Development of a Hierarchical Approach to Assess the Impacts of Transport Policies

The Madrid case study

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Abstract: To make our cities sustainable is one of today's major challenges. The complexity of this task requires suitable planning tools. The aim of this paper is to present a hierarchical modelling approach to assess the effects of transport and land use projects and instruments. First a brief definition of the overall objective sustainability is given. This is followed by the description of the suggested hierarchical approach. A strategic, dynamic land use and transport interaction model builds the basis and is linked to models on a different spatial and functional level. A case study covering the Spanish region of Madrid (ﬁComunidad de Madridﬂ) was selected to demonstrate the applicability. In particular the effects of the public transport infrastructure projects, the extension of the metro line number 9 and bus lanes on all radial highways, should be assessed. It is demonstrated that the suggested approach is applicable and suitable. The overall effect of the metro line extension and the bus lanes is positive. Nevertheless their contribution to a sustainable urban region is limited. Comprehensive strategies are needed to achieve the objective of sustainability. It could be shown that the projects can even have some negative local effects in the long term.

1. INTRODUCTION

Sustainability is one of today's major challenges. A widely accepted definition is based on intergenerational equity and sub-objectives. Studies provide evidence that our cities do not fulfil the requirements of

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sustainability. Sustainability requires the consideration of global, regional and local effects. Therefore a hierarchical assessment approach was developed. Basis is a dynamic land use and transport interaction model working on a strategic level. Effects on land use and regional travel patterns are predicted for the whole region. The results, settlement patterns and origin-destination matrices, are disaggregated in the corridors affected by the projects. An assignment model is applied to these areas. This allows the assessment of environmental effects on local and regional level. Finally the modelling results are assessed by applying a modified cost benefit analysis.

The work presented here assesses transport policies of the city of Madrid to determine their environmental effects and their contribution to the objective of sustainability. The case study covers an area of about 8,000 km^2 with about 5 million inhabitants. Land use is characterised by a rapid development of housing and businesses in the outskirts. As a result a high share of people commutes between the periphery and the core city. Although Madrid has an extensive metro line system, this causes high levels of congestion. Indicators show that the land use and transport system are not sustainable. Several instruments to improve the situation have been proposed. The case study covers a selection of them: two projects finalised in the 90ies (extension of a metro line and a bus and high occupancy vehicle lane) and a recent proposal of bus lanes on all radial highways.

The case study delivers methodological advice as well as policy recommendations. The feasibility of the hierarchical approach to assess the contribution of transport projects to sustainability is demonstrated. Potential improvements for future research are highlighted. The contribution of specific projects, the extension of a metro line and bus lanes, towards the overall objective of sustainability is shown.

2. THE OBJECTIVE OF SUSTAINABILITY

2.1 Definition

Sustainability can be defined as equity between today's and future generations (May et al. 2003). I.e. "A sustainable land use and transport system does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage" (May et al. 2003 p. 12). Another definition is that a sustainable system "does not leave any negative impacts or costs for future generations to solve or bear – present builders and users of the system should pay such costs today" (Schipper et al. 2005 p. 621). Both definitions are basically equivalent and stem from the findings of the Brundtland Commission (WCED 1987). Furthermore the use of a set of sub-objectives and indicators is suggested to make these general definitions operational (May et al. 2003; Schipper et al. 2005). Sub-objectives are amongst others “Careful treatment of non-renewable resources”, “Protection of the environment” or “Equity and social inclusion” (May et al. 2003 p. 13).

2.2 Indicators

Minken et al. (2003) and Schipper et al. (2005) suggest a wide range of indicators to assess sustainability towards its sub-objectives. Consumption of land, consumption of fossil fuels and atmospheric emissions are amongst them. Land and fossil fuel are non renewable resources. Their consumption might limit the opportunities of future generations and is therefore suitable as an indicator to measure the sub-objective “Careful treatment of non-renewable resources”. Local atmospheric emissions endanger the environment and are therefore suitable to represent the sub-objective “Protection of the environment”. Accessibility can be interpreted as a proxy for the sub-objective “Equity and social inclusion”. The development of these indicators in combination with a modified cost-benefit-analysis as suggested by (Minken et al. 2003) is used to assess the contribution of policies to the objective of sustainability.

