# Location and transport effects of high occupancy vehicle and bus lanes in Madrid

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**Abstract:**

Sustainability is one of today's major challenges. A widely accepted definition of sustainability is based on intergenerational equity. Cities worldwide do not fulfil the requirements of sustainability. The work presented here investigates whether transport policies in Madrid contribute to the objective of sustainability. The "Comunidad de Madrid" is situated in the heart of Spain. It covers an area of 8,000 km$^2$. About 5.4 million people live within the whole region. The city of Madrid itself has about 2.9 million inhabitants. The situation is characterised by a rapid development of housing and businesses in the outskirts of the city. Traffic is characterised by a high share of commuting into the core city. Although Madrid has an efficient metro line system, this results in a high level of peak hour congestion. As well land use as transport do not fulfil the requirements of sustainability. Different measures were proposed and realised to remedy the current situation. One of these measures is a bus and high occupancy vehicle (HOV) lane. The existing HOV lane covers a 16 kilometres long stretch of the highway A6. The Spanish ministry of public works furthermore proposes bus lanes on all radial highways. The strategic, dynamic land use and transport interaction model MARS (Metropolitan Activity Relocation Simulator) is used to assess the effects of this proposal. MARS covers the total "Comunidad de Madrid". Effects on land use and regional travel patterns are predicted with this model. A modified cost-benefit-analysis is used to assess the potential of the bus lanes.

**Keywords**: Sustainability, HOV lanes, bus lanes, land use and transport model, assessment

## Introduction

Sustainability is one of today's major challenges. A widely accepted definition of sustainability is based on intergenerational equity and a set of sub objectives. Numerous studies provide evidence that cities worldwide do not fulfil the requirements of sustainability. The work presented here investigates whether transport policies of the municipality of Madrid contribute to the high level objective of sustainability.

The “Comunidad de Madrid” is situated in the heart of Spain. It covers an area of about 8,000 $km^2$. About 5.4 million people live within the whole region. The city of Madrid itself has about 2.9 million inhabitants. The situation is characterised by a rapid development of housing and businesses in the surroundings of the city. Traffic is characterised by a high share of people commuting into the core city. Although Madrid has an efficient metro line system, this results in a high level of peak hour congestion. The bus based public transport is heavily affected by this congestion. The Madrid land use and transport system does not fulfil the requirements of sustainability.

To remedy the current situation different instruments and measures have been proposed and realised. One of these is a bus and high occupancy vehicle (HOV) lane. The HOV lane covers a 16 kilometres long stretch of the highway A6 and was opened in the year 1995. Recently the central government suggested to construct more than 100 kilometres bus lanes on all radial highways entering Madrid. The strategic, dynamic land use and transport interaction model MARS (Metropolitan Activity Relocation Simulator) is used to assess the effects of this proposal. MARS covers the whole “Comunidad de Madrid”. Effects on land use and regional travel patterns are predicted with this model. The potential of the application of the HOV/bus lanes to all radial highways is assed by using a modified cost benefit analysis.

## The objective of sustainability

One of several possible definitions of sustainability is equity between today’s and future generations (May et al. 2003). That means that the activities of today’s generation should not limit or hinder the opportunities of future generations. 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. Basically these two definitions are equivalent. The use of a set of sub-objectives is suggested to make them operational (May et al. 2003). Two of these sub-objectives are careful treatment of non-renewable resources and protection of the environment (May et al.

2003). The following section “Indicators of sustainability” defines indicators which are suitable to measure these two sub-objectives. An important aspect in the selection of the sub-objectives and indicators is that the integrated land use and transport model MARS, employed later in the case study, has to be able to calculate them in a reasonable way. E.g. the sub-objective “Contribution to economic growth” cannot be taken into account because modelling macro-economic development is not within the scope of a regional model like MARS. Another example is that due to the strategic character of MARS it is not possible to calculate car noise emissions and imissions. To do so the MARS results would have to be fed into models on a more detailed level of dis-aggregation.

## *Indicators of sustainability*

(Minken et al. 2003) summarises a wide range of suggestions for indicators to measure sustainability and 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 is therefore suitable as an indicator to measure sustainability. Atmospheric emissions are directly linked to the consumption of fossil fuels and their production endangers the environment. The model MARS is able to calculate these indicators.

The observation of statistical data for the indicators consumption of land, consumption of fossil fuels and atmospheric emissions shows that today’s cities are not sustainable. The instruments which have been applied in the past were not effective enough to achieve the goal of sustainability. The following section illustrates this observation for Madrid.

## *The “Comunidad de Madrid”*

The “Comunidad de Madrid” is situated in the heart of Spain. It covers an area of about 8,000 $km^2$. About 5.4 million people live within the whole region. The city of Madrid itself has about 2.9 million inhabitants. The situation is characterised by a rapid development of housing and businesses in the surroundings of the city (see Figure 1). Traffic is characterised by a high number of people commuting into the core city. The share of car trips is high during the peak period than during the rest of the day (see Figure 2). 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 very attractive. As well the land use as the transport system do not fulfil the requirements of sustainability.

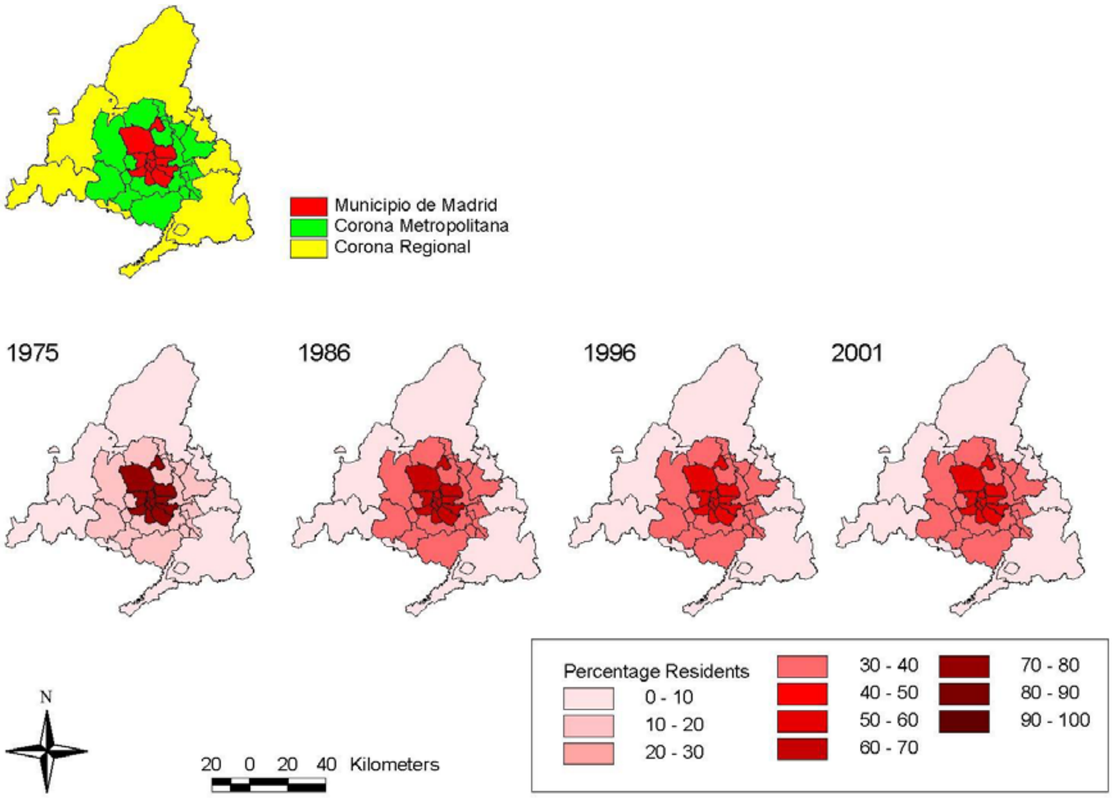


Figure 1: Development percentage of residents in the centre and the outskirts (CAM 2001)

