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ABSTRACT

This paper discusses the evaluation of synergies that derive from the implementation of policy packages designed to promote the use of public transportation and limit traffic congestion in urban areas. In this study, we propose the application of a land-use and transportation integrated (LUTI) model to study the outcomes from the implementation of several policy packages. We apply the long-term strategic LUTI model MARS-Madrid to analyze a case study in Madrid, Spain. The analyzed policies include a road pricing scheme (congestion charge) and the increase in the level of service of public transportation. Different scenarios, involving the implementation of respectively each one of these policies separately or both policies contemporaneously, are simulated and compared to the base scenario. We evaluate the effects of these policies on several transportation indicators and on social welfare, and discuss the optimization of these policies in isolation or combined as a policy package. The study provides insights on the suitability of the proposed LUTI modeling approach to evaluate the impact of transportation policies in urban and metropolitan areas, and it supports the evaluation of synergies from transportation policies, a topic that is not enough studied in the literature.

Keywords: transportation policies, synergies, land-use transportation modeling, MARS, public transportation, pricing.

INTRODUCTION

Urban regions face serious problems associated with land consumption and rapid land-use and transportation development. As a consequence, planners and decision-makers have an increasing need to improve their knowledge and access decision support tools able to evaluate policy strategies that can contribute to reduce traffic congestion, to increase quality of life, or to ensure future economic prosperity (Pfaffenbichler, Emberger and Shepherd 2008).

The integration of transportation policies in broader plans and policy packages in urban and regional planning allows a more efficient and successful way to address transportation problems in complex urban areas (Hull 2008). This is particularly important for the definition of packages of policies that are designed to increase the efficiency of transportation, and to increase environmental sustainability and quality of life in urban areas. Single isolated policies have often proven to provide only limited results (Geerlings and Stead 2003; van Wee 2002; May et al. 2001). The correct estimation of the benefits (and costs) associated with these policy packages directly depends on the ability to properly assess the impacts of the contemporaneous implementation of multiple policies in planning. Unfortunately, the evaluation of synergies associated with multiple policies is a rather complex task, which is seldom studied in details in the evaluation of the outcomes from transportation policies.

The contemporaneous implementation of several strategies can produce various results, depending on the way the policies interact. The European Project SPECTRUM-D4 (Mayeres et al. 2003) identifies four different types of interactions that can exist: complementarity, additivity, synergy and perfect substitution. A detailed description of each one of these types of interaction is provided by May, Kelly and Shepherd (2006).

In this paper, we adopt the concept of synergy to refer to a (predominantly) positive effect that can derive from the contemporaneous adoption of multiple policies. According to this definition, a synergy is associated to the *increase in the benefits* (and/or, respectively, a decrease in costs) associated with the contemporaneous adoption of two or more policies, whose total effects are larger than the sums of the effects that would be obtained if each policy was implemented separately. This concept is strictly connected to the concept of *complementarity* of the implemented policies: therefore, the definition of (positive) synergies is one of the main targets that planners and decision-makers should try to achieve in the definition of the policies to adopt in planning (Santos, Behrendt and Teytelboym 2010).

The major research difficulty with this process lies in the correct evaluation of the possible outcomes from these complex policy packages. The identification of synergies among policies (if/where they exist) is in fact not a trivial task: researchers are therefore called to cooperate with transportation planners and policy makers to develop robust methodologies for the evaluation of these policy synergies, and to identify possible solutions that optimize such strategies in planning through the maximization of their outcomes (Tight and May 2006).

This topic has been investigated through several modeling approaches (May, Kelly and Jopson 2008; Shepherd et al. 2006; Zhang et al. 2006; May and Still 2000; Fowkes et al. 1998; May and Roberts 1995). European Union (EU) funded research projects, as PROSPECTS (Minken et al. 2003), PROPOLIS (Lautso et al. 2004) and SPECTRUM (Grant-Muller 2005) also provided stimulus to investigate the effects of synergies through the application of comprehensive modeling approaches. These projects contributed to improve the design of integrated policy strategies in planning through the development and application of land-use and transportation modeling simulations in several European cities. These research projects laid out a modeling framework that can evaluate the results from the adoption of policy packages and the synergies associated with various combinations of transportation policies. The results of these projects confirmed how the development of integrated strategies (i.e. “bundles of policies”) can have high environmental, economic and social impacts in urban areas. Such impacts are often considerably more beneficial than those that would be achieved if each policy was implemented separately. Besides, the research projects confirmed the importance of including these policies in well-designed strategy packages that are shaped according to a strategic *vision* for the future growth of the city (May, Kelly and Shepherd 2006).

According to May and Roberts (1995), there are different sources of synergy that should be considered in the formulation of integrated combinations of transport instruments: complementarity, financial support, and public acceptability. In other words, the following cases may exist:

- Instrument A improves the effectiveness of an instrument B;
- Instrument A improves the acceptability of an instrument B;
- Instrument A creates an economic incentive or finances the implementation of instrument B.

The most important issues that need to be addressed when investigating the synergies from transportation policies are: 1) the identification of the optimal combination(s) of policies to implement, given that the results of each policy may vary depending on the way other policies are implemented; and 2) the selections of the policies and interventions that are necessary and sufficient to achieve the required targets of efficiency, equity and maximum performance in planning. As May, Kelly and Shepherd (2006) point out, several restrictions and/or limitations (e.g. budget and local regulations) might exist: these limitations need to be considered in the process of policy evaluation and in the investigation of synergies, as they might limit the possible policy options and/or the applicability of the proposed packages of policies.

This study focuses on one of the issues mentioned above: the identification of the optimal combination of policies to achieve a set of objectives in planning. We adopt two main assumptions in this study: the first one is the adoption of a land-use and transportation interaction context for the evaluation of policy results. Therefore, the development of strategies to increase sustainability in transportation requires a holistic approach to the analysis of these relationships, so that transportation, land-use planning and environmental analyses could be more effectively coordinated for the achievement of the proposed goals (ECMT 2001).

Regarding the second assumption, we here limit the scope of this study to the analysis of the interactions between two transportation policies. Previous research has suggested that synergistic effects may increase dramatically when additional policies are added (Wood 2007), as the number of possible synergistic interactions increases notably (assuming that most of these interactions generate positive synergies[1]). In this study, given the large number of policies (and the differences among them), the analysis is restricted to just two instruments that generate a policy package. In particular, in the empirical study presented in the following sections, congestion pricing is chosen following the *Pigouvian* tradition of charging for the external costs produced by an agent's decision[2]. This policy instrument charges car users for

[1] The presence of additional policies might further increase the level of synergies or reduce it, depending on the dominant effect of the more complex interactions among these policies. The evaluation of these complex policy packages is indeed not an easy task to develop, as the total effect of a policy package may significantly differ from the sum of the single policy effects. Each combination of policies should be specifically studied for a correct assessment of the specific interactions. Further extensions of this project will explicitly model the effects of policy packages with more than two transportation or land-use policies.