3. A HIERARCHICAL ASSESSMENT APPROACH

3.1 Motivation

The objective of sustainability requires a joint consideration of global effects like greenhouse gas emissions, regional effects like changes in land use and local effects like pollutant emissions. No single model is able to cover all these levels simultaneously. Sub-objectives like “*Contribution to economic growth*” (May et al. 2003, p. 13) require the endogenous modelling of macro-economic developments. This is impossible at the regional or local level. On the other end of the spectrum strategic regional models cannot calculate local indicators like noise and pollutant emissions. To overcome these limitations the idea of a hierarchical approach linking models covering different levels of dis-aggregation was borne.

3.2 The Integrated Land use and Transport Model MARS

The starting point of the work presented here was the regional, dynamic, integrated land use and transport model MARS (**M**etropolitan **A**ctivity **R**elocation **S**imulator). The basic underlying hypothesis of MARS is that settlements and the activities within them are self organizing systems. Therefore it is sensible to use the principles of synergetics to describe collective behaviour (Haken 1983).

MARS assumes that land-use is not constant but rather part of a dynamic system that is influenced by transport infrastructure. Therefore at the highest level of aggregation MARS can be divided into two main sub-models: the land-use model and the transport model. The interaction process is implemented through time-lagged feedback loops between the transport and land-use sub-models over a period of 30 years.

Two person groups, one with and one without access to a private car are considered in the transport model part. The transport model is broken down by commuting and non-commuting trips, including travel by non-motorized modes. Car speed is volume and capacity dependent and hence not constant. Energy consumption and emission sub-models utilize speed dependent specific values. The land-use model considers residential and workplace location preferences based on accessibility, available land, average rents and amount of recreational space. Decisions in the land-use sub-model are based on random utility theory. Due to its strategic characteristic MARS uses a rather high level of spatial aggregation. The output of the transport model are accessibility measures by mode for each zone while the land-use model yields workplace and residential location preferences per zone.

MARS is able to estimate the effects of demand and supply-sided instruments whose results can be measured against targets of sustainability. They range from demand-sided measures, such as public transport fare (increases or decreases), parking or road pricing charges to supply-sided measures such as increased transit service or capacity changes for road or non-motorized transport. These measures can be applied to various spatial levels and/or to time-of-day periods (peak or off-peak).

To date MARS was applied to six European cities (Edinburgh, Helsinki, Leeds, Madrid, Oslo, Stockholm and Vienna). Within the project SPARKLE (**S**ustainability **P**lanning for **A**sian cities making use of **R**esearch, **K**now-how and **L**essons from **E**urope) MARS is adopted and applied to the Asian cities Ubon Ratchasthani, Thailand and Hanoi, Vietnam (Emberger et al. 2005). An extensive testing was carried out with historical data of the city Vienna (Pfaffenbichler 2003). A full description of MARS is given in (Pfaffenbichler 2003).

A MARS model of the Madrid region was available from the research project PROSPECTS - **P**rocedures for **R**ecommending **O**ptimal **S**ustainable **P**lanning of **E**uropean **C**ity **T**ransport **S**ystems (May et al. 2002; Pfaffenbichler and Emberger 2003). This model was used as a starting point in (Vieira 2005). A re-calibration of the model was performed. The land use part was calibrated to observed changes in the number of housing units, residents and workplaces in the industrial and the service sector between 1996 and 2001. The transport model part is calibrated to fit the origin-destination matrices by mode as observed in the 1996 household survey (CRTM 1996). As an example for the model testing a comparison of MARS results and the 1996 Madrid travel survey for total daily trips is shown in *Figure 1*. Both, the fit and the slope of the linear regression are satisfying. The resulting model was utilized for the case study presented here.

