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Modelling Land Use and Transport Policies to Measure Their Contribution to Urban Challenges: The Case of Madrid

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Abstract: Urban areas play a key role in the development of European territories, and it is essential for them to be sustainable and efficient. However, the European cities are facing some challenges related to certain trends that are threatening their sustainable development and operational efficiency. In this paper, we compare the contribution of three policy measures—cordon toll accompanied by public transport improvements, teleworking and re-densification—to address different city challenges. The policy assessment requires a long term simulation tool, i.e., the MARS (Metropolitan Activity Relocation Simulator) model, which is able to consider interactions between land use and transport systems. The simulations of the different policy scenarios were carried out for the case of Madrid in the period 2012–2031. The contribution of the policy measures to address the city challenges was measured through different indicators. The results indicated that the three policy measures contributed to the time efficiency challenge, by saving time for the commute, reducing congestion and improving the traffic flows at peak hours. The most effective policy in this regard is the teleworking measure. Another challenge addressed by the three policies was the accessibility to PT. The three policy scenarios, when simulated, showed higher PT use, especially the cordon toll scenario. However, the only policy that really contributed to the energy, emissions and pollution city challenges was the re-densification measure, which reduced travel distances and encouraged a mobility that relies more on PT and slow modes.

Keywords: land use and transport model; policy assessment; city challenges; teleworking; cordon toll; re-densification

1. Introduction

Seventy per cent of the European population lives in cities, which is the main driving force of the respective national economies [1]. However, to drive a sustainable development, these urban areas need to face some problems such as unemployment, inefficiency, segregation, pollution and urban sprawl [1,2]. Both threats and opportunities emerge in urban areas, raising the city challenges [2]. The analysis of the challenges faced by the cities in their efforts to achieve a more sustainable development, gives a high priority to integrated transport and land use planning [3–7]. In this context, the land use and transport interaction models are key tools to analyse the impacts that may arise from urban planning decisions [8–10].

In this framework, the European research project INSIGHT-7 FP was proposed with an objective to develop management tools that could help European cities to formulate and evaluate policies to achieve

a sustainable urban development [11]. In the first stage of the project, the main challenges existing in the European cities were identified, linked to some indicators to measure the progress towards each challenge. In the subsequent stages, four urban models were developed for four European cities. These models are expected to address some of the challenges identified. In the final stage, three land use and transport policies were selected for their potential to overcome the city challenges. Each policy was simulated and tested by one or two of the four urban models. The simulations allowed evaluating the contribution of the policies to meet the urban challenges. The evaluation framework, based on urban challenges, indicators and policies, was validated by some ten external advisors. These external advisors were selected by the project consortium for their expertise in urban planning and policy making in European cities, to assess all the outcomes of the project. The modelling tools were also assessed by these experts. The data presented in this paper resulted from the work carried out by the authors during the project in collaboration with the rest of the consortium.

In this paper, we compared the contribution of the three transport and land use policies selected in INSIGHT project—cordon toll, teleworking and re-densification—to address different city challenges in the case of the Madrid Region. The contribution was measured in terms of the indicators identified at the beginning of the project. The policy assessment was carried out by simulating the policies with a Land Use and Transport Interaction (LUTI) model, which considered the assessment indicators for the period 2012–2031. The literature review on these topics showed that other studies have used LUTI models to analyse the effects of pricing schemes [12,13], and teleworking policies [14]. Very few studies have used LUTI models to analyse anti-sprawl policies, and these few studies are more related to TOD developments [15], than to re-densification processes. However there are no studies comparing policies of such different nature using the same tool.

2. Materials and Methods

2.1. Determining the European Urban Challenges

Urban areas play a key role in the development of European territories, thus it becomes indispensable for them to be sustainable and efficient [16]. However, European cities are facing some trends which are threatening their sustainable development and operational efficiency [17]. The first step of the project INSIGHT was to determine the main urban challenges in European cities [18], through an extensive review of some documents from the European and international institutions [1,2,4,19–23].

