expresses the objective function of network users of different classes $m$, in terms of their value of travel time VOTT$m$, who seek to minimize their perceived generalized travel cost by taking both residential location and route choices. This procedure is formulated as an unconstrained minimization problem expressed in equation (7).

Formally, the binary parameter $\delta_{rk}$ takes the value 1, if link $a$ is part of the path $k$ of the feasible path set $K_{rs}$ followed by users of group $m$ between $r$ - $s$, or 0 otherwise. Assuming that the demand function $D_{rm}$ is nonnegative and strictly decreasing
with respect to the cost of paths between \( r - s \), then 
\[
q^r_m = D^r_{ms} \left( S^r_m \right) \quad \text{and} \quad S^r_m = D^r_{ms} \left( q^r_m \right),
\]
where \( D^r_{ms} \) is the inverse demand function and \( S^r_m \) is the perceived travel cost function. The latter function is expressed in relation to the expected value \( E \) of the total path travel cost \( C^r_{km} \), as follows:
\[
S^r_m(x) = E\left[ \min_{k\in K^r} \left\{ C^r_{km} \right\} \right] C^r(x),
\]
with
\[
\frac{\partial S^r_m(C^r)}{\partial C^r_{km}} = P^r_{km},
\]
where \( P^r_{km} \) denotes the probability that users of class \( m \) select path \( k \) between \( r - s \) pair. Then, the measure of probability \( P^r_{km} \) depends on the following utility function:
\[
U^r_{km} = -\theta C^r_{km} + \epsilon^r_{km},
\]
where \( U^r_{km} \) expresses the utility of users of class \( m \) selecting path \( k \) between \( r - s \) pair, \( \theta \) is the path cost perception parameter and \( \epsilon^r_{km} \) is a random error term, independent and identically distributed (iid) for all routes, which is here assumed to follow a Gumbel distribution, hence, yielding a logit model.

The path travel cost \( C^r_{km} \) is expressed in monetary terms, as a composite function of the value of travel time (VOTT) and toll charge:
\[
C^r_{km} = \sum_{a\in A} VOTT_m a^r_{a,km} t(x_a) + \sum_{a\in A} S^r_{a,km} p_a
\]

The adoption of the stochastic user equilibrium (SUE) assumption denotes that the resulting equilibrium flows correspond to the most probable (expected) flow pattern. The effect of this stochasticity on the performance of the upper-level problem is represented through the expected value operator in equation (1).

The estimation of the demand responses related to residential location selection with respect to path travel cost is based on the following relationship:
\[
D^{(n)}_{ms} = D^0_{ms} \exp(uC^r_{ms}), \quad \forall \ r, s, m
\]

where \( D^0_{ms} \) refers to the potential demand (or the demand at zero cost) expressing the maximum desire for travel of users of class \( m \) for the \( r - s \) pair and \( u \) is a scaling parameter that controls the users willingness to alter residential location.

The solution of the lower-level unconstraint combined trip-distribution and assignment problem can be obtained by a recursive estimation of the demand levels in the network conditions as provided by the route choice process. Changes in the demand level are estimated by an algorithm based on the method of successive averages (MSA) [15]. In the following section a hybrid evolutionary algorithm is presented able to provide an estimation of the Pareto Front for the above presented multi-objective optimization problem.

### 4 An Evolutionary Approach to the Multi-Objective Network Design and Pricing Problem

When dealing with multi-objective optimization problems, where the solution of problem is consisted by conflicting objectives then optimality conditions corresponds to a compromise among them. This compromise can be determined in advance forming a desirable combination among the conflicting objectives by providing a suitable parametric composite function, using scaling parameters for each objective. The determination of the set of optimal tradeoffs among conflicting objectives composes the so-called Pareto Front (PF). PF can be approximated usually by altering the scaling parameters among the objectives and estimating the optimum of the unique composite function [16]. This method is computational intensive since requires extensive runs in order to identify new PF points.