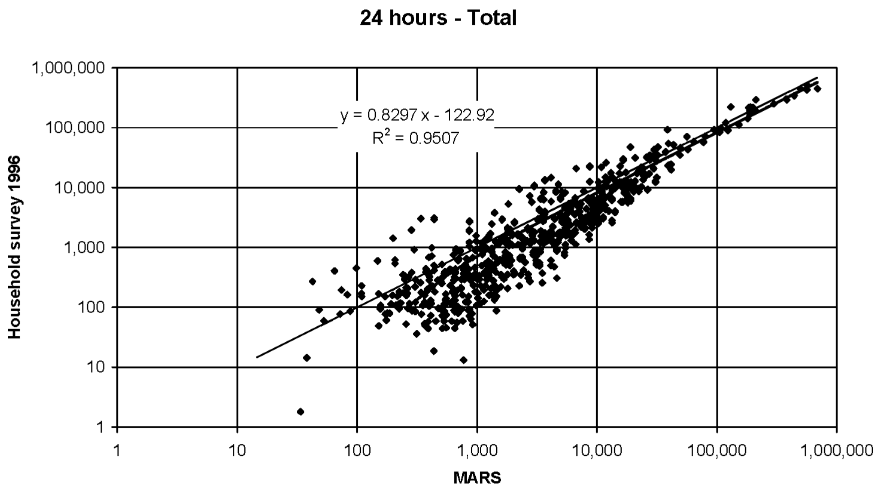

Figure 1. Comparison of the MARS model results with the results of the 1996 household survey (CRTM 1996) – daily trips total per zone.

3.3 First Steps

A first step to realize such a hierarchical approach was to link the MARS model of the region Madrid with a spatially higher dis-aggregated transport demand model of the corridor of the radial highway A3 (Vieira 2005). Five zones of the MARS model, which are directly affected by a metro line extension, were split up into the 28 census zones of the corridor A3. The relevant MARS output (number of residents, number of workplaces, car speed etc.) were dis-aggregated to census zones after achieving a reasonable conformity between empirical and calculated data for the base year 1996. The transport demand model was fed with the dis-aggregated MARS model results for the years 1996, 2005 and 2025. The next step, currently ongoing in a follow up PhD-thesis, is to link the results of the transport demand model to an assignment model. The commercial German software VISUM (www.ptv.de) is used in this process.

Another attempt to combine MARS with an assignment model was made within consultancy work for the Viennese municipal department 18. MARS origin-destination (OD) matrices for the years 2020 and 2030 were dis-aggregated and assigned to a VISUM transport network. Gravity type models were used for the dis-aggregation. The limitation was that there was no feedback of the VISUM results back into the MARS model. In the EU-funded research project STEPS (**S**cenarios for the **T**ransport system and **E**nergy supply and their **P**otential effect**S**, http://www.STEPs-eu.com) MARS was linked to models of a higher geographical level. The development of car ownership and vehicle fleet composition as output from the European model ASTRA was fed into a MARS model of Edinburgh. The world energy market model POLES was used to calculate the development of fuel prices.

3.4 Process

Figure 2 illustrates the proposed process of linking the MARS model with a spatially more dis-aggregated assignment model in the base year. The same procedure is suggested for each of the following MARS model years. The difference is that the left part of *Figure 2* with the OD matrices from the household survey is missing. The long term objective is to fully integrate a link with feedback loops to an external assignment model in each MARS iteration.

3.5 Dis-aggregation

A simple algorithm was used in (Vieira 2005) to dis-aggregate the MARS land use results. New developed housing units and businesses were distributed to the census zones in proportion to the area available for the corresponding type of land use. Gravity type models were used to disaggregate OD matrices were used in the work for the Viennese municipal department 18. The use of more sophisticated algorithms is foreseen for future applications. E.g. the same principles as used within the model MARS could be used in the dis-aggregation.

4. THE MADRID CASE STUDY

4.1 Case Study Area

The region "Comunidad de Madrid" is situated in the centre of Spain (*Figure 3*). It covers an area of about 8,000 km^2 and is populated by about 5.4 million people. Land use is characterized by a rapid development of housing and businesses in the surroundings of the city. The share of population living there steadily increases (*Figure 2*). As a result a high share of people commutes between the outskirts and the core city. The share of car trips is higher during the peak period than during the rest of the day (CRTM 1996). Although Madrid has an efficient metro line system and about 55% of the people commuting into the city use public transport (CRTM 1996), this results in a high level of peak hour congestion. The bus based part of the public transport system is stuck in congestion and therefore not attractive. Neither the land use nor the transport system currently do fulfil the requirements of sustainability.