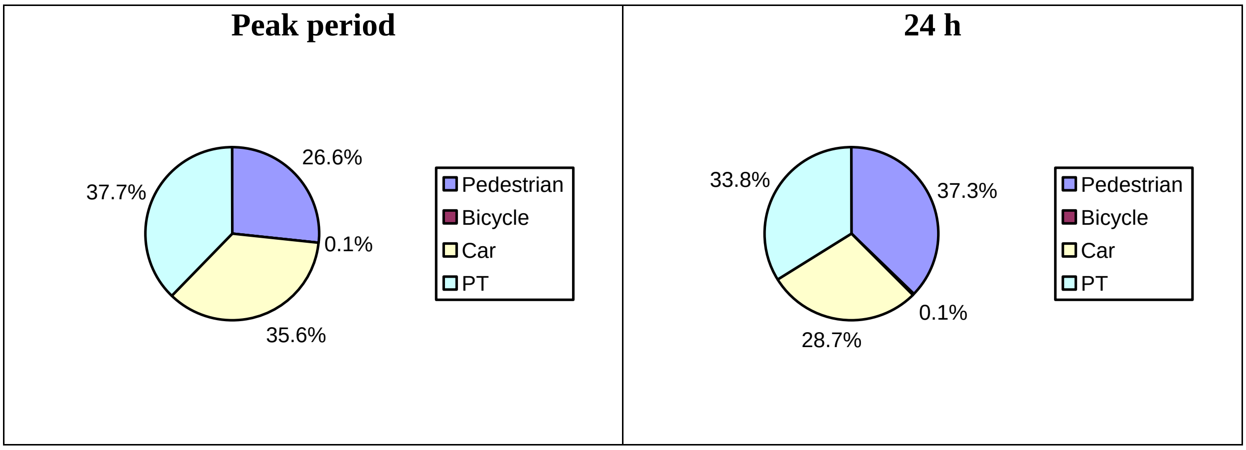


Figure 2: Modal share Comunidad Madrid in 1996 (CRTM 1996)

## *High occupancy vehicle and bus lanes*

### The existing high occupancy vehicle and bus lane A6

The BUS/HOV system within the highway A6 is comprised of a 12.3 km reversible double lane from Las Rozas to Puerta de Hierro and a 3.8 km BUS-ONLY lane connected to the Moncloa interchange. Figure 4and Figure 5 show the BUS-ONLY part near the Moncloa interchange under normal operation conditions and during a breakdown. There are 3 entries – inbound – or exits – outbound (see Figure 3). The system operates in a reversible basis with the following timetable:

- Restricted access to buses and HOVs:
    - Inbound Madrid: from 6:00h to 12:30h Monday to Friday
    - Outbound Madrid: from 13:30h to 22:00h Monday to Friday
- Unrestricted access on holidays and weekends.

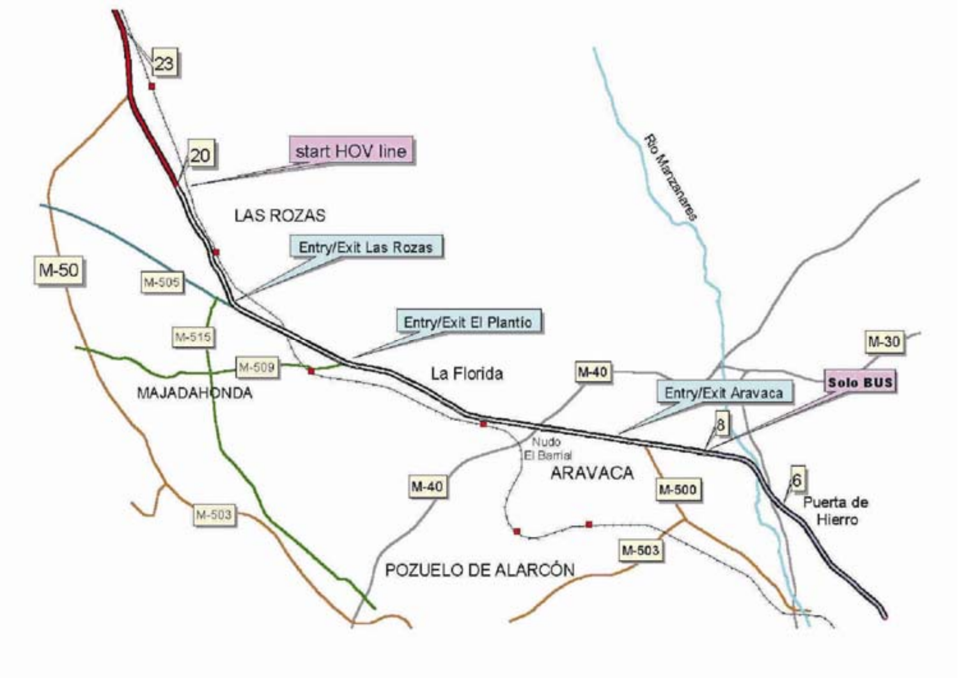


Figure 3: BUS/HOV lane, stretches and access points (Monzón et al. 2003)

Figure 4: The bus lane A6 approaching the PT interchange Moncloa during the morning peak in normal operation (05/011/2004, photo by P. Pfaffenbichler)

Figure 5: The bus lane A6 approaching the PT interchange Moncloa a bus broke down and blocked several other buses during the morning peak (04/011/2004, photo by P. Pfaffenbichler)

Prior to the implementation of the BUS/HOV facility, the situation in the A6 corridor was characterised by chronic congestion problems. The opening of the BUS/HOV lane improved the situation. In addition, the greater reliability achieved for the suburban bus services has fostered their use through a substantial increase in bus patronage - from 24% in 1991 to 36% in 2001. The observed changes in transport demand are shown in Table 1. The BUS/HOV lane A6 has significantly reduced peak travel times for bus and HOV lane users (see Figure 6 and Table 2).

Table 1: Demand evolution, A6 morning peak (7-10h) inbound trips in 2001 (Monzón et al. 2003)

| Year | HOV lane | | | | Conventional lanes | | | | Total A6 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | BUS | | HOV | | BUS | | Other Vehicles | | | |
| | veh. | pax. | veh. | pax. | veh. | pax. | veh. | Pax. | veh. | pax. |
| 11/1991 | | | | | 244 | 6,602 | 15,810 | 21,430 | 16,054 | 28,032 |
| 11/1995 | 268 | 10,430 | 5,640 | 12,471 | 92 | 1,170 | 9,960 | 11,371 | 15,960 | 35,442 |
| 11/1996 | 295 | 10,905 | 5,747 | 11,823 | 87 | 1,115 | 14,976 | 16,945 | 21,105 | 40,788 |
| 11/1997 | 334 | 12,050 | 4,884 | 10,979 | 116 | 1,865 | 13,108 | 15,041 | 18,442 | 39,935 |
| 11/1998 | 346 | 12,040 | 6,245 | 13,100 | 80 | 910 | 14,004 | 15,792 | 20,675 | 41,842 |
| 11/2001 | 478 | 14,110 | 6,634 | 13,059 | 131 | 2,260 | 15,307 | 16,350 | 22,550 | 45,779 |