[2] Road pricing policies which aim to reduce the use of private vehicles and to promote modal shift to public transportation or non-motorized modes of transportation, have been introduced, or proposed, in several EU cities.

trips to the city center. The second policy instrument deals with an improvement in the public transportation (PT) service frequencies. A priori, if congestion pricing is implemented, travelers' surplus is expected to decrease as the full price that car drivers pay is larger than the time cost they pay without congestion pricing. Thus, congestion pricing generates an increase in the total social welfare because tax collection becomes higher than traveler surplus reduction. This makes the reinvestment of congestion charge revenues an important opportunity to provide subsidies for public transportation and improve scheduled PT services. This represents one of the most commonly recognized successful combinations of transportation policies in urban areas.

In this research, we build on the previous experience in the literature to analyze the possible synergies from a combination of transportation policies in an urban region. Our work focuses on the definition of the optimal levels of the proposed policies that are required to achieve sustainability targets (maximum social welfare, in the empirical case study presented in this paper). We first develop scenarios in which the implementation of each policy is optimized "in isolation". Then, we simulate the scenarios in which more than one policy is developed at the same time. We compare the results from the implementation of the base scenarios with those containing the implementation of the package of different policies. Then, we compare the level of social welfare resulting from each scenario, under the assumption of optimal policies optimized "per se", or in combination in a policy package to reach an optimal strategy.

The remainder of this paper is organized as follows: after this brief introduction, the next section discusses the methodology adopted for this study. It briefly describes the land-use and transportation interactions (LUTI) model MARS-Madrid and the cost-benefit analysis methodology used in the analysis of scenarios. The following section describes the case study for the metropolitan area of Madrid (Spain) and provides details on the policy scenarios to optimize. Then, we present the analysis of the results and the comparison between the optimization processes; evidences of synergies in policy scenarios are highlighted. The final section offers some concluding remarks and discusses the relevant findings from this study in terms of policy recommendations that can be derived from the analysis of synergies.

THE EVALUATION AND OPTIMIZATION OF STRATEGIES IN TRANSPORTATION PLANNING

One of the main problems in the evaluation of synergies in planning is associated with the large number of possible policy instruments that could be implemented. Another issue is that policy-makers have difficulty in identifying the partial effects that can be obtained from each policy and the way multiple policies interact when included in a more complex planning strategy. Additional complexity is also associated with the estimation of the externalities that these policies would generate on additional components of the urban and regional system (social or environmental externalities, effects on the relocation of activities and residences). Many of these externalities cannot be easily quantified, and are often subject to the interpretation of the local decision-makers and influenced by cultural background and local regulations.

In this paper, we propose a modeling approach that allows evaluating policy synergies through the application of a strategic land-use transportation modeling framework. The proposed modeling approach simulates the impact of the policy packages over time. It thus improves the depth of the analysis significantly, and contributes to reduce possible biases that might underestimate (or eventually overestimate) the outcomes from the policies with simpler evaluation methods.

In order to obtain an understanding of different transportation policies interaction, we adopt a system dynamics (SD) approach to transportation modeling. The proposed methodology is based on the use of the land-use transportation interaction model MARS-Madrid linked to an optimization procedure in order to maximize an objective function through different policies design. Figure 1 shows the interaction between all the sub-models: the LUTI model, the policy instruments, and the optimization tool. The LUTI model and the optimization procedure are integrated by means of an objective function (OF), based on a dynamic cost-benefit analysis development. There is also a link between the optimization routine and the LUTI model through the transport policies. The intensity of the policy is changed in each iteration through the OF maximization seeking process (maximization of social benefits in this study).

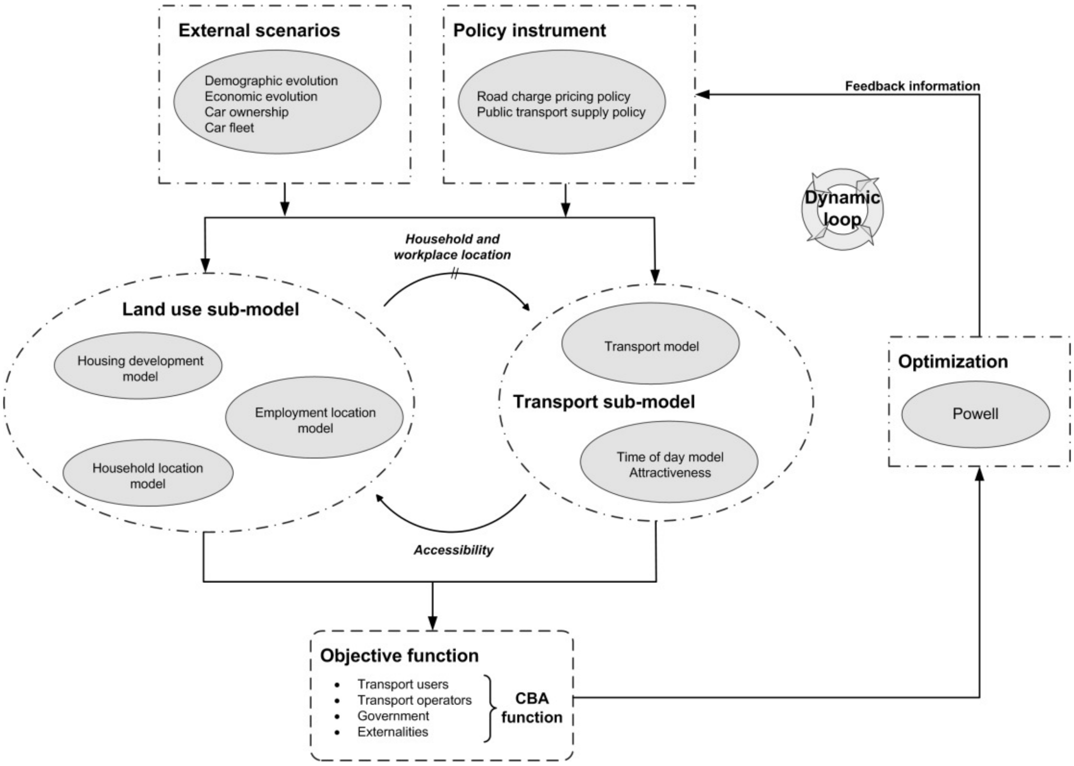

Figure 1 - Dynamic long-term loop of the integrated process. Basic structure of the evaluation and optimization model