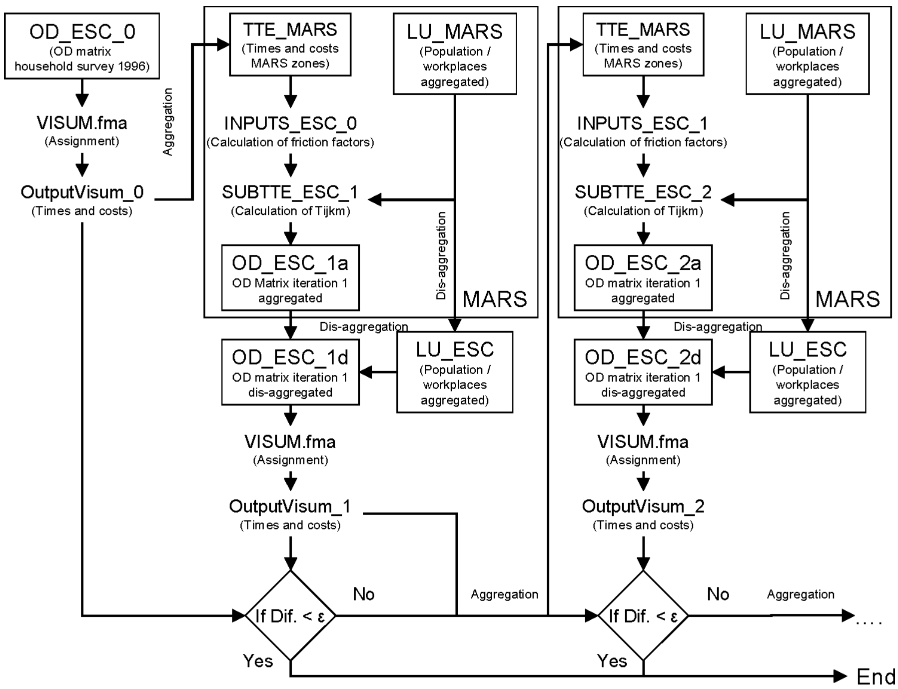

Figure 2. Linking the Madrid MARS model in the base year with an assignment model.

4.2 Extension of the Metro Line Number 9

The municipalities Rivas-Vaciamadrid and Arganda del Rey are situated in the corridor of the highway A3 in the South-East of the city of Madrid (*Figure 4*, detail X). Due to the relative proximity many residents commute into the city of Madrid. When public transport was solely bus based the share of public transport trips was only about 21% in 1996 (CRTM 1996). The situation was worsened by a rapid development of housing, service sector business and industry within the corridor (*Figure 5*). The authorities reacted with the decision to extend the metro line number 9 from its former end station Puerta de Arganda until Arganda del Rey (*Figure 4*). The extension, opened in 1999, consists of four new metro stations: Rivas Urbanizaciones, Rivas Vaciamadrid, Poveda and Arganda del Rey. Details about the planning process and the funding of the project have been published elsewhere (Monzon 2003; Monzon and Gonzalez 2000). A more detailed description is also given in (Vieira 2005).

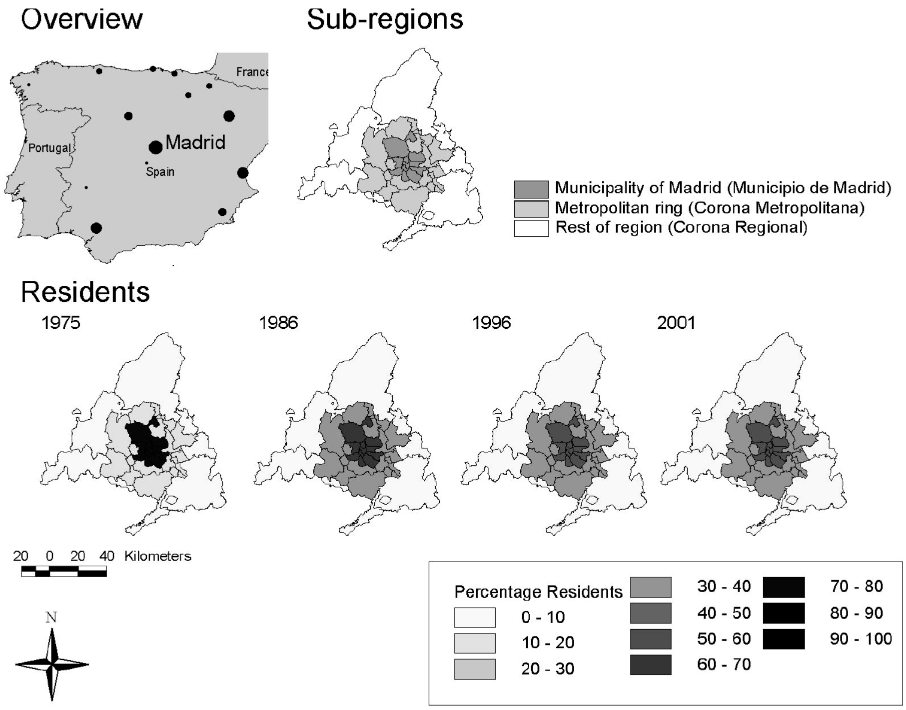

Figure 3. Development of the share of residents living in the core city and the outskirts (CAM 2001).