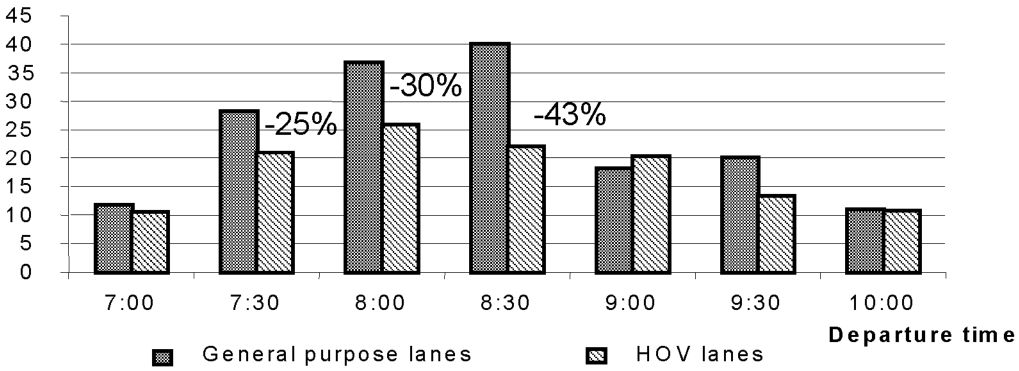


Figure 6: Travel time (minutes) for a 15 km access road; A6 morning peak, 2001 (Monzón et al. 2003)

Table 2: Traveltime autobus Las Rozas – Moncloa on an average working day (Pozueta Echavarri 1997)

| Period | 1991 | March 95 | | June 95 | | Nov. 95 | |
|---|---|---|---|---|---|---|---|
| | | (min) | (%) | (min) | (%) | (min) | (%) |
| 07:00 – 08:00 | 26 | 11 | -57.7 | 13 | -50.0 | 16 | -38.5 |
| 08:00 – 09:00 | 32 | 12 | -62.5 | 14 | -56.3 | 17 | -46.9 |
| 09:00 – 10:00 | 27 | 12 | -55.6 | 10 | -63.0 | 11 | -59.3 |

The costs for the construction of BUS/HOV lane A6 were about 56.6 million Euros (Pozueta Echavarri 1997). This gives costs of about 3.3 million Euro per kilometre.

## Proposed bus lanes

On the 16th of March 2005 the Spanish minister Magdalena Álvarez presented the plan to construct more than 100 kilometres of two-way bus lanes within the Comunidad de Madrid (Javier Barroso 2005). It is planned that all radial highways into the city of Madrid will be equipped with bus lanes. Details of this plan can be seen in Table 3 and Figure 7.

Table 3: New bus lanes for Madrid (Javier Barroso 2005)

| Nr. | Name | From – To | Distance (km) | Costs ($10^6$ Euro)* |
|---|---|---|---|---|
| A1 | Autovía de Burgos | M40 – San Sebastian de los Reyes | 7.0 | 46.2 |
| A2 | Autovía de Barcelona | M30 - Torrejón | 15.0 | 99.0 |
| A3 | Autovía de Valencia | M30 - Arganda | 19.0 | 125.4 |
| A4 | Autovía de Andalucía | M30 - Valdemoro | 18.5 | 122.1 |
| A42 | Autovía de Toledo | Plaza Elíptica – Border to Toledo | 19.5 | 128.7 |
| A5 | Autovía de Extremadura | M40 - Móstoles | 13.0 | 85.8 |
| A6 | Autovía de A Coruña | Las Rozas - Villalba | 17.4 | 114.8 |
| Total | | | 109.4 | 722.0 |

* 3.3 million Euros/kilometre lane as calculated from (Pozueta Echavarri 1997)

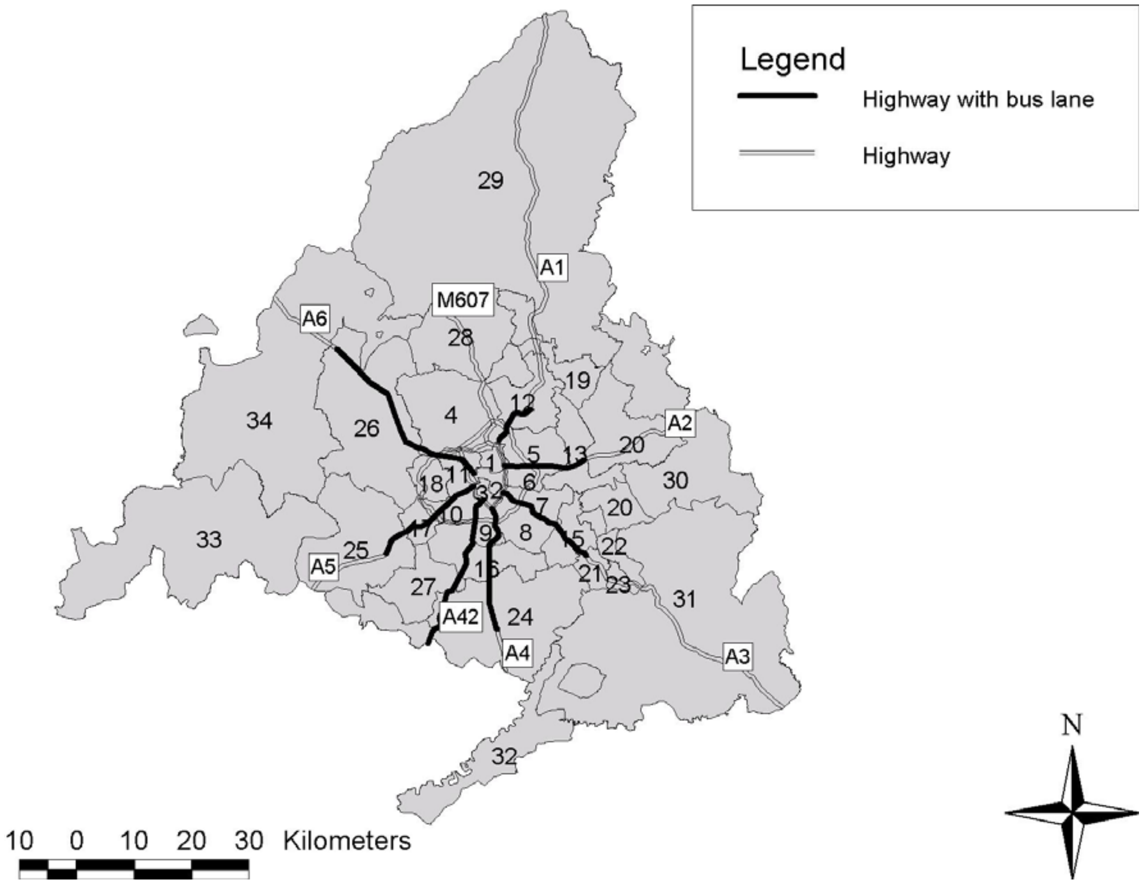


Figure 7: Proposal for a system of bus lanes in Madrid (Javier Barroso 2005)

### *The integrated land use and transport model MARS*

MARS is an integrated strategic and dynamic land-use and transport (LUTI) model. The basic underlying hypothesis of MARS is that settlements and the activities within them are self organising systems. Therefore it is sensible to use the principles of synergetics to describe collective behaviour (Haken 1983a; Haken 1983b).

MARS assumes that land-use is not a constant but is 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-motorised modes. Car speed in the MARS transport sub-model is volume and capacity dependent and hence not constant. The energy consumption and emission sub-models of MARS utilise speed dependent specific values. The land-use model considers residential and workplace location preferences based on accessibility, available land, average rents and amount of green space available. Decisions in the land-use sub-model are based on random utility theory. Due to its strategic characteristic a rather high level of spatial aggregation is used in MARS. In most case studies this means that the municipal districts are chosen as travel analysis zones. The outputs 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 several demand and supply-sided instruments whose results can be measured against targets of sustainability. These instruments range from demand-sided measures, such as with 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-motorised transport. These measures, furthermore, could be applied to various spatial levels and/or to time-of-day periods (peak or off-peak).

To date the model MARS was applied to the following six European case study cities Edinburgh, Helsinki, Leeds, Madrid, Oslo, Stockholm and Vienna. Currently a MARS model of Lisbon, Portugal is set up within a PhD-thesis. Within the ongoing project SPARKLE (Sustainability Planning for Asian cities making use of Research, Know-how and Lessons from Europe) MARS is adopted and applied to the Asian cities Ubon Ratchasthani, Thailand and Da Nang, Vietnam (Emberger et al. 2005). To test the model MARS an extensive back casting exercise was carried out with data of the city Vienna (Pfaffenbichler 2003). A full description of MARS is given in (Pfaffenbichler 2003).