The Strategic Model MARS-Madrid

MARS-Madrid is a dynamic land-use and transportation interaction (LUTI) model based on the Metropolitan Activity Relocation Simulator (MARS) modeling framework (Pfaffenbichler 2008). MARS-Madrid is a strategic, dynamic model, which integrates elements of the land-use and the transportation systems: the basic underlying hypothesis of MARS is that settlements and activities within them are self-organizing systems. The model is based on the principles of systems dynamics (Sterman 2000) and synergetic (Haken 1993). The development of the first MARS dates back to more than 13 years ago, and it was partially funded by the European Union research projects: OPTIMA (May, Shepherd and Timms 2000), FATIMA (May and Timms 2000) and PROSPECTS (Minken et al. 2003). To date, MARS models have been developed for many European cities (Edinburg, Helsinki, Leeds, Madrid, Oslo, Stockholm, Bari and Vienna), some cities in Asia (Chiang Mai and Ubon

Ratchathani in Thailand, and Hanoi in Vietnam) and in Porto Alegre, Brazil (Becker Lopes 2010). The first application of a MARS model in the United States has been recently developed for Washington D.C. (Hardy 2012).

MARS-Madrid benefits from the commonalities with the other MARS models and the advantages that derive from the joint development with the other products belonging to the MARS modeling framework. The MARS-Madrid was developed to simulate the future development of the land-use and transportation over time. It simulates the outcomes from the implementation of policies in planning through the application of a fast and rather aggregated modeling system. The model is able to support policy evaluation and scenario testing over long-term horizons. It uses the concepts of causal loop diagrams (CLD) from the system dynamics, which provide the basis to study the relationships of cause and effect among the variables of the transportation system and the land-use. MARS-Madrid is designed for fast execution on most hardware environments, and it does not include an assignment step. The current version of MARS is implemented in Vensim®, a System Dynamics programming environment. The model is based on the analysis of speed vs. O-D demand relationships, and includes speed-flow functions that simulate the existing transport network. These functions are calibrated for the Madrid Network using a transport model developed in the PTV-VISUM® commercial modeling software.

The application of a LUTI model to the evaluation of the impacts of transportation policies is a major improvement over the use of traditional four-step travel demand models. MARS-Madrid includes a land-use component and explicitly simulates the interaction between the transportation system components and the relocation of residences and economic activities over time. Transportation demand is often considered a derived demand from the need to participate in activities and to reach the required destinations. At the same time, the accessibility to places is affected by the characteristics and performance of transportation. This has important effects on the location of residences and economic activities. The direct and complex relationship between transportation and the urban activity system (Manheim 1979) sets the basis for the instable equilibrium that exists between transportation supply and demand.

MARS-Madrid includes two main sub-models, a transportation model and the land-use model. The transportation model simulates the travel behavior of the population that lives in each studied area, depending on the location of residences and workplaces. The land-use model simulates the generation and allocation of new housing units and the location of workplaces for two main categories: production and services. Additional model components compute energy consumption from transportation and the generation of a set of greenhouse gases (GHG) and other pollutant emissions from transportation. Table I provides summary information on the model MARS-Madrid.

The model simulates the land-use as part of the urban dynamic system, which is affected by the modifications in the transportation system. Similarly to other MARS models, it works with a significant level of aggregation and is useful to make long-term assessments. In the current version of the Madrid model, the interactions between land-use and transportation are simulated on a 30-year period, from 2004 to 2034.

Pfaffenbichler, Emberger and Shepherd (2008) provide additional information on the development of the first MARS model, and the way this model was calibrated and validated using data for the city of Vienna from 1981 to 2001. Guzmán (2011) describes the calibration and validation methods and data for MARS-Madrid.

Table I - MARS-Madrid main properties and features

Model Feature	MARS-Madrid Model
Number of zones	90
Travel modes	Car, public transportation (bus and rail), slow
Congestion effects	OD-specific speed-flow curves for trips (V/C ratios)
Generalized costs	In-vehicle time, access/egress time, parking search time, waiting times, transfer times, car costs, PT fares
Journey purposes	Commute, others
Household features	Employed population, car ownership, household income
Mode and destination choice	Simultaneous choice
Demand response	Commute trips are inelastic. Constant travel time budget
Land-use response	Yes

The Objective Function: a Dynamic Cost-Benefit Analysis

This section of the paper discusses the appraisal method and the objective function adopted in the scenario evaluation. In this study, policy scenarios are evaluated in terms of their fulfillment of a social welfare objective (according to the concepts of the welfare economics). The definition of the social welfare objective function depends on both the specific parameters to be used to evaluate the policy packages and the time period in which policies are evaluated. For instance, under a sustainability framework, congestion, pollution, resource consumption, social exclusion and deterioration of quality of life are all relevant problems that authorities must face in the definition and selection of policy strategies they support.

Transportation planners usually apply Cost-Benefit Analyses (CBA) or Multi-Criteria Analysis (MCA) (Shiftan, Kaplan and Hakkert 2003; Bristow and Nellthorp 2000) as appraisal methods. Both methods can be integrated into the MARS modeling environment. The MARS model of Edinburgh (Shepherd and Pfaffenbichler, 2006) was combined with an MCA in the European research project STEPS (Fiorello et al. 2006). Guzmán (2011) used the MARS-Madrid model in combination with a MCA and CBA appraisal approach.

These approaches are usually based on the evaluation of policy results with a static, discrete approach applied over a limited interval of time (Shepherd et al. 2006). Several limitations of these approaches for the evaluation of policies in land-use and transportation planning have been discussed (van Wee 2007), in particular for the evaluation of new transportation infrastructure projects. Additional, limitations exist due to the difficulties associated with the quantification of some policy outputs in monetary terms, the analysis of social equity and the evaluation of eventual synergies of multiple policies (Doll and Jansson 2005).