2.1.1. Challenges of Cities as Living Environments

The urban areas constitute to the **living environment** of a large fraction of the European Population, so the quality of life in these areas should be as high as possible [1,21]. This concern is globally widespread. Meeting the urban health challenge was one of the objectives set by the United Nations in Agenda 21, where the poor living conditions in urban areas around the world were reported [24]. The main causes of the degradation of the European cities are **pollution**, noise and the lack of **safety and security** [19]. These problems have a strong relation with an excessive traffic volume—a growing problem throughout Europe [21,22]. Most of the road accidents (69%) occur in cities [25]. Traffic also contributes to many gaseous air pollutants and suspended particulate matter: road transport accounts for a 30% of the fine Particulate Matter (PM) in urban areas [26]. The human environment should be preserved not only for the present but also for the future generations [27]. Cities are responsible for a significant part of GHG emissions, and therefore should be considered as key players in the **climate change** mitigation [4].

Another challenge related to the society is the **demographic decline**. The ratio of a working-age population is decreasing due to the low birth rate, the increase in life expectancy and the migration of active population due to the lack of job opportunities [2].

Finally, all citizens expect cities to satisfy their needs in terms of **education**, health care and transportation in an equitable manner [3]. This is getting more complicated due to the growing polarisation and socio-spatial segregation [2,23]. Urban transport systems are related to this trend, as they are expected to provide access for different needs [22,28].

2.1.2. Challenges Related to the Efficiency of Urban Systems

Urban environments drive economic development and are the main centres of many public services [3]. Almost 85% of the EU's GDP is generated in urban areas [21]. Cities can contribute to **economic growth and job creation**, by creating a competitive framework and enhancing productivity [2]. However, the recent economic crisis has made this challenge more difficult to achieve. Cities have been especially exposed to the economic recession, which has severely affected the competitiveness, productivity and operational efficiency of services [29].

Another important barrier to overcome the economic competitiveness is the **inefficient consumption patterns**, where European cities have a great scope for improvement, especially regarding **energy consumption** in housing and transport sectors [20]. Moreover, the transport sector is characterised by a predominance of non-renewable energy source, mainly oil, due to the car dependence [4]. This excessive car usage gives rise to another problem related to efficiency and competitiveness. The increased traffic in European cities results in chronic congestion, with the adverse consequences, which are expressed in terms of delays and consequent economic losses [21,22].

Finally, the spatial dispersion of urban areas is one of the biggest barriers to achieve efficient cities [19]. **Urban sprawl**, understood as the spread of low-density urban settlements around the core city, has been the main characterising growth pattern of European cities in the last few decades [2]. Urban sprawl contributes to the fragmentation of living and working spaces and segregates commercial activities and residents far away from city centres, adversely affecting economic dynamics [23]. The dispersion of urban areas is typically accompanied by an increase in the housing and transport spending, growing congestion levels, the extension of urban infrastructures and a more costly provision of public services [19].

At the initial stage of INSIGHT project, ten city challenges aligned with these topics were determined, together with some indicators to measure the progress in addressing the challenges [18]. All these outcomes were validated by some experts and policy makers with the consultation of stakeholder that was a part of the project [30]. All these outcomes are summarised in Table 1.

Table 1. City challenges and indicators assessed by stakeholders.

City Challenges			Validated Indicators [1]
Cities as living environments	Enable social development, in an equitable, healthy and safe manner; and minimise the impacts on environment	Liveable at human level	5 indicators related to the quantity and quality of the areas in the city devoted to people.
		Equal, safe and secure society	11 indicators related to the provision and access to main needs and services, accidents, crime and inequalities
		Pollution	8 indicators for measuring air and noise pollution
		Climate Change	3 indicators for measuring GHG emissions
		Demographic decline	4 indicators for measuring the ageing of the population, and the shrinking of the active population
		Education and culture	2 indicators related to education in school and cultural services
Cities as efficient urban systems	Constitute appropriate frameworks for economic growth and efficiency; and minimise the consumption of resources	Economic activity	5 indicators related to the job creation, and economic growth
		Efficient use of resources (i.e., time)	3 indicators related to the time spent in travelling to work or studies, wasted time in congestion or unused space in the city
		Energy efficiency	9 indicators measuring the energy consumption from different sources
		Urban sprawl	3 indicators for measuring the dispersion of the population

[1] Considered relevant and related to the challenge. Source: [18,31].