A well calibrated and tested MARS model covering the "Comunidad Madrid" is available from an ongoing PhD-thesis (Vieira 2005). As an example for the model testing the comparison of the MARS results for daily trips by mode with the results of the 1996 Madrid travel survey is shown in Figure 8 to Figure 11. As well the fit as the slope of the linear regression between the MARS results and the statistical data are satisfying. This model was utilised for the case study presented in the following sections.

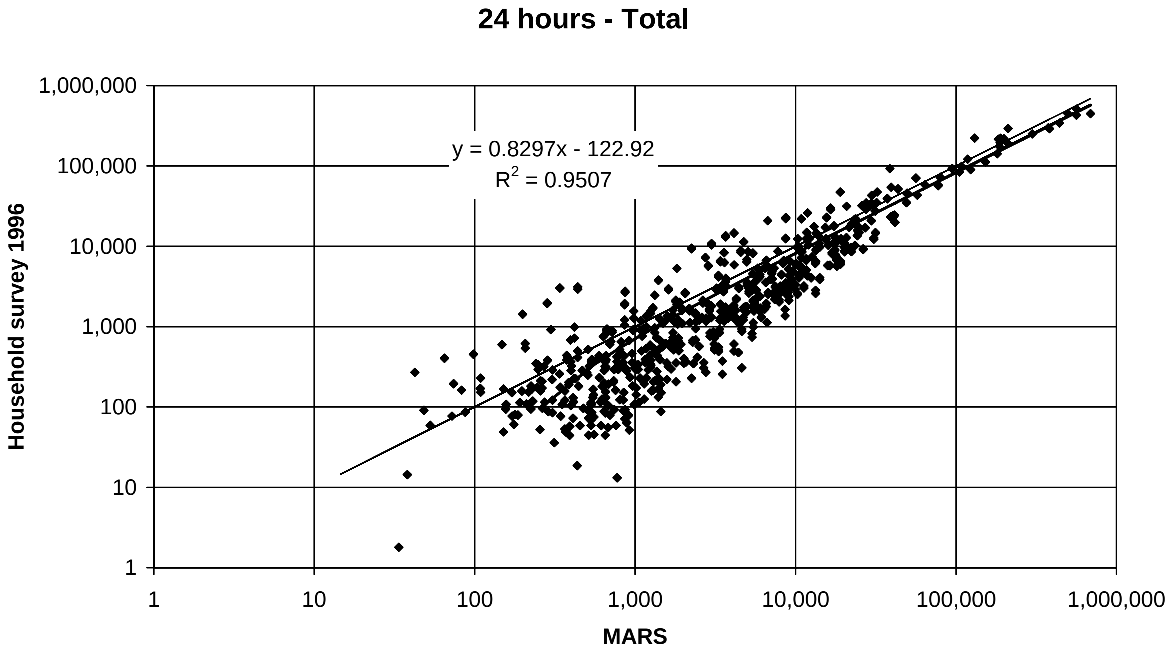


Figure 8: Comparison of the MARS model results with the results of the 1996 household survey (CRTM 1996) – daily trips total

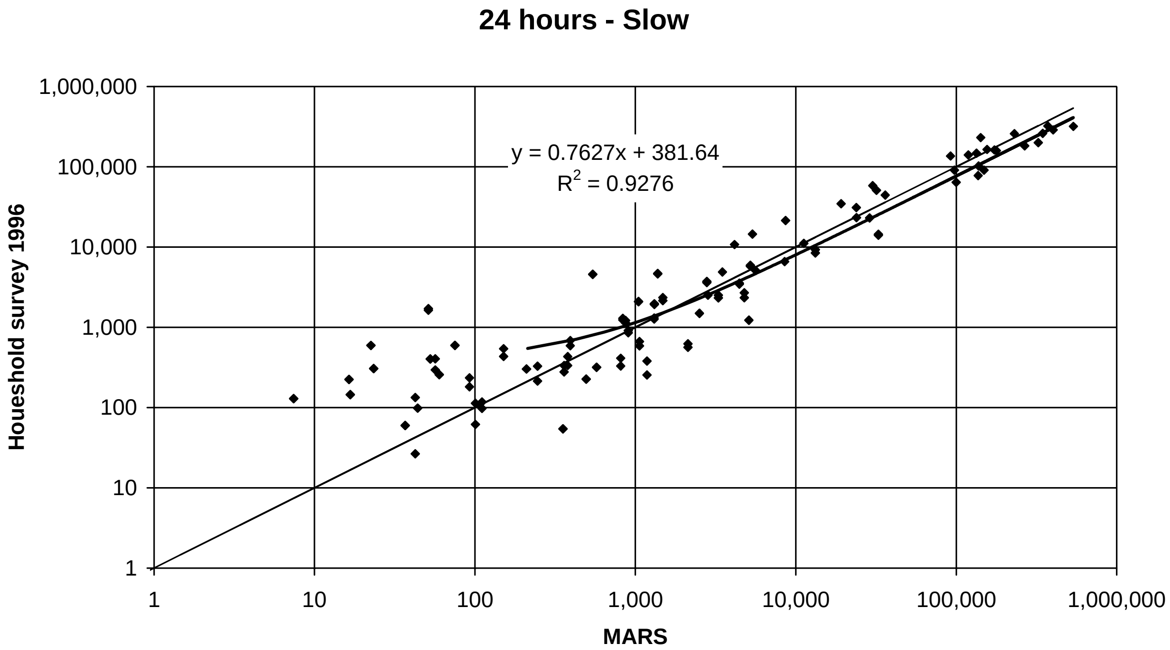


Figure 9: Comparison of the MARS model results with the results of the 1996 household survey (CRTM 1996) – daily trips slow modes

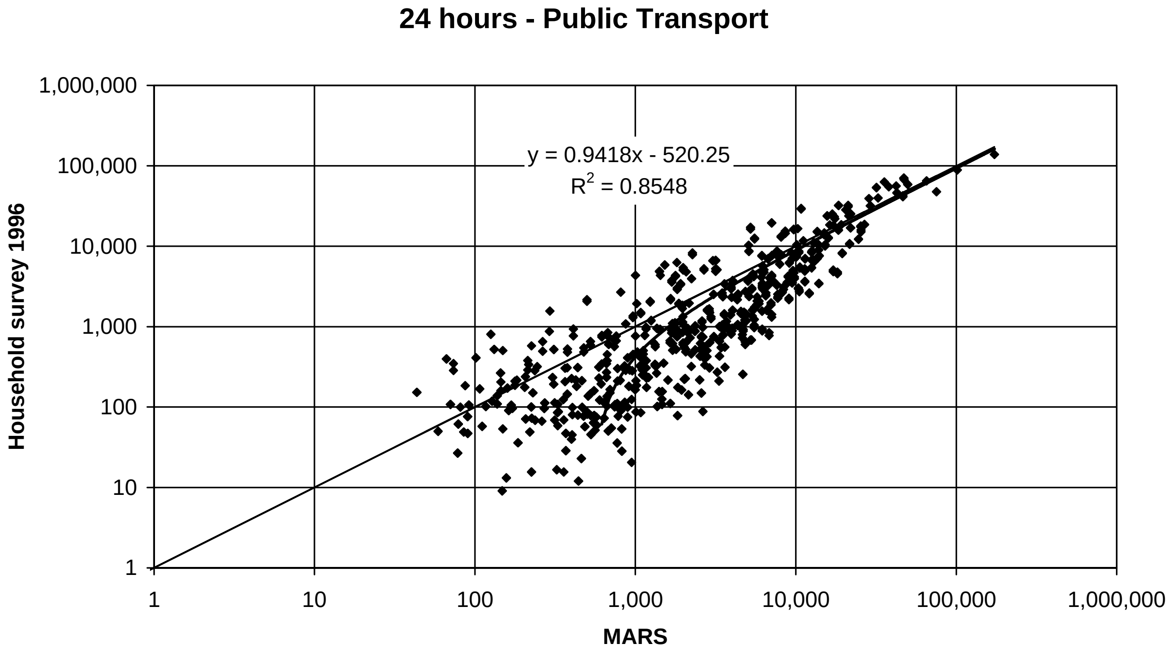


Figure 10: Comparison of the MARS model results with the results of the 1996 household survey (CRTM 1996) – daily trips public transport