CBA evaluation is often used as part of decision support tools to help in the selection of policies to implement in transportation (Damart and Roy 2009). In this paper, we evaluate the impact of the suggested policies on a long-term horizon, simulating the effects that derive from the implementation of the policy packages in terms of their negative and positive impacts on each category of agents. We consider four different social agents for which the policy impacts are evaluated: transportation users, transportation operators, public administration, and environmental externalities. We use a CBA approach to estimate the changes in the users' perceived costs that result from the changes introduced in the transportation system. The analysis includes all monetary costs associated with any possible trip (e.g. public transportation fares, tolls, fuel prices, etc.).

We defined an objective function that measures the difference between the perceived costs resulting from the implementation of one or more policies in the urban area and the similar costs in the base scenario (do-nothing). The objective function includes the following elements:

a) Changes in the consumer surplus [$\Delta CS_{ij}(t)$] in the year *t* (this term includes the monetary costs/savings and the time savings, or delays, for the transportation users, by mode);
b) Costs/benefits for the system operators [$\Delta O_{ij}(t)$] in the year *t* (this term includes the revenues from PT fares, parking charges and road pricing, by mode);
c) Changes in the costs/benefits for the local administrations [$\Delta G_{ij}(t)$] in the year *t* (this term includes the revenues from fuel taxes and maintenance costs for the transportation infrastructures by mode without taking into account the subsidies for PT);
d) Social and environmental externalities [$\Delta E_{ij}(t)$] in the year *t* (this term includes the costs/benefits from the reduction of accidents, GHG emissions and air quality, measured by the amount of emitted NOx and PM_{10}).

We estimate the changes in consumer surplus using the methodology presented by Sugden (1999), which provides acceptable approximate results. A similar approach to the one adopted in this study was also adopted also for estimating the users' benefits in the evaluation of transportation projects (Jara-Díaz 2007). We express all cost components with the net present value (NPV) of the implemented strategy, using the social discount rate *r*=4.8% (Souto Nieves 2003). The final equation for the computation of the objective function (*OF*) is:

$$OF = \sum_{t=2004}^{2034} \sum_{ijm} [1/(1+r)^t] \cdot \left[\Delta CS_{ijm}(t) + \Delta O_{ijm}(t) + \Delta G_{ijm}(t) + \Delta E_{ijm}(t)\right] \quad (1)$$

Where *i* and *j* are the origin and destination of each trip, and *m* is the transportation mode.

The consumer surplus (user benefits) include users' money savings and time savings that derive from the policy implementation; the operators' benefit equals revenues minus the operating costs; the government benefits include those from fuel tax revenues and maintenance road costs; the external benefits include those from reductions in accidents, emissions, and pollutants. These benefits are calculated from the MARS-Madrid model and the appraisal framework. In order to obtain a framework able to assess a multimodal transport system, it is necessary to have a dynamic CBA based on a benefit distribution by transport mode and by origin, according to the approach advocated in Sugden (1999). The disaggregated welfare function for the transportation users is given by:

$$\Delta CS_{ijm} = \frac{1}{2} \sum_t \sum_{ijm} \left(T_{ijm}^0 + T_{ijm}^1\right) \cdot \left[\left(t_{ijm}^0 - t_{ijm}^1\right) + \left(\left(c_{ijm}^0 + \tau_{ijm}^0\right) - \left(c_{ijm}^1 + \tau_{ijm}^1\right)\right)\right] \quad (2)$$

Where T_{ijm} is the demand for trips between *i* and *j* by mode *m*; t_{ijm} is travel time multiplied by the value of time; c_{ijm} is operational mode costs (fuel + fixed costs) and finally τ_{ijm} is the costs corresponding to fares, parking fees and other charges. The superscript *k* is used to denote either the do-nothing scenario (*k*=0) or the scenario that is tested (*k*=1).

Equation (3) shows the value of net benefits for the operators. This equation depends on the total revenues from each scenario (which include PT fares, toll revenues and parking charges) and total costs associated with the operation of transportation services. All revenues and costs are computed in terms of net present value, of respectively revenues and costs over the 30 year included in the modeling simulation. However, in the definition of the future costs associated with the proposed policies, we do not consider the initial infrastructure costs associated with the proposed interventions (which are difficult to estimate, and will highly depend on the specific technologies and solutions that will be chosen). We treat parking operators, the toll operators and the PT operators as a unique "operators" category.

In a similar way, equation (4) represents the government benefits (or losses) resulting from the changes in fuel tax revenue ΔF_{ij} and the changes in the cost of road maintenance ΔM_{ij}. Finally, equation (5) represents the value of the externalities associated with green-house gas emissions ΔGHE_{ij}, air pollution ΔP_{ij} and safety ΔS_{ij}.

i. Operator benefits:

$$\Delta O_{ijm} = \sum_t \sum_{ijm} T^1_{ijm} \cdot \left(\tau^1_{ijm} + c^1_{ijm}\right) - T^0_{ijm} \cdot \left(\tau^0_{ijm} + c^0_{ijm}\right) \tag{3}$$

ii. Government benefits:

$$\Delta G_{ijm} = \sum_t \sum_{ijm} \left(T^1_{ijm} - T^0_{ijm}\right) \cdot \left(F_{ijm} + M_{ijm}\right) \tag{4}$$

iii. Externalities:

$$\Delta E_{ijm} = \sum_t \sum_{ijm} \left(T^1_{ijm} - T^0_{ijm}\right) \cdot \left(GHE_{ijm} + P_{ijm} + S_{ijm}\right) \tag{5}$$

The values of operating costs (c_{ijm}) and travel time (t_{ijm}) depend on the trip mode and on the origin-destination pair (distance and travel time). The operating costs (by mode) vary depending on the modeled scenario, and trip destinations change as an effect of a change in travel costs: travelers with higher time costs may choose to make shorter trips or use cheaper modes. Accordingly, the consumer surplus can be rewritten separating the various component terms – for commuting and other mobility – by modes of transport *m*.

Optimization Process

In this study, an optimization routine maximizes the objective function through the search for an optimal set of values for one or more parameters. The optimization method uses the Powell algorithm (Powell 1964) to search for a local minimum in a quadratic function for a set of independent linear vectors, without using partial derivatives. The method reaches convergence with a limited number of iterations and ensures a high precision level (Renders and Bersini, 1994). A detailed discussion of the algorithm is available from Brent (1973), and the complete algorithm is reported by Press et al. (2007).

This method can be applied to optimize several types of transportation and land-use policies. In this study, we apply the optimization routine to select the best policy levels for three sets of variables: a toll-pricing policy that charges passenger vehicles that access the city center of Madrid, with the possibility of varying tolls over time, from the short term to the long term, and the frequency of bus services in the city.