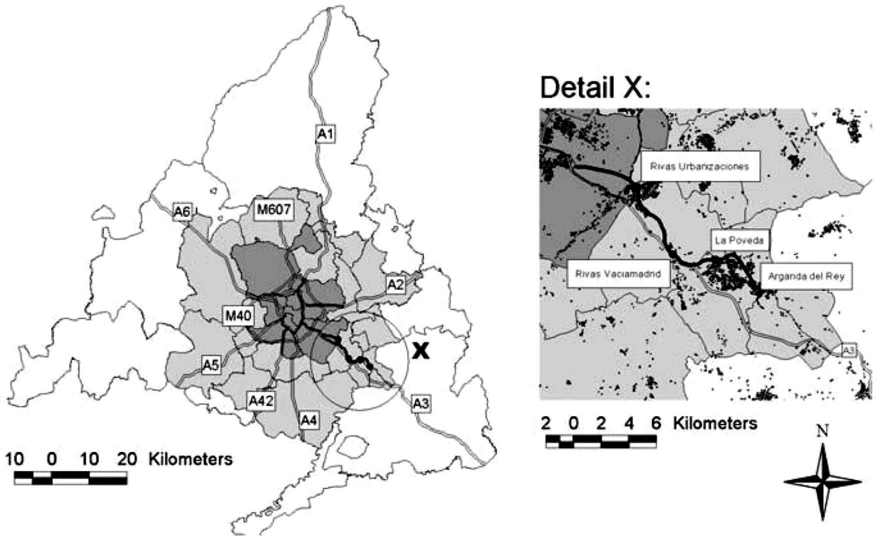

Figure 4. Extension of the metro line number 9 from Puerta de Arganda to Arganda del Rey.

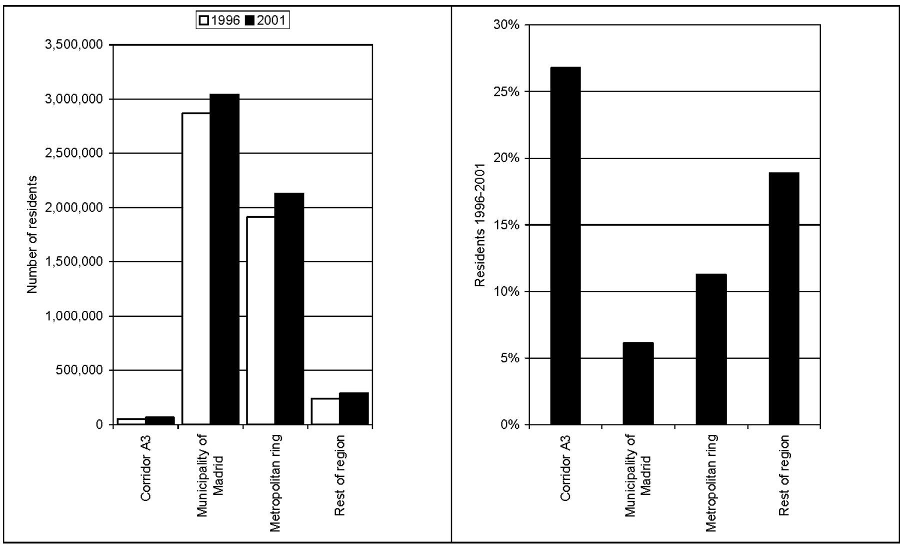

Figure 5. Number of residents and residential growth rates (1996-2001) in the different regions of the case study area.

4.3 Bus Lanes on Radial Highways

Recently the Spanish minister Magdalena Álvarez presented plans to construct more than 100 kilometres of two way bus lanes on all radial highways (Javier Barroso 2005). There are two principle possibilities to construct bus lanes: either to build extra lanes or to dedicate existing lanes to bus use only. While capacity for cars stays the same with the first possibility, it is reduced with the second one. Both possibilities were used later in the case study. The scenarios are named “New Lanes” and “Replace Car Lanes” respectively. Currently no official cost estimates for the new bus lanes exist. The investment costs for building the bus lanes in the scenario “New Lanes” were estimated with 722 million Euros using costs of 3.3 million Euros per kilometre (Pozueta Echavarri 1997). The investment costs for the scenario “Replace Car Lanes” will be lower and were roughly estimated with 300 million Euros.