2.2. MARS: A LUTI Model for the Case of Madrid

2.2.1. The Case Study of Madrid: Main Features of the Region and Regulatory Framework

Four European cities, London, Madrid, Barcelona and Rotterdam, were considered in the INSIGHT project as the case studies to be analysed. One of the main objectives of the project was to develop urban models for each specific case study. These urban models should serve as simulation tools for policy implementation. This paper is based in the case of Madrid, where the developed and improved simulation tool is the MARS model. The MARS (Metropolitan Activity Relocation Simulator) model was created by Pfaffenbinchler [32], who developed it for the first time for the city of Vienna. This model is a macro strategic LUTI model, which works on the basis of causal loop diagrams (CLD) and represents the cause and effect relations between transport and land use. This model is appropriate for a long term policy making, since it has the predictability up to 30 years.

Madrid Region has a population of 6.4 million inhabitants. The region is organised into administrative units, called municipalities. One of these municipalities is the city of Madrid, where a 50 percent of the region's population live [33].However, this percentage is gradually decreasing due to the urban sprawl [7]. The whole city covers an area of 8026 km^2 area, of that, 12% is urbanised [34]. Previous studies on the challenges that Madrid is facing [31,35] give high priority to the problem of urban sprawl and to the economic downturn in the period of economic crisis. During this period of economic crisis, energy consumption and emission levels have decreased together with the activity levels. However, the environmental challenges should not be overlooked, especially if economic growth is expected.

There are three plans especially dealing with the mobility and urban development in Madrid Region. The first one is the Sustainable Mobility Strategic Plan 2013–2025, which was elaborated by the public transport authority in Madrid Region [36]. The objectives of this plan include coordination between land use and urban transport, improving transport efficiency and accessibility, and a shift towards soft modes. Some of the policy actions proposed include the restriction and regulation of cars, the establishment of workplace mobility plans and the implementation of safety features to reduce traffic accidents. Another strategic plan related to urban mobility is the air quality plan 2013–2020 [37], which proposes several measures related to urban transport, e.g., the promotion of cleaner fuels, the establishment of low emissions zones, improvement of infrastructures for pedestrians and bicycles and expansion of the public transport network. As regards to urban planning, the prevalent land law no. 9/2001 [38] contains some general principles such as the need to coordinate urban development with the development of the transport network, duty to provide accessibility to all and responsibility to preserve the environment. There is no document dealing with an integral strategic plan for the transport network and urban land development [39].

In this paper, we present the results of implementing three different policy measures, by the simulation of the MARS model. These policies are cordon toll together with public transport expansion; promotion of teleworking and re-densification measures. The two transport measures are closely related to some action lines proposed by the strategic plans being implemented in Madrid Region, such as restriction of cars, improvement of the public transport network and the establishment of workplace mobility plans. The land use policy measure, re-densification, would be appropriate in the context of Madrid, since the city is facing a clear trend towards urban dispersion [7].

2.2.2. Main Features of MARS Model for Madrid

The fundamental principle of mobility analysis and forecast is the spatial separation of activities and people, which requires them to travel [40]. Transport and land use systems have a mutual influence, and the interaction between them has certain implications that can only be perceived in the long term [41]. One of the complex processes in the modelling of large urban areas for planning purposes is to adequately model the interaction between the transport system and the spatial distribution of residents and activities [42]. LUTI modelling has been investigated since the 1960s as a tool to