A previous version of the optimization process was presented by Guzmán et al. (2013; in press). The application of the optimization technique helps researchers define the optimal levels for the studied policies in order to maximize the objective function, i.e. social welfare. It reduces the computation time required to test several different levels of the proposed policies in the transportation and land use model. In our study, we allow different values for the initial and final characteristics of the selected policy instruments, with a gradual application of the policy instruments over time. The optimization process maximizes the objective function through the estimation of a) the optimal values for the policy instruments (congestion charge tolls and bus frequency); b) the year in which policies should be introduced and c) the total time (i.e. number of years) over which policies should be gradually modified until reaching the final optimal long term conditions.

SIMULATION SCENARIOS AND RESULTS

The proposed policy optimization approach is applied to the metropolitan area of Madrid, a highly urbanized region of about 8.000 km^2, with 6,458,684 inhabitants (in 2010). The central business district (CBD) of the city occupies the central 55 km^2 and it has a population of about 1 million inhabitants. The remaining parts of the metropolitan area of Madrid include four circular rings (Figure 2).

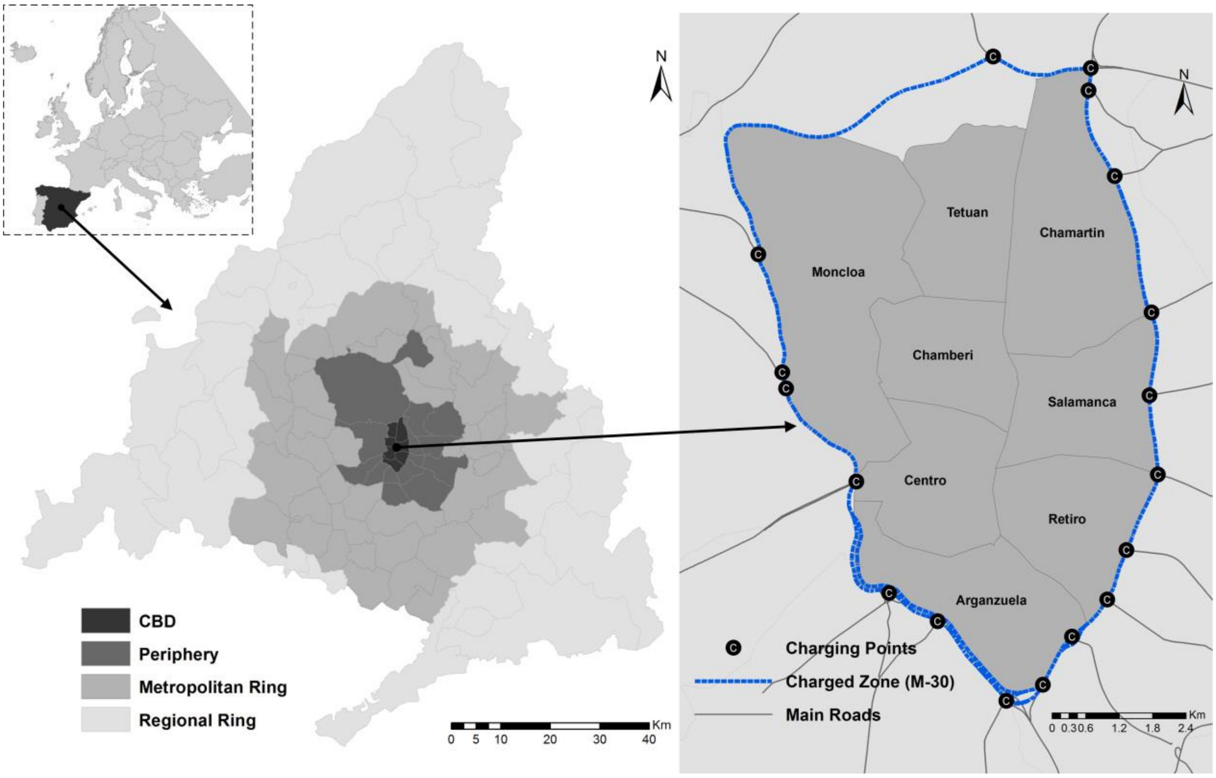

Figure 2 - Study area: the metropolitan area of Madrid, Spain

The model MARS-Madrid simulates the interaction among transportation and land-use in the entire described area, and is based on the analysis of 90 modeling zones. The model uses external forecasts for economic growth, demographic trends and car ownership obtained from the Regional Institute of Statistics of the Community of Madrid (Region of Madrid) (INE 2010). Base year for all simulations is 2004.

Table II shows the modal split data that were used in the calibration of MARS-Madrid for the base year. The mode split for both commuting trips (home-work) and other trips (home-other) is calculated using the Madrid 2004 mobility survey (CRTM 2004). Other data inputs that were used in this study include:

- Constant travel time budget: 87 min (CRTM 2004).

- Average trips by worker: 2.04.
- Time value (commuting and other, 2004 prices): 10.45 €/h and 5.70 €/h (Monzón, Fernandez and Jordá 2008).

Table II - Mode split calibration data

Mode	Commuting trips	Other trips	Total
Slow	12.3%	24.2%	20.5%
Bus	15.7%	18.2%	17.4%
Rail	26.3%	19.3%	21.5%
Car	45.7%	38.3%	40.6%

The cost unit values for externalities (Table III and IV) were obtained from the European Project "Developing Harmonized European Approaches for Transport Costing and Project Assessment" (Bickel et al. 2005). As shown in the above equation, the investment costs are not taken into account.

Table III - Estimated emissions value [€/t]

Year	Avg. CO_2 value	Avg. NOx value	Avg. PM_{10} value
2004-2009	22	5,300	2,873
2010-2019	26		
2020-2029	32		
2030-2039	40		

Note: all costs are in 2004 prices (€)

Table IV - Estimated casualties avoided

Fatality	Severe injury	Slight injury
1,193,686	147,755	11,171

Policies and Scenarios

MARS-Madrid, in its current version, runs with base year 2004 and allows simulations until 2034. We run a do-nothing scenario, which does not include either congestion pricing or any improvement on public transportation. Besides, in this study we analyze scenarios that involve the following transportation policies:

- *Congestion charge for the access to the CBD*: this policy simulates the introduction of a toll to access the most central area of the city with private vehicles. The toll is charged to vehicles that access the central area of the city, inside the freeway M-30 ring, as shown in Figure 2. Congestion charge tolls are introduced with different pricing structure for peak and off-peak periods.
- *Modification to public transportation services*: the policy simulates a modification in the frequencies of bus services. This scenario tests the effects of an eventual increase (or decrease, respectively) in the bus frequency in the region of Madrid. Bus operating costs are computed for each level of frequency in order to estimate the effects of the policy on public transportation operators.