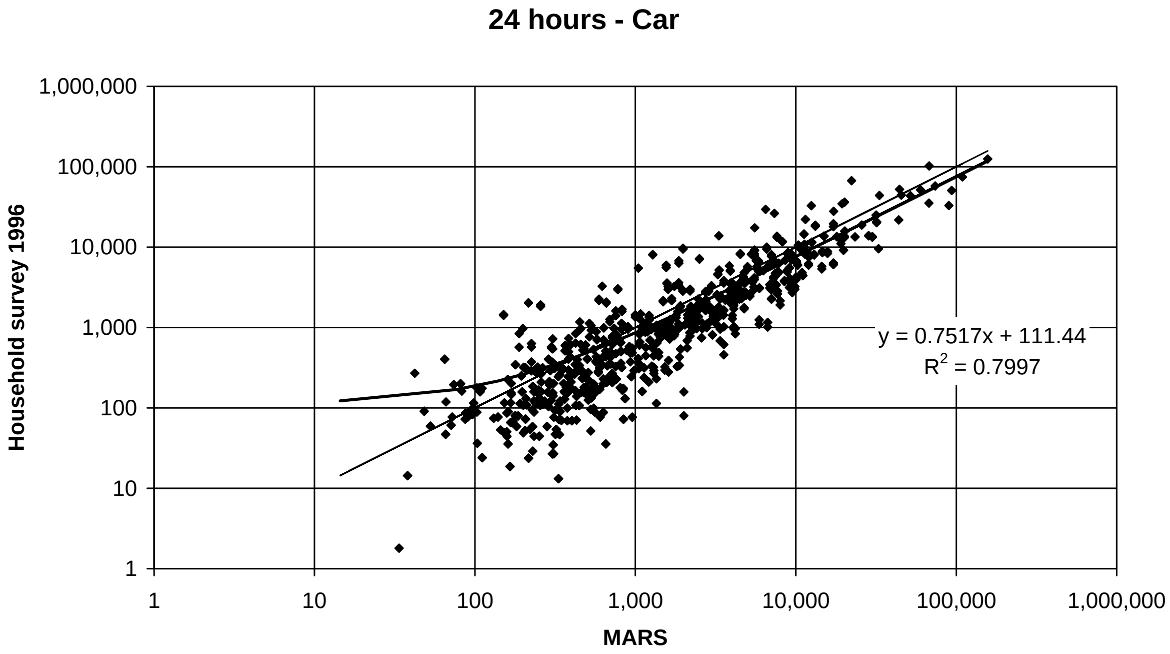


Figure 11: Comparison of the MARS model results with the results of the 1996 household survey (CRTM 1996) – daily trips car

## *Case study "Comunidad de Madrid"*

There are two possibilities two realise the proposed bus lanes: either to build new extra lanes or to dedicate existing lanes to bus use only. While capacity for cars stays the same with the first opportunity it is reduced with the second one. Both possibilities were used in the model calculations presented below. The first possibility is referenced as scenario "New Lanes", the second one is referenced as scenario "Replace Car Lanes". Both scenarios are compared with a scenario "Do Minimum".

### Transport

Figure 12 and Figure 13 present the results for the daily trips by mode during the peak period and 24 hours. The total number of trips is growing in all different scenarios due to the overall growth of population in the study area. As a result of the bus travel time reduction during the peak period the number of PT users increases significantly compared with the "Do Minimum" scenario (Figure 12). Due to the additional effect of the road capacity reduction the increases are higher in the scenario "Replace Car Lanes".

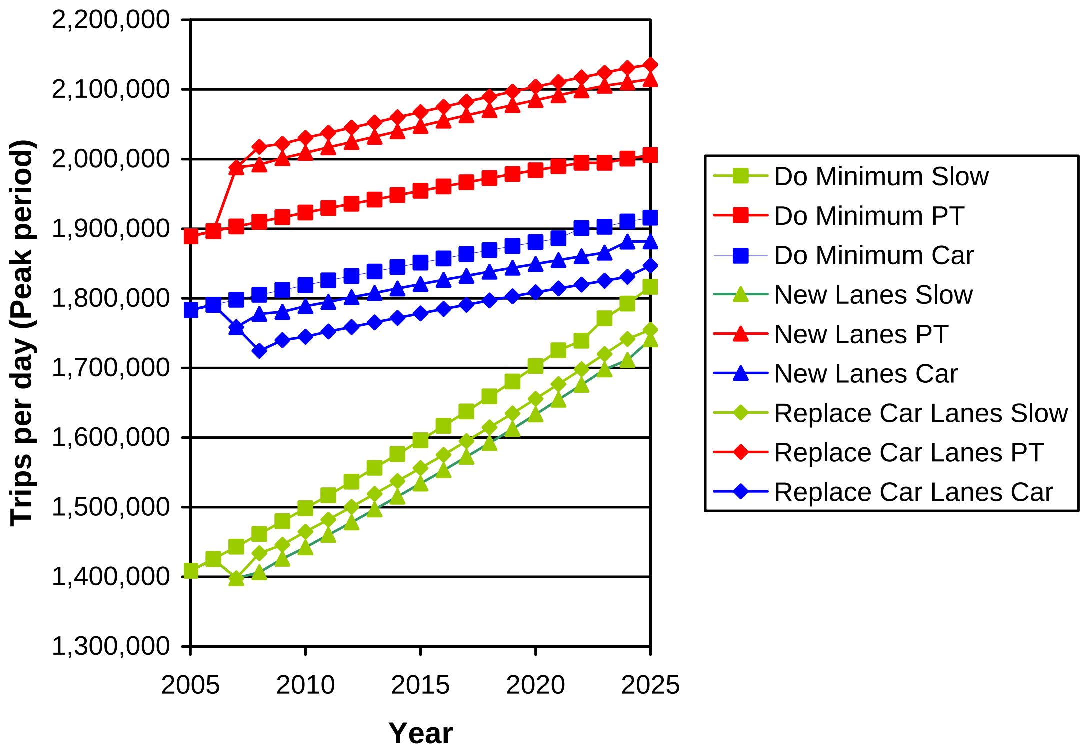


Figure 12: Trips per day by mode during the peak period

The situation for the off peak period and 24 hours is more complex. No travel time savings for bus users occur during the off peak period. But as the model MARS is based on the assumption of constant travel time budgets, the time savings from the peak period will be spent during the off peak period. Therefore the total number of trips in off peak increases. In the scenario “Replace Car Lanes” car trips are reduced due to the effect of the reduced road capacity (Figure 13).