support strategic urban planning [8]. Lowry Model of Metropolis [43] was the first attempt to quantify the land use transport feedback cycle in a single integrated model. After the Lowry Model, many spatial interaction location tools have been developed, aiming at modelling the location of human activities as origins and destinations of trips, e.g., METPLAN [44] and PECAS [45]. Other LUTI models do not predict actual spatial interactions but the opportunity for spatial interactions are expressed as accessibility. Compared to the first urban models, which were static equilibrium models, accessibility-based location models, such as INPUD [46], MUSSA [47], DELTA [48] and MARS, tend to be more dynamic, attempting to capture the dynamics of urban processes. Sheperd [10] suggested applying the dynamic approaches in LUTI models. He argued that the land use and transport systems interact at different time scales. The land use changes are much slower than transport changes. These time lags and the complex interactions between them offer an ideal situation for the implication of the system dynamic approaches. Shepherd [10] highlighted the MARS model among others, due to its validation and transferability between cities. The model has already been applied to more than 20 cities around the world [49].

The MARS model is implemented in Vensim®, a System Dynamics programming environment. The model includes a transport sub-model that simulates the travel behaviour of the population, a housing location sub-model and a workplace location sub-model. The sub-models are executed iteratively over a period of up to 30 years, being linked by two factors, namely the accessibility and the location of households and workplaces [50]. Figure 1 shows the basic components of the Model. The **external scenarios and policy instruments** are inputs for the MARS model. The external scenarios include a number of variables in relation to demographic and economic growth, transport data and land use development. The policy instruments are policy interventions which modify the conditions of the land use sub model or the transport sub-model. The **transport sub-model** generates and distributes the trips of residents between the different zones and for different modes. The **land use sub-model** allocates workplaces and residents in the different zones. The accessibility to workplaces acts as an output in the transport model, while as an input in the location sub-models. The distribution of residents and workplaces acts as an output in the land use model. The results from this iterative process are used for assessing the policy instruments.
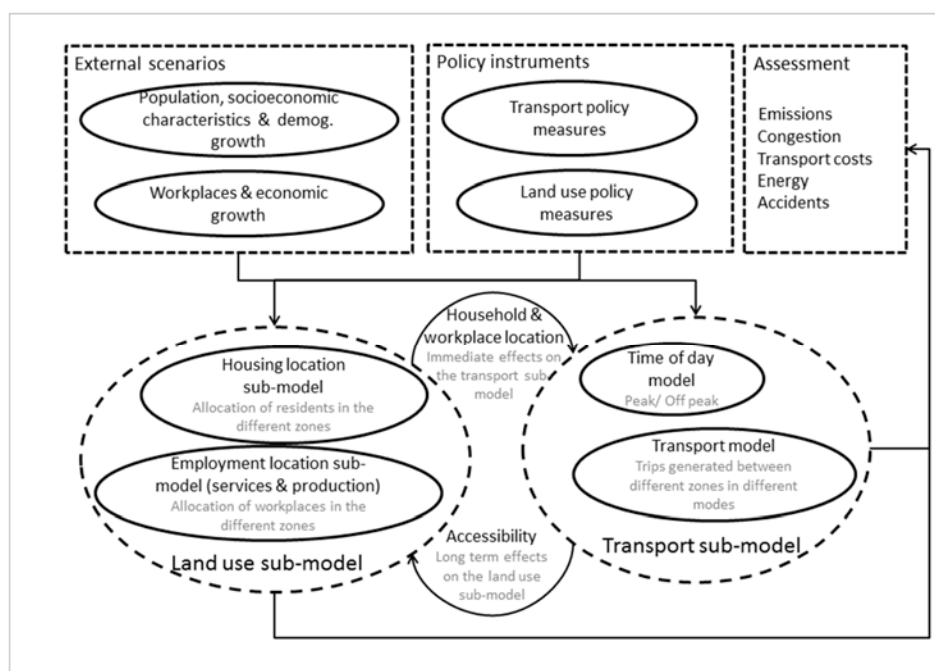

Figure 1. The basic structure of the MARS model for the case of Madrid. Source: [50], the figure is adapted to the case study of Madrid.