We develop scenarios that simulate specific "policy profiles": each policy can in fact be implemented with different characteristics over time: we define the main characteristics of a policy profile $X(t_A)$ and $X(t_L)$ (see Figure 3) as the levels of the policy attributes respectively in the short run (the value of the policy when it is introduced) and in the long run (the final policy value after the intermediate adjustments). Similarly, t_A is the year in which the policy is introduced (t_A=2010 in this study) and t_L identifies the long-term horizon on which the policy is evaluated (t_L=2034). In this case, t_L= t_H.

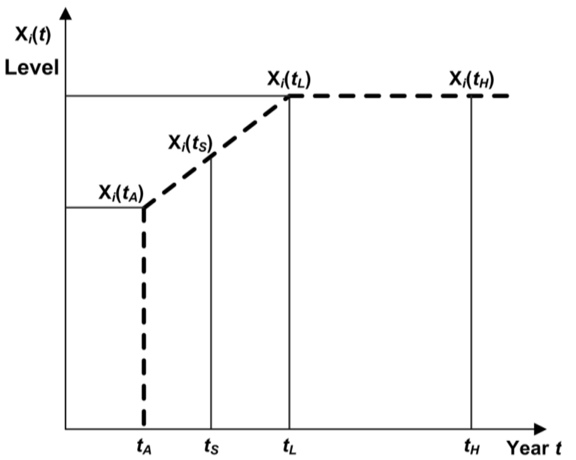

Figure 3 - Instrument profile for continuous instruments

We assume simple characteristics of the policy instruments during their time of application, in agreement with Emberger et al. (2008): successful policies should be easily understood by transportation users and easy to develop for the decision-makers and system operators. We therefore include only flat and linearly increasing tolls and policy values in the definition of the scenarios to simulate (we do not consider more complex functions for the policy levels):

- Toll **[T]**: in this scenario, we search for the optimal value of the congestion charge toll (Figure 2), in order to maximize the social welfare measured by equation (1).
- Public transportation-Bus **[B]**: in this scenario we optimize the frequency for the bus system in the entire region (starting from the current values of frequencies in the base scenario) to optimize the objective function (1).
- Combined scenario **[T+B]'**: this scenario evaluates the results from the contemporaneous adoption of the two policies described above, using the levels that have been optimized in the previous scenarios. This scenario is useful to evaluate how the results of the adoption of two policies vary if the policies are implemented simultaneously (we still use the policy profiles that were optimized individually).
- Optimized combined scenario **[T+B]**: in this scenario we search for the optimal values of the two policies through the joint optimization of the two policy profiles. This scenario maximizes the positive synergies that can derive from the contemporaneous implementation of the two policies and achieves (in case of non-null positive synergies) a higher level of social welfare than in the previous scenario [T+B]'.

Model Results and Evaluation of Synergies

All four scenarios were solved as optimization problems using the MARS-Madrid modeling framework for all land-use transportation interaction simulations, and searching for the maximization of the described objective function (except for scenario [T+B]' where we estimated isolated optimal solutions for [T] and [B] and then ran the scenario in the MARS-Madrid model to compute the policy results). Table V summarizes the results from the simulation of the proposed scenarios in MARS-Madrid. Results are presented in terms of maximum NPV of the objective function for the 30 year period from 2004 to 2034.

Table V - Optimal results

Scenario	Policy	MARS-Madrid range	Optimum MARS-Madrid	
			***t_A* (2010)**	***t_L* (2034)**
[T]	Toll value peak	€ 0 – 8	€ 1	€ 2
	Toll value off-peak *	€ 0 – 8	€ 0	€ 0
	Bus frequency	n/a	n/a	n/a
[B]	Toll value peak	n/a	n/a	n/a
	Toll value off-peak *	n/a	n/a	n/a
	Bus frequency	-50% to +200%	0%	60%
[T+B]'	Toll value peak	€ 0 – 8	€ 1 **	€ 2 **
	Toll value off-peak *	€ 0 – 8	€ 0 **	€ 0 **
	Bus frequency	-50% to +200%	0% **	60% **
[T+B]	Toll value peak	€ 0 – 8	€ 1	€ 4
	Toll value off-peak *	€ 0 – 8	€ 0	€ 0
	Bus frequency	-50% to +200%	0%	100%

Notes: *The optimal result for the off-peak toll value is zero (traffic congestion is rather low during off-peak time, and the benefits from this policy are limited), similar to the results from May et al. (2006) and Shepherd et al. (2006). **The policy levels in the scenario [T+B]' are the optimal values estimated in [T] and [B], respectively.

Table VI reports some indices of the performance of the transportation system for all scenarios and compare them to the base scenario: performance indices include mode share, average speed for cars and buses, average trip distance, CO_2 emissions per capita, and others. In the toll scenario [T], car mode share is lower than in the base scenario, mainly as an effect of tolls that reduce trips by car from the suburban areas to CBD with an increase in PT ridership. However, the average trip distance also increases as an effect of the longer detours caused by the presence of tolls to access the CBD. The two counteracting effects somehow balance each other in terms of CO_2 emissions, with a modest reduction in the total emissions associated with this scenario.

Table VI – Transport indicators of the proposed scenarios (2034)

	Base case	[T]	[B]	[T+B]'	[T+B]
	Do-nothing	Toll scheme	Bus freq.	Toll + Bus*	Toll + Bus**
Car demand [pax·km/year]	2.53E10	2.53E10	2.51E10	2.51E10	2.52E10
Bus demand [pax·km/year]	0.49E10	0.46E10	0.70E10	0.71E10	0.75E10
Avg. car speed peak [km/h]	31.65	32.17	33.14	33.70	34.36
Avg. bus speed peak [km/h]	21.46	21.62	24.47	24.66	25.63
Car use peak [%]	47.8	47.3	45.3	44.8	44.0
Bus use peak [%]	14.3	14.5	21.0	21.3	23.6
Avg. car trip distance [km]	18.55	18.62	18.47	18.54	18.58
Avg. bus trip distance [km]	11.57	11.58	10.83	10.84	10.54
Avg. car distance to CBD [km]	21.34	21.39	21.22	21.28	21.32
Avg. bus distance to CBD [km]	16.30	16.32	14.85	14.88	14.37
Avg. car trip cost peak [€/trip]	2.41	2.66	2.42	2.67	2.87
Avg. bus trip cost peak [€/trip]	0.68	0.68	0.70	0.70	0.70
CO_2 emissions [t/inh]	0.91	0.90	0.91	0.91	0.93

* Optimal values from isolated policies
** Joint optimization of the policies

In the public transportation scenario [B], more passengers switch from the use of private cars to PT as an effect of the increase in frequency of PT that is applied to the entire study area (while tolls are only charged in the central part of the city). This scenario generates a reduction in the number of cars on the road network with a significant increase in the average speed for both cars and buses. It also generates a very relevant increase in social equity, as a result of the investments in PT that redistribute income across social classes and reduce the ratio of transportation costs/available income, especially in lower income zones.