Here an evolutionary mechanism able to directly provide a PF approximation, introduced by [17] will be utilized. In this hybrid genetic algorithm (GA) it is suggested en elitist GA, a distance-based Pareto genetic algorithm (DPGA), which attempts to emphasize the progress towards the Pareto-optimal front and the diversity along the obtained front by using fitness measure. Following a current notation, the algorithm maintains two populations: one standard GA population \( P_t \) where genetic operations are performed, and another elite population \( E_t \) containing all non-dominated solutions found thus far.
The initial population $P_0$ of size $N$ is created at random. The first population member is assigned a positive random fitness $F_1$ (chosen arbitrarily) and is automatically added to the elite set $E_0$. Thereafter, each solution is assigned a fitness based on its distance from the elite set, $E_t = \{e(1) : k = 1,2,\ldots,K\}$, where $K$ is a number of solutions in the elite set. Each elite solution $e(k)$ has $M$ function values, or $e^{(k)} = (e_1^{(k)}, e_2^{(k)}, \ldots, e_M^{(k)})^T$. The distance of a solution $x$ from the elite set is calculated as follows:

$$d^{(k)}(x) = \sqrt{\sum_{m=1}^{M} \left( e_m^{(k)} - f_m(x) \right)^2} \quad (12)$$

For the solution $x$, the minimum $d(k)(x)$ of all $k=1,2,\ldots,K$ is found as follows:

$$d_{\text{min}} = \min_{k=1}^{K} d^{(k)}(x) \quad (13)$$

and the index $k^*$ for the minimum distance is also recorded. Thereafter, if the solution $x$ is a non-dominated solution with respect to the existing elite set, it is accepted in the elite set and its fitness is calculated by adding the fitness of the elite member with minimum distance from it and its distance from the minimum member:

$$F(x) = F(e^{(k^*)}) + d_{\text{min}} \quad (14)$$

The elite set is updated by deleting all elite solutions dominated by $x$, if any. On the other hand, if the solution $x$ is dominated by any elite solution, it is not accepted in the elite set and its fitness is calculated as follows:

$$F(x) = \max \left[ 0, (F(e^{(k^*)}) - d_{\text{min}}) \right] \quad (15)$$

In this way, as population members are evaluated for their fitness, the elite set is constantly updated. At the end of the generation (when all $N$ population members are evaluated), the maximum fitness $F_{\text{max}}$ among the existing elite solutions is calculated and all existing elite solutions are assigned a fitness equal to $F_{\text{max}}$. At the end of a generation, selection, crossover and mutation operators are used to create a new population.

It is interesting to note that a non-dominated solution lying a large distance away from the existing elite set gets a large (better) fitness. This helps in two ways. First, if the new solution dominates a few members of the elite set, the fitness assignment procedure helps in emphasizing solutions closer to the Pareto-optimal set. A distant solution here means a solution distant from the existing elite set but closer to the Pareto-optimal front. Assigning a large fitness to such a solution helps to progress towards the Pareto-optimal front. On the other hand, if the new solution lies in the same non-dominated front along with the elite solutions, the fitness assignment procedure helps in maintaining diversity among them. A distant solution here means an isolated solution on the same front. Assigning a large fitness to an isolated solution helps to maintain diversity among obtained non-dominated solutions. This novel evolutionary approach has been never used before for addressing a multi-objective formulation of multi-level programming problems as in the network design and pricing problem with environmental considerations.

5 Computational Results and Discussion

5.1. Experimental setup of the study

The proposed modeling framework is implemented into a suitably selected part of the urban road network of Athens, Greece, that is composed of primary and secondary roads, which are linked with a closed orbital urban highway, called Attiki Odos. The network (see Figure 1) covers the most densely populated region along the highway, where the heaviest daily traffic volumes are observed. It is composed of 54 (internal and connecting) links servicing the demand represented by a $10 \times 10$ O-D matrix. The physical and operating characteristics of the internal links of the network under study, has been previously used in [18], while the same assumptions regarding the construction costs (normalized for a representative design hour) stands here too.

Based on the socio-economic and travel characteristics of the case study area, two VOTT user classes are identified. The first class I has an hourly VOTTI = 4.0 €, representing primary commuters and more valuable trips, and refers to the 80% of the traveler population, while the second class II has an hourly VOTTII = 1.5 €, representing discretionary trips or more elastic trips, and refers to the 20% of the traveler population.
The minimum and maximum toll levels are set equal to $p_{\text{min}} = 0 \, \text{€}$ and $p_{\text{max}} = 7 \, \text{€}$. The optimal toll and capacity choices are examined for the private highway links (21 $\leftrightarrow$ 18 $\leftrightarrow$ 15 $\leftrightarrow$ 12) based on the demand pattern in the travel period (design hour). In order to calculate the travel time at link $a$, the well-known Bureau of Public Roads (BPR) function is used, as follows:

$$t_a(x_a) = t^0_a \left( 1 + \mu \left( \frac{x_a}{G_a} \right)^\beta \right), \quad \forall a \in A \quad (16)$$

where $t^0_a$ is the link travel time at free-flow conditions, $\mu$ and $\beta$ are parameters referring to local operating conditions (in this study, $\mu = 0.15$ and $\beta = 4$) and $G_a$ is the maximum traffic capacity at link $a$.