The MARS model for the case of Madrid was developed and calibrated first time by Guzmán [51], who applied it to maximise the welfare of pricing policies [12]. Later, Wang [52] made some developments in the model, which improved the sensitivity of the model to capture the changes in the accessibility-to-jobs levels produced by transport policies (i.e., [13,53]). Finally, in the framework of the INSIGHT project, the MARS model for the case of Madrid was updated and re-developed. Further explanations on the concepts, specifications and improvements of the model are provided in Appendix A.

MARS model divides the whole Region of Madrid into 90 zones (Figure 2). These zones, classified by Guzmán [51], are homogeneous territories in the terms of socioeconomic characteristics and mobility patterns. In the city of Madrid, where 50% of the Region' population lives, the zone aggregation is served at a district level. In the metropolitan ring, where 42% of the population lives, the zones correspond to different municipalities. The zones in the regional ring, which only account for 8% of the population, comprise various municipalities.
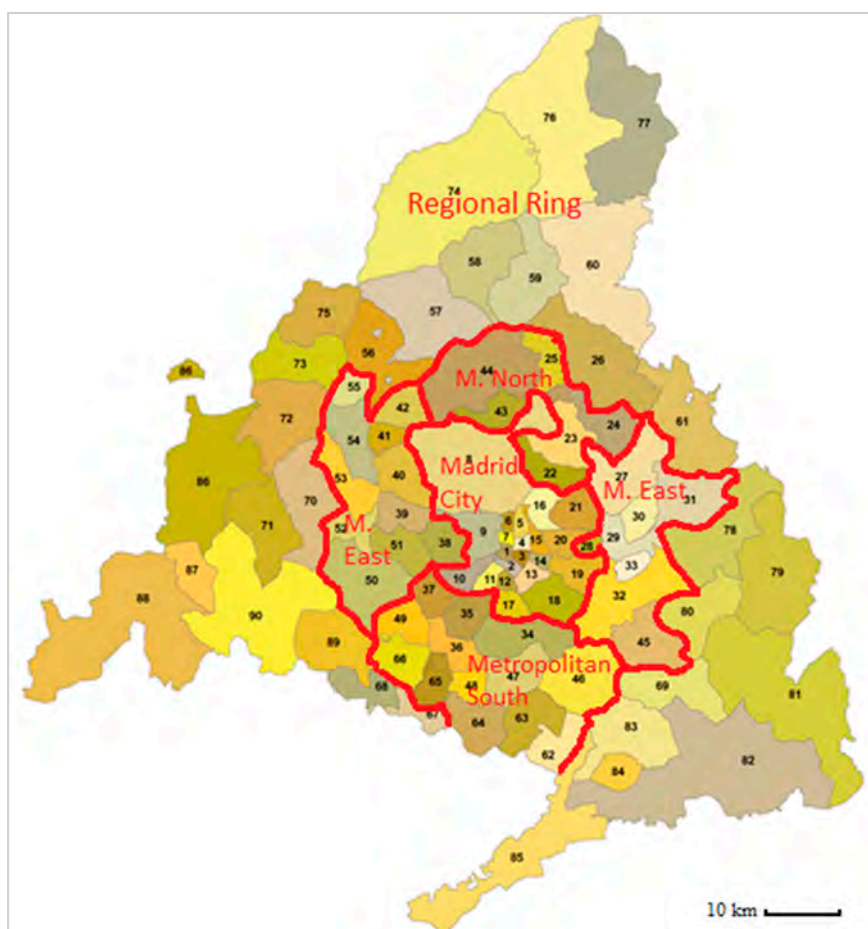
Figure 2. The zones of the MARS model for the city of Madrid. Red lines indicate the aggregated regions.

The reliability of the MARS model largely depends on the quality of the input data, which is implemented by the disaggregation of zones. The data needed for the exogenous variables and for the calibration process can be divided into three types [53]:

- **Socio economic data**, i.e., population per zone and population growth per aggregated region (city, metropolitan north, east, south or west and regional ring), household budget per zone, motorisation rate per zone, etc., were mainly obtained from the official statistical sources, provided by institutions at the city, regional and national levels [33,54,55].