To facilitate the evaluation of the possible synergistic effects of the policies, Table VII reports the differences in the performance indices respectively between the combined scenario [T+B]' and the single-policy scenarios [T]+[B], and between the jointly optimized scenario [T+B] and the single-policy scenarios [T]+[B]. These results provide insights on the eventual synergies obtained from the contemporaneous adoption of the two proposed policies.

Table VII – Difference in performance measures between each policy scenario and the base scenario in the final year 2034 and evaluation of synergies

	[T]	[B]	[T+B]'	[T+B]	[T+B]' – ([T]+[B])	[T+B] – ([T]+[B])	[T+B] Synergies
	Changes from baseline scenario [%]						
Car demand	+0.16	-0.80	-0.66	-0.40	+0.02	+0.24	-
Bus demand	+0.50	+53.49	+54.30	+64.33	+0.31	+10.34	+
Avg. car speed peak	+1.65	+4.72	+6.47	+8.58	+0.10	+2.21	+
Avg. bus speed peak	+0.74	+14.03	+14.92	+19.42	+0.15	+4.65	+
Car use peak	-1.03	-5.20	-6.32	-7.98	-0.09	-1.75	+
Bus use peak	+1.41	+47.29	+49.37	+65.32	+0.67	+16.62	+
Avg. car trip distance	+0.37	-0.42	-0.08	+0.16	-0.03	+0.21	-
Avg. bus trip distance	+0.06	-6.39	-6.31	-8.91	+0.02	-2.58	-
Avg. car distance to CBD	+0.26	-0.54	-0.28	-0.10	0.00	+0.18	-
Avg. bus distance to CBD	+0.14	-8.85	-8.72	-11.85	-0.01	-3.14	+
Avg. car trip cost peak	+10.18	+0.22	+10.53	+18.78	+0.13	+8.38	+
Avg. bus trip cost peak	-0.11	+2.35	+2.24	+2.13	0.00	-0.11	+
CO_2 emissions	-0.05	+1.05	+0.99	+2.80	-0.01	+1.80	-

Note: We compute synergies in the scenario [T+B], highlighting changes that are beneficial for environmental sustainability with the sign "+". All results in the table are computed as changes in the performance measure indices between the simulated scenario and the base reference scenario (do-nothing) for year 2034.

Already in the scenario [T+B]', which is based on the simultaneous adoption of the policies at their optimal individual level, the model predicts an improvement in most indices: in particular, car use is reduced, with a contemporaneous increase in PT ridership. The magnitude of the positive effects obtained with this combined scenario becomes even larger in the scenario [T+B], in which the policy levels are optimized jointly. This scenario allows for a larger reduction in car use, a larger increase in PT ridership and improvements in travel speed. All scenarios, however, produce an increase in CO_2 emissions due to the increased bus frequency and the longer car travel distances.

The outputs of the simulation show an interesting result: negative synergies may exist among policies. For example, in the [T+B] scenario, most synergistic effects for the car mode (car demand, car distance, car trip cost) are negative (i.e. results are inferior to the sum of scenarios [T] and [B]). This might be explained because travel distance is greater, as some car users change their usual destinations (e.g. CBD) for other destinations, favored by the contemporaneous speed increase. For CO_2 emissions, the results are always negative because total travel volume (passenger·km) in the alternative scenarios is higher than in the do-nothing scenario and the additional bus services contribute to the increase in CO_2 emissions.

Table VIII summarizes the results of each scenario in terms of the various components of the objective function in the CBA: consumer surplus, operators, government and social benefits which are part of the total social benefits. The table reports changes in the components of the social welfare function from the do-nothing scenario. Positive synergies, as identified in the previous sections, are shown in this table with a positive sign in the right column.

Table VIII - Cost-benefit analysis: total changes in objective function and possible synergies achieved in the proposed scenarios [M€, Net Present Value]

	[T]	[B]	[T+B]'	[T+B]	[T+B]' – ([T]+[B])	[T+B] – ([T]+[B])
	NPV per indicator [M€]				Synergies [M€]	
Time savings car	216.22	820.73	1,025.97	1,343.93	-10.98	+306.98
Time savings PT	65.53	1,404.22	1,480.92	2,148.66	+11.17	+678.91
Operational car costs	8.48	30.76	38.58	50.23	-0.67	+10.98
Congestion pricing fee	-879.68	0.00	-868.83	-1,307.37	10.84	-427.70
Congestion pricing revenues	836.24	0.00	814.55	1,176.93	-21.96	+340.69
Parking charges revenues	-147.09	-33.06	-177.81	-248.76	+2.35	-68.61
PT fares revenue	20.81	650.72	674.71	953.68	+3.19	+282.16
Operational PT costs	0.00	-1,393.89	-1,393.89	-2,326.18	0.00	-932.28
Fuel tax revenues	-2.35	-96.44	-99.02	-117.04	-0.24	-18.26
Road maintenance costs	-2.49	13.92	11.71	12.53	+0.28	+1.10
Environmental benefits	1.00	-5.03	-3.92	-20.19	+0.11	-16.16
Accidents costs	-48.41	-53.39	-100.82	-147.85	+0.97	-46.06
Consumer surplus	-589.45	2,255.72	1,676.64	2,235.44	+10.36	+569.17
Operator benefits	709.96	-776.24	-82.42	-444.32	-16.15	-378.04
Government benefits	-4.83	-82.52	-87.32	-104.51	+0.03	-17.16
Externalities benefits	-47.41	-58.41	-104.74	-168.04	+1.08	-62.22
Total social welfare (OF)	**68.27**	**1,338.55**	**1,402.15**	**1,518.57**	**-4.67**	**+111.75**

Note: All results are computed as change in NPV per indicator between each policy scenario and the do-nothing baseline scenario.