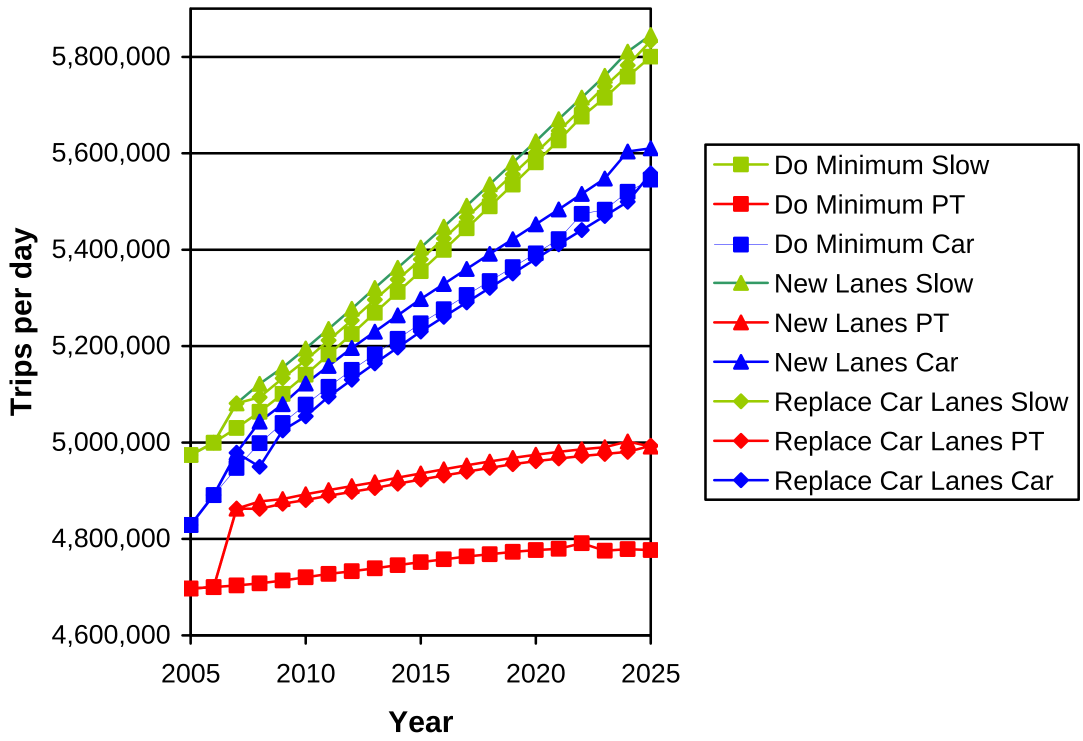


Figure 13: Trips per day by mode (24 h)

The bus lanes increase the modal share of public transport significantly in the short run (Figure 14). In the long run the modal share of public transport goes back to about the initial value (Figure 14). This behaviour coincides with the observations in the aftermath of the installation of the BUS/HOV system on the A6. Nevertheless the modal share of public transport remains significantly higher than in the scenario “Do Minimum”.

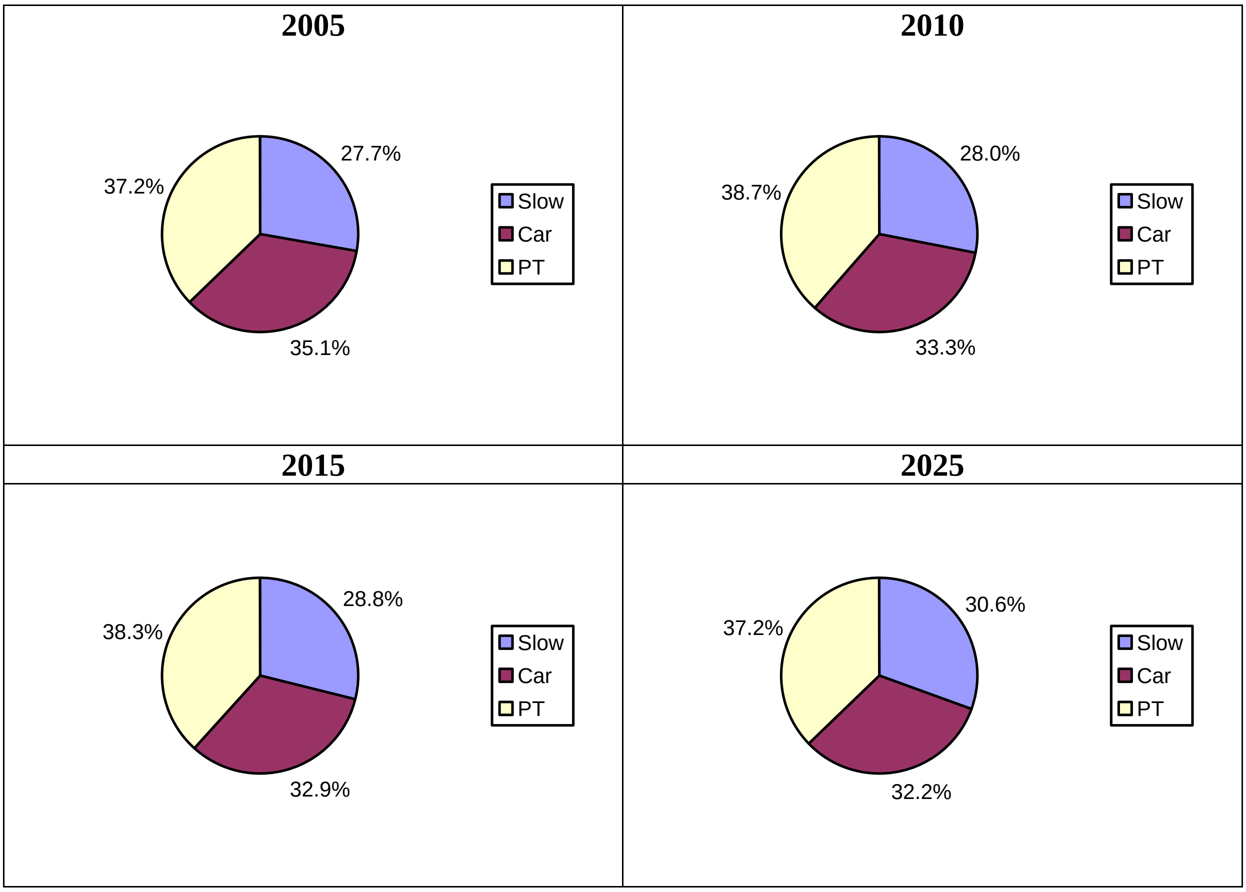


Figure 14: Modal share peak period scenario “Replace Car Lanes” between 2005 and 2025

## Land use

The installation of the bus lanes is also affecting the land use system. On the one hand directly due to land consumed by additional highway lanes. On the other hand indirectly due to changes in location choices. Figure 15 illustrates this with the difference in the number of residents by zone between the bus lane scenarios and the scenario “Do Minimum”. Accessibility is the link between transport and location decisions. In the scenario “New Lanes” highways are less congested at least in the short term. In combination with changes in rent and land price this increases the relative attractiveness of the zones in the “Corona Regional”. Population therefore increases in these zones in the scenario “New Lanes”. This is not the case in the scenario “Replace Car Lanes” and therefore the outermost districts loose population. Nevertheless the pattern of land use changes caused by the bus lane system is not very clear. The location decisions are determined by relative differences between zones rather than absolute changes. Therefore it is possible that one zone with bus lane connection looses population while another one gains population. A more detailed future analysis is needed to clarify this issue. One reason for the unclear picture might be that the bus lanes are quite evenly distributed around the city centre.