5. CASE STUDY RESULTS

A modified cost benefit analysis as laid out by (Minken et al. 2003) is used to assess the results of the modelled transport projects towards the objective of sustainability. Additionally the following indicators are used to monitor the development of the scenarios:

- local emissions (NO_X, VOC),
- greenhouse gas emissions (CO_2),
- number of residents per zone and
- accessibility per zone.

5.1 Cost Benefit Analysis

Table 1 summarizes the results of the modified cost benefit analysis. The effects are assessed over a period of 30 years. The interest rate was estimated with 6%. The result for the scenario “extension of the metro line number 9” is slightly positive. The group gaining the highest benefit are public transport users. Their time savings are worth about 220 million Euros which represents 2/3 of all benefits generated. The group paying for the strategy are public transport operators. They bear about 60% of total costs while receiving just 7% of total benefits. Land use property owners gain additional profit while property users have to bear higher costs. The environmental benefits account for 5% of the total benefits.

Both bus lane scenarios result in a welfare surplus. Both have in common that the positive result is driven by the highly positive value of public transport user time savings. Car user time savings are positive in the scenario “New lanes” and negative in the scenario “Replace Car Lanes”. The same is true for car user costs. In both scenarios public transport operators create about the same revenues from additional fares. The government finances the investments in both scenarios. The total external costs are negative for “New Lanes” and positive for “Replace Car Lanes”. The present value of finance is negative for all three scenarios, i.e. they increase public spending compared to “Do minimum”.

Table 1. Results of the cost benefit analysis (million Euros).

Group	Source of costs and benefits		Value (million €)		
			Line 9	New	Replace
User	Public transport	Time savings	221.5	1,181.8	1,140.8
	Car	Time savings	–3.5	112.7	–255.1
		Money	4.0	33.3	–81.2
	Residences (rent, mortgage)		–123.5	–148.0	–340.7
Operator	Public transport	Investment	–113.3	–722.0	–300.0
		Operating costs	–77.6	–5.9	0.0
		Revenues	22.4	141.4	123.8
	Road	Maintenance	–0.4	0.0	0.0
	Residences		71.1	151.1	346.3
Government	Fuel tax, Parking		–8.5	1.3	17.7
Society	Accidents, local emissions		10.2	–36.0	–5.5
(external costs)	Greenhouse gas emissions		5.2	6.9	12.7
Total			7.6	716.6	658.8

5.2 Atmospheric Emissions

The potential of the metro line extension to reduce emissions is rather limited. For the local pollutants NO_X and VOC it is about –0.1% to –0.2%. The potential to reduce CO_2-emissions is of the same order of magnitude. They are reduced by about –0.2% in the years following the implementation but the reduction decreases continuously to about –0.1% in the long run. The detailed analysis of NO_X and VOC emissions at the local level shows a reduction in the short term but a significant increase in the long term (about -–3% for both in 2005 but +23% for NO_X and +38% for VOC in 2025). There are explanations. First, more residents move into the corridor with the metro line extension than without (see section 5.3). Therefore the number of trips and hence car trips is in the long term higher than in the scenario “do minimum” (*Figure 6*). Secondly, average car speed increases in the short run years due to the reduced number of car trips. Thus making travel by car more attractive and stimulating car use.

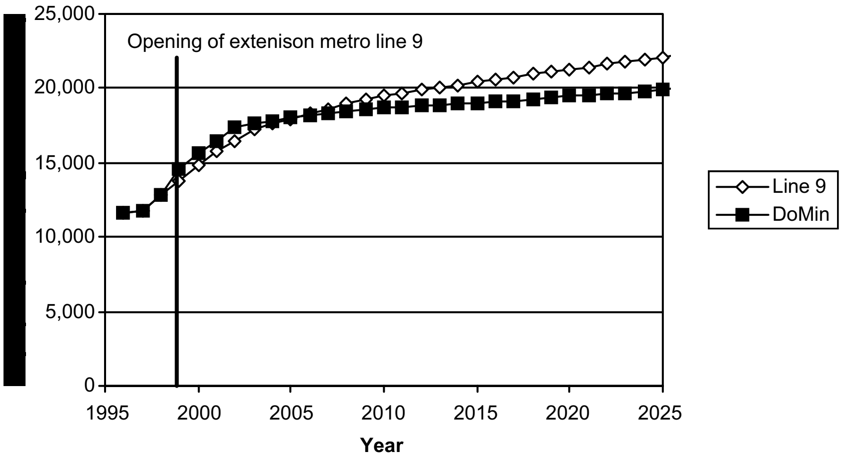

Figure 6. Development of the number of car trips originating in the corridor A3.