The results show that the congestion pricing (scenario [T]) has a negative impact on consumer surplus, but it generates a positive social welfare because toll revenues more than compensate travelers' surplus reduction. These results highlight that these types of policies may encounter a strong social opposition. However, congestion pricing schemes generate significant increase in NPV for operators' finances, which may create the conditions for complementary measures that compensate the negative change in consumer surplus.

The outcomes of scenario [B] show that an isolated policy that improves bus frequency generates a large increase in social welfare. However, this is often done at the expense of operators (or, more often, the local government that subsidizes PT). This strategy also produces losses for other agents: modal shift from car to bus causes lower revenues from fuel taxes and parking charges, increases travel speed and accident rates as well. More passengers·km travelled causes higher emissions. Overall, better PT services (including the necessary subsidies) is a policy that increases total social welfare and consumer surplus. Not surprisingly, PT improvement is one of the policies that receive the largest public support and acceptability. However, it is a quite expensive policy for the public decision maker.

The outcomes from the scenario simulation show the potential benefits associated with the implementation of two instruments that can be mutually advantageous and generate synergies. However, we highlight how when the isolated optimal schemes found for the scenarios [T] and [B] are enforced together, without any additional policy optimization, the model predicts a negative synergy. Subsequent analysis has suggested that this occur mostly because both strategies mainly impact on the same group of users: their combined impact on social welfare is therefore lower than the sum of their individual impacts. This evidence is very important, as it shows the importance to evaluate both policies jointly to avoid an overestimation of the policy outcomes. More generally, in many contexts, the combination of several transport policies generates benefits that are different from the sum of the results of each individual policy (often, the combined benefits are greater than any of the individual benefits, demonstrating some complementarity).

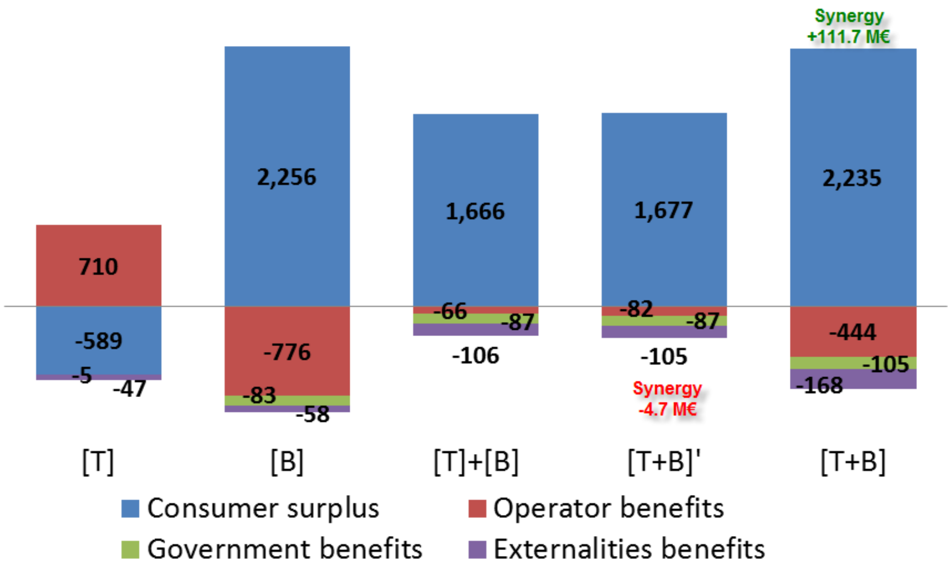

Figure 4 - Values of objective function (by agent component) in the proposed scenarios

Policy synergies can be enhanced if both policy instruments are optimized together, as in the scenario [T+B]. This can be done either with a bottom-up (where individual instruments are selected and then optimized) or a top-down approach (where the strategy is defined roughly and used to define a set of specific policy instruments). The optimization method may help make them more effective. When both instruments are optimized jointly, the scenario [T+B] reaches a higher level of total welfare (see Figure 4). In this case, the acceptability problem of the congestion charge is overcome and mitigated. And lastly, congestion pricing instrument can finance a significant portion of the improvement in PT operation. The scenario [T+B] provides insights about the maximum synergies that can be obtained with the simultaneous implementation of the two policies when the levels of the policies are optimized jointly through the maximization of the social welfare for the Madrid region.

The results from the scenario analysis are very important for their value in planning. Besides, they highlight the need for planners to test strategies and policy packages with advanced tools that can fully evaluate the interaction among policies. Optimization techniques may help select the policy instruments, the details for each specific policy, and also package different policy instruments in a policy package.

CONCLUSIONS

This study investigates the results from the implementation of different policies in planning through the application of an integrated land-use transportation model. The application of the proposed methodology is useful to evaluate the way different policy instruments interact with each other in a policy package. The modeling approach evaluates the outcomes from the policy packages including both short-term and long-term effects. Besides, it helps in the evaluation of synergies from policy packages, a task that is often a challenge in planning.

We apply the proposed method to the evaluation of the impact of different policies, namely a congestion pricing scheme and an increase in public transportation services, in the metropolitan area of Madrid. Through the use of an optimization technique, we find solutions (policy levels) that maximize an objective function (total social welfare). The analysis of costs and benefits helps identify the optimal levels of the studied policies.

As an isolated policy, the improvement of bus frequency achieves larger levels of social welfare than congestion pricing. However, improving PT generates a large negative financial impact on operators which may require increased subsidies to public transportation. On the other side, congestion pricing has a negative impact in consumer surplus, although it generates a positive social welfare because toll charges collection compensates travelers' surplus reduction. These results highlight that this type of policy may encounter a strong social opposition. However, congestion pricing schemes generate significant increase in the net present value for operators' financial revenues that may create space to promote reinvestments in transportation.

Through the combination of the individual optimal policies, revenues from congestion pricing partially cover the needed subsidies for public transportation. Although some policy synergies occur, the total social welfare decreases, mostly because both strategies impact on the same groups of users. This highlights the risk of overestimating the impact from these planning policies if analyzed in isolation in many evaluation studies. The optimization of the combined policy scenario that includes these policies in the proposed modeling approach shows that a higher level of welfare is possible for different levels of these policies.

Overall, the use of integrated models that simulate the dynamic interaction of transportation and land-use systems significantly contributes to finding the combination of policies that maximize social welfare. The proposed approach helps evaluate policy synergies, and can be used to support decision makers in the definition of policy packages that increase environmental sustainability. Future developments of the current research will explore the analysis of more complex scenarios that include three or more transportation or land-use policies.

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