Concerning demand elasticity scalar, a relatively large value $u = -0.1$ is used, standing for an increased willingness of the users to drastically respond to network design and pricing strategies. Additionally, the constant $k$ that reflects the total demand allowable to change residential location outside the study area (Equation (8)) is set equal to 0.6, while term $L$ is taken to be 0.95.

Finally, the emissions are calculated by function (8) using $\omega_1 = 72.73$, $\omega_2 = 3398$ and $\omega_3 = 0.02326$.

These values were derived by modifying the NETCEN database’s basic formula [19] in order to adapt to the driving pattern and reflect the fleet composition and age distribution of vehicles in the study area. This function estimates EURO II car CO2 emissions in g/km. In the next section, numerical results for two representative cases are presented and analyzed, in order to gain some insight on the ability of the proposed network design and pricing framework to provide Pareto optimal strategies for the above described part of the realistic network of Attiki Odos.

### 5.2. Numerical results

Next the framework is applied to the complete objective vector as described in equation (1). The results are presented in Figure 2. Although for computational time purposes the population of the GA used here is relatively small (200 individuals) producing 100 estimates on the PF, it is possible to derive the complex relationship among these three conflicting objectives, a relationship that is not evident without conducting such an analysis. It can be observed that despite the complexity of the search space, the proposed framework is efficient in providing a wide range of alternative optimal solutions, which can be used for further investigation related to social choice issues and sustainable network development policy initiatives.

Using the framework described in Section 3, an additional experiment has been conducted: the investigation of the relationship among Total Travel Time Cost vs. CO2 emissions. In doing so for the current network setup, where an urban highway is servicing the larger part of the demand providing increased service times (free-flow speed of 120Km/hr) leading to increased emissions (see Figure 3), it is possible to model the users necessary recessions in total network Level of Service (LoS) in benefit for carbon emissions.
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
4.2

1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2

Figure 3. Pareto Front for the Total Travel Time vs. Total CO2 Emissions model

In Figure 3 that relationship is provided, where the PF exhibits the relaxation on the LoS requirements that should be made in order to provide sustainable transportation development. The increment of Total Travel Time Cost in this paper is achieved through a policy of not providing enough capacity to the highway or by imposing low toll rates (increasing traffic flow and thus travel time), but it can be interpreted as a speed control policy for environmental objectives. Such evidence can enhance the social understanding and awareness on transportation planning related policy issues, leading to more rational social choices.

6 Conclusions and Outlook

This paper proposes an optimization framework able to support policy initiatives to the problem of designing and pricing of new urban transportation facilities like urban highways by taking into account carbon footprint (related to vehicle driving conditions) management. The framework is based on a game-theoretic vector multi-objective formulation of the joint decisions of investments and pricing of new urban highways, by taking into consideration the complex decisions of network multi-class users for location selection and route choice. The resulted multi-level optimization problem is solved by a novel evolutionary distance-based genetic algorithm, able to provide an approximation of the resulted Pareto Front for the conflicting objectives of invested capital returns, total social cost and the environmental performance. The proposed framework has been applied to a properly selected part of a realistic network of Athens, Greece, where a closed urban highway is currently operating under a public-private-partnership concession. The results provide evidence on the ability of the proposed policy support framework to provide optimal tradeoffs among the conflicting objectives. Such results can significantly improve social awareness and thus acceptance of alternative transportation-related environmental-oriented strategies, leading to the commonly stated sustainable development policies.

As a work of outlook, the current problem setup is applied following the restricted (but representative) minimization case only for CO2 emissions. A natural model extension would be to take into account a wider range of road traffic-related emissions, like particle matters (PMs), NOx, or others. Also, a more elaborative location selection model can be used for capturing users responses to alternative transportation development plans. Such extension could significantly amplify design inefficiencies of realistic transportation network.

References:

[10] Yang, H. and Meng, Q., Highway pricing and capacity choice in a road network under a