In the short run the bus lanes increase the modal share of public transport significantly. In the long run the modal share of public transport goes back to about the value of the base year. This behaviour coincides with the observations in the aftermath of the installation of the bus/HOV lane on the A6 (Monzón et al. 2003). Nevertheless it remains significantly higher than in the scenario “Do Minimum”. The scenario “Replace Car Lanes” significantly decreases NO_X and VOC emissions, while the scenario “New Lanes” only has significant effect on VOC emissions. Both scenarios reduce CO_2-emissions. The relative amount is small: about −0.3% for “New Lanes” and about −0.5% for “Replace Car Lanes”. Even these small reductions are in danger of being lost in the long term. Especially in the scenario “New Lanes”: the additional road capacity is filled up again and CO_2-emissions are above the “Do Minimum” levels in the years 2023 and 2024.

5.3 Residents

The metro line extension increases the attractiveness of Rivas and Arganda as a living place. More people decide to settle within the corridor (*Figure 7*). The location choice within the corridor is determined by two main factors: availability of land and proximity to the metro stations. Overall land consumption increases slightly due to the fact that development densities are lower in the corridor A3 than in the core city.

The pattern of land use changes caused by the bus lane scenarios is not very clear. The location decisions are determined by relative differences between zones. But as the bus lanes are quite evenly distributed around the city centre the differences are not very distinct. A more detailed analysis o clarify this issue is planned.

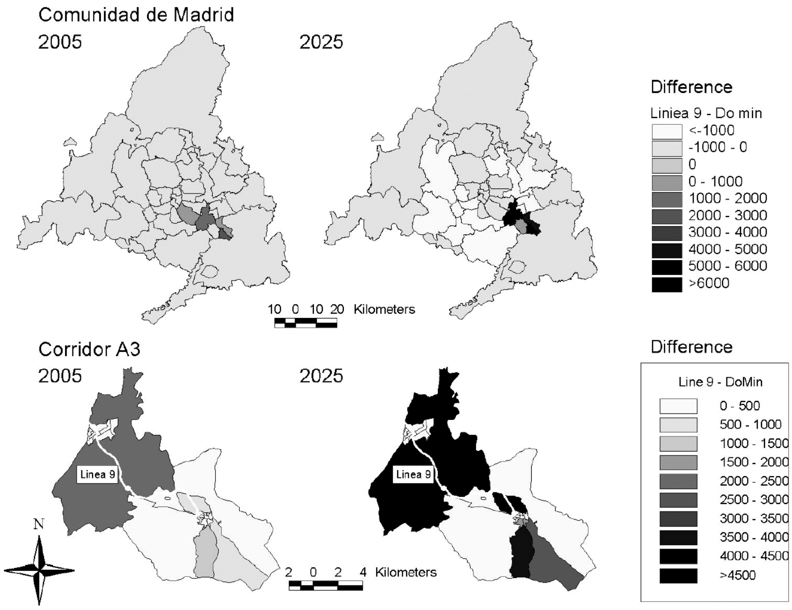

Figure 7. Difference between the scenarios extension of the metro line 9 and do minimum in the number of residents by zone for the years 2005 and 2025.

5.4 Accessibility

Accessibility is measured as the number of working places which can be reached within a weighted by travel time. The difference in the accessibility by public transport in the scenarios "line 9" and "do minimum" is shown in *Figure 8*. It is obvious that the metro line extension increases the public transport accessibility of the corridor significantly.

In both bus lane scenarios, accessibility by public transport increases. It is highest in the bus lane corridors. In "New Lanes", accessibility by car increases slightly in the whole region. The increase is highest in the bus lane corridors. In "Replace Car Lanes", accessibility by car decreases in the bus lane corridors where road capacity for cars is reduced. Due to the overall reduction in car trips it increases in the other zones.

6. SUMMARY AND CONCLUSIONS

This paper presents a hierarchical approach to assess transport and land use projects against the high level objective of sustainability. The proposed approach makes use of simulation models on different spatial and functional levels. The case study presented here links a strategic, dynamic land use and transport interaction model with a detailed transport demand model. Combinations with assignment and a macro-economic model are in process.