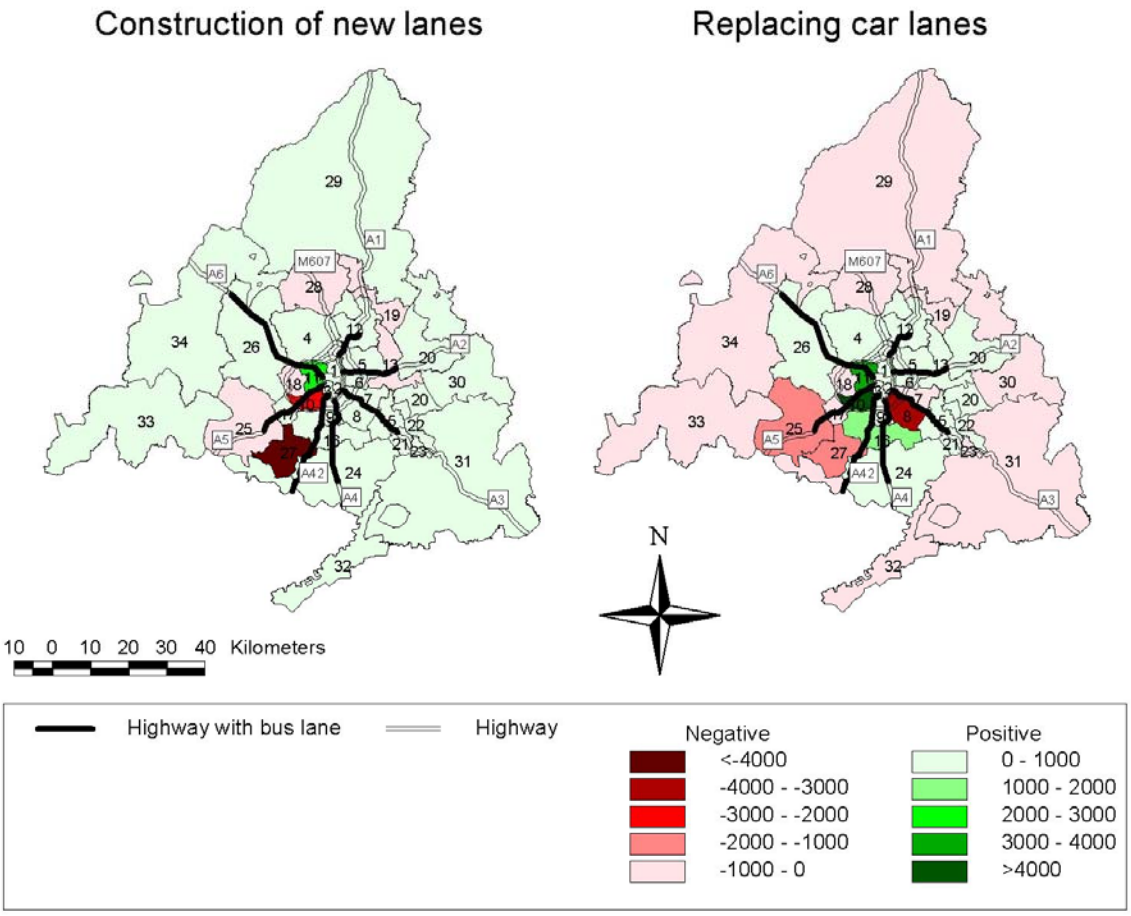


Figure 15: Difference in the number of residents per zone scenario – do minimum

## Accessibility

Accessibility in MARS is defined as the number of locations (workplaces, residents) which can be reached in a certain period of time (Equation 1). Time as weighted as shown in Equation 2.

$$ {}^{WP}A_i^m(t) = \sum_j N_j^{WP}(t) * f\left(t_{ij}^m(t)\right) $$

Equation 1: Accessibility of workplaces

$$ f\left(t_{ij}^m(t)\right) = Max\left(0,\ 10^{-4} * \left(t_{ij}^m(t)\right)^2 - 0.0183 * t_{ij}^m(t) + 0.75\right) $$

Equation 2: Weighting function time

**Legend**:

${}^{WP}A^m{}_i(t)$ .............. Accessibility of workplaces by mode m in zone i in year t

$N^{WP}{}_j(t)$ ................ Number of workplaces in zone j in year t

$f(t^m{}_{ij}(t))$ .............. Weighted function of travel time from i to j by mode m in year t

$t^m{}_{ij}(t)$ .................. Travel time from i to j by mode m in year t

Accessibility changes as expected (Figure 16). Accessibility by public transport increases in both bus lane scenarios. The increase is highest in the bus lane corridors. In the scenario “New Lanes” accessibility by car increases in the whole study area. The increase is highest in the bus lane corridors. In the scenario “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.

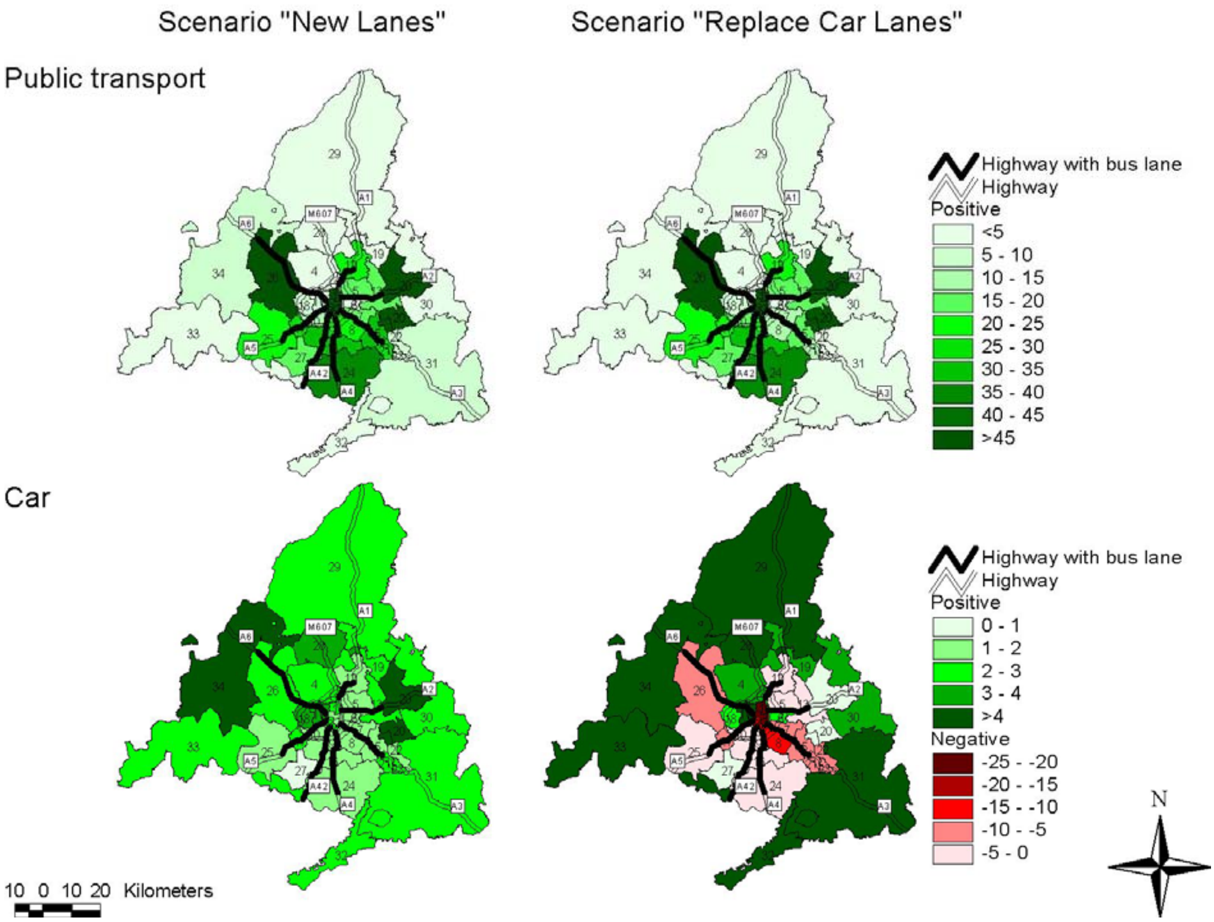


Figure 16: Percentage change of accessibility of workplaces in the year 2025 relative to the scenario “Do Minimum”

## $CO_2$-emissions

Both bus lane scenarios reduce the $CO_2$-emissions (Figure 17 and Figure 18). But the relative amount is very small: about -0.3% for the scenario “New Lanes” and about -0.5% for the scenario “Replace Car Lanes”. Even these small reductions are in danger of being lost in the long run years. 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. The instrument “bus lanes” is by far not sufficient to achieve the overall $CO_2$-emission targets.