After giving an operational definition of sustainability the hierarchical approach and the employed models were described. The case study region of Madrid was chosen to demonstrate practicability. In particular the task was to assess the projects of a metro line extension and bus lanes on radial highways.

A cost benefit analysis including external costs of accidents and atmospheric emissions was carried out. The result of the metro line extension is positive but the surplus is small. Public transport users receive the highest benefits in form of time savings. These represent 2/3 of the benefits generated. Public transport operators bear about 60% of the total costs while receiving just 7% of the benefits. Property owners gain profit while property users have to bear higher costs. The environmental benefits account for 5% of the total benefits.

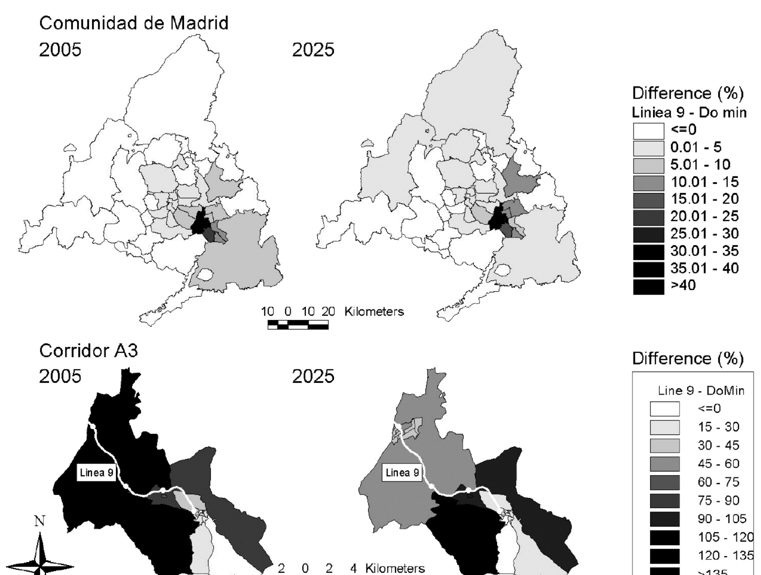

Figure 8. Relative change in the accessibility of working places by public transport between the scenario extension metro line 9 and do minimum.

The welfare surplus created by the bus lanes is higher than that of the metro line extension. As the bus lane scenarios cover a wider area this was expected. About 70% of the benefits are created by time savings. Public transport operators and government are financing the surplus. They bear 30% ("Replace Car Lanes") to 80% ("New Lanes") of all costs. The reduction of greenhouse gas emissions is small for both and makes up less than 1% of the benefits. External costs of the scenario "New Lanes" are even negative due to increased accident costs caused by higher car speed.

Different indicators were used to assess effects on a more local level. The attractiveness of the corridor A3 benefits from the expansion of the metro line. Accessibility by public transport improves. Investors are attracted to develop living space and more people locate in the corridor. The results for NO_X and VOC emissions are ambiguous. Although they decrease in the short term, they increase in the long term. The main reason is the growth in population. This demonstrates that the use of a land use and transport interaction model is essential for assessing sustainability.

Public transport accessibility improves in the bus lane corridors. Modal share of public transport increases in the short term but goes back to initial values in the long term, which is still higher than in the scenario "Do Minimum". "Replace Car Lanes" decreases NO_X and VOC emissions, while "New Lanes" only has a significant effect on VOC. The increase in accidents caused by higher car speed offsets improvements in the category external costs. The effects on land use need further investigation. From a sustainability viewpoint the option "Replace Car Lanes" has to be favoured.

Although the analysed projects are substantially big especially from a financial viewpoint, they affect only a rather small area of the total region. Their potential to reduce negative environmental impacts is limited. Single projects like these are not able to achieve the goal of a sustainable city or urban region. A comprehensive strategy including other complementary instruments like pricing would be necessary.

Summing up, the use of already available tools (detailed assignment models, detailed transport demand models and dynamic land use transport interaction models) and their linking together delivers useful information on different spatial and temporal levels and produce so synergies. Local impacts can so estimated in more detail (e.g. output from detailed assignment model) whereas more regional impacts (e.g. output from LUTI-model) can be taken into consideration at the same time. We think that the here introduced hierarchical approach is an innovative and feasible way forward to generate more accurate information for decision making in an urban and regional context.

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