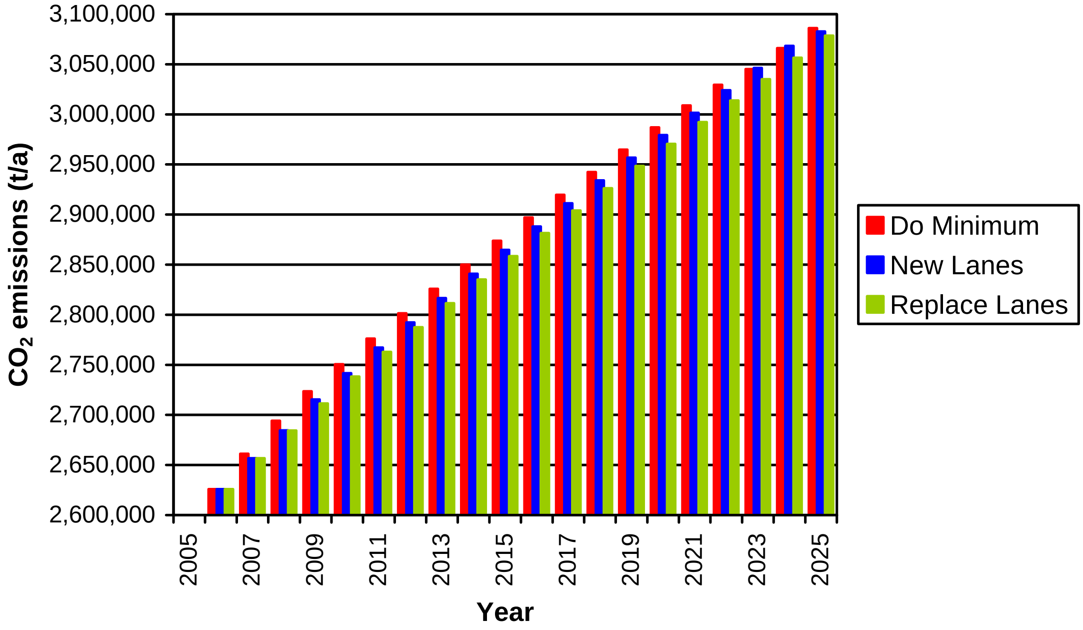


Figure 17: Yearly $CO_2$-emissions by scenario

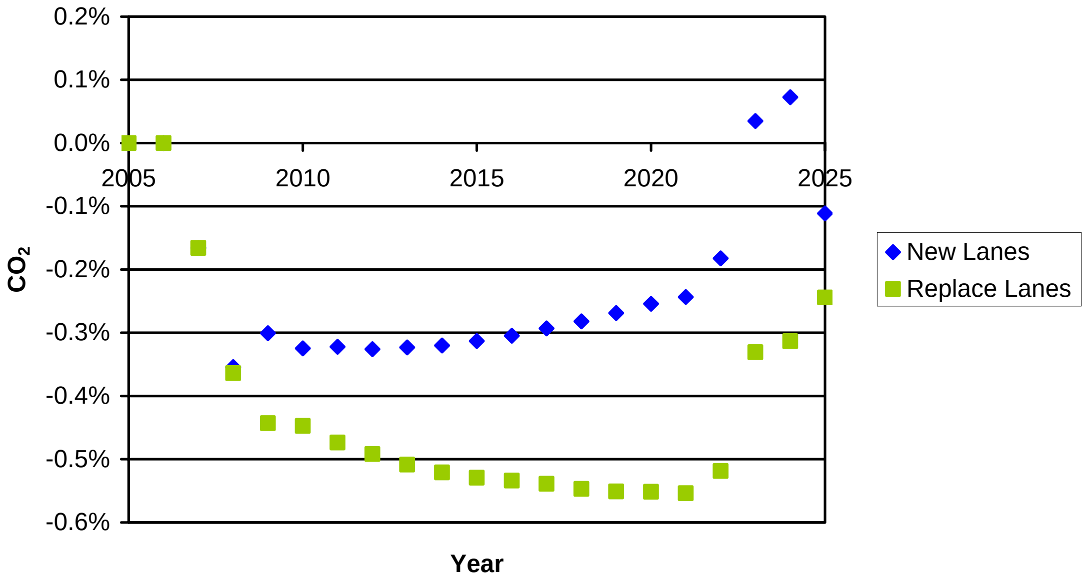


Figure 18: Percentage change of $CO_2$-emissions relative to the scenario “Do Minimum”

## Cost benefit analysis

A cost benefit analysis including the external costs of accidents, $CO_2$-, $NO_X$-, HC- and PM-emissions was carried out for the two bus lane scenarios. Currently no official cost estimates for the bus lanes exist. The investment costs for building the bus lanes in the scenario “New Lanes” was therefore estimated with 722 million Euros (see Table 3). The investment costs for a scenario “Replace Car Lanes” will be lower and were therefore estimated with 300 million Euros. The interest rate was estimated with 6%. The results are summarised in Table 4 and Table 5. Both scenarios result in a positive value for the objective function. But nevertheless there are significant differences. Both have in common that the positive result is driven by a highly positive value for PT 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 PT operators gain about the same amount from the additional fares. The government has to pay for the investments in both scenarios. The external costs are negative for the scenario “New Lanes” and positive for the scenario “Replace Car Lanes”.

Table 4: Cost benefit analysis scenario “New lanes”

| User | | | | Public transport operator | Govern-ment | External costs | Objective function |
|---|---|---|---|---|---|---|---|
| Time savings | | Revenues and costs | | | | | |
| PT | Car | PT | Car | | | | |
| 1181.8 | 112.7 | 0 | 33.3 | 135.5 | -720.7 | -29.1 | 713.5 |

Table 5: Cost benefit analysis scenario “Replace Car Lanes”

| User | | | | Public transport operator | Govern-ment | External costs | Objective function |
|---|---|---|---|---|---|---|---|
| Time savings | | Revenues and costs | | | | | |
| PT | Car | PT | Car | | | | |
| 1140.8 | -255.1 | 0.0 | -81.2 | 117.9 | -282.3 | 7.2 | 647.3 |

## *Conclusions*

The dynamic transport and land use interaction model MARS was used to assess the effect of a current proposal to install bus lanes on all radial highways leading into the city of Madrid against the overall objective of sustainability. Experience with the existing BUS/HOV system within the A6 was utilised in this process.

The overall conclusion from the work presented here is that the proposed bus lanes contribute to the overall objective of sustainability. But nevertheless it has to be mentioned that their contribution is rather small. The modal share of public transport is increased in the short term but goes back to initial values in the long term. Which is still higher than in the scenario “Do Minimum”. The reduction of greenhouse gas emissions is very small for both the “New Lanes” and “Replace Car Lanes” scenario. The total external costs of the scenario “New Lanes” are even negative due to increased accident costs caused by higher car speed. The option “Replace Car Lanes” clearly has to be favoured from a sustainability point of view.

The positive results of the cost benefit analysis are mainly driven by the time savings of public transport users. The use of time savings is not undisputed (Emberger et al. 2004). Without time savings both results would be negative. The losses are much higher for the scenario “New Lanes” than for the scenario “Replace Car Lanes”. The results are furthermore sensitive to investment costs. These costs should be redefined when more details about the proposal are publicly available.

There are some issues open for additional research. First of all the current representation of the instrument bus lanes in the model MARS is rather crude. There is no information about the positions of entry and exit points or bus stops within the bus lanes. Currently all zones crossed by bus lanes benefit to a certain extent. If there is no entry/exit point or bus stop in the zone this will definitely not be true. Therefore it seems useful to revise and refine the model representation of the instrument bus lanes.

The land use response pattern is a bit unclear. Therefore it would be useful to analyse the causes for the location choices in detail. To gain more insight it is suggested to model and analyse each radial highway separately and in combination.

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