- **Basic data** on **land use** development and **economic growth**, i.e., the functional proportion of land use (resident, production and service), land prices, expected growth of economic activity etc., were mainly obtained from the structural statistic databases at the regional level [56], and from international databases containing economic projections [57].
- Basic **data of transport mobility**, i.e., trip distance, speeds and time between the zones in different modes, car operating costs, the value of time, car occupation rate, etc., since the MARS model is an aggregated model and does not have a transport network, were partly obtained from VISUM transport model, which was executed through road network of the model (e.g., [58]). Some other transport data were obtained directly from the CRTM [36]. Besides that, the Madrid MARS model was calibrated by using three household mobility surveys conducted in Madrid in 1996, 2004 and 2014. The calibration process involved adjusting the values for the MARS model as external variables.

The main features of the model are summarised in Table 2.

Table 2. Main features of the MARS model [1].

Model Features	MARS for Madrid
No of zones	90
Demographics	Average household budget, household size, motorisation, etc.
Land use changes	Simulates land use changes depending on changes in accessibility and population growth rates
Allowed time period for predictions	30 years
Modes of travel	Car, public transport (bus, metro, urban train), slow mode (walking and cycling)
Congestion effect	Depends on the origin-destination speed-flow curves for commute trips
Friction factor (Generalised costs)	In-vehicle time, monetary costs, access/egress, parking search time, waiting time, transfer time
Journey purpose	Commute, other
Time periods	Peak hour and off-peak hours
Transport choice	Simultaneous mode and destination choice (not route, the model does not have a transport network)
Transport demand	Inelastic commuting trips and time budget essentially constant

[1] Source: [51].

2.2.3. Model Outputs for Policy Assessment

The purpose of this paper was to measure the contribution of different policy measures to meet city challenges. For this, we simulated the implementation of three policy measures in Madrid, using the MARS model. The effects of the policies should be measured in terms of the indicators validated in the first stage of the project (Table 1). However, the MARS model is focused on territorial and transport dynamics, while the city challenges and indicators were designed following a more open approach. Tables 3 and 4 show the role, if any, of each indicator in the MARS model. Only the indicators given as an output by the MARS model were used for the policy assessment.

The results of the model rely on the input data, especially on the growth projections for the economy and population. The growth projections are mostly provided by official statistical sources, which usually consider linear trends [33,54,55]. This is a simplification that may be different from reality [59]. However, we do not expect the modelling results to provide an accurate prediction of the future trends in terms of emissions or accidents, which are highly dependent on external conditions. What we expect from the modelling results is the possibility to determine if, under the same baseline

conditions, certain policy actions could contribute to reduce emissions, accidents, etc. In general, the model should help us to analyse which policies could contribute to address different city challenges.

Table 3. Socio-environmental challenges: Indicators for Madrid and their role in the MARS model.

City Challenges	No of Validated Indicators [1]	Madrid (2012)	Role in the Mars MODEL
Liveability	Pedestrians & cyclists injured in traffic accidents (no./year)	27.9	-
	Space for pedestrian use (km^2)	102	-
	Length of bicycle lanes (km)	290	-
	Road land occupation (km^2)	90	-
	Green areas (km^2)	160	**Input**
Equal, safe and secure society	Use and coverage of PT (Million Pax-km/year)	11,839	**Output**
	Use and coverage of PT within the main city	5191	**Output**
	Use and coverage of PT within the suburbs	1702	**Output**
	Income inequality: S80/S20 (ratio)	6.6	-
	Cost of main needs, share of the household budget devoted to main needs (housing, nutrition, health, education and transport) (%)	62.1	Only transport costs are the **output** of the MARS model
	Essential services provision in each zone: space devoted to health, educational and social services (km^2)	86	The provision of essential services in each zone is considered as an **input** in the MARS model (acting as a factor of attractiveness of each zone for residents &workplaces)
	Essential services provision in the main city	25	
	Essential services provision in the suburbs	60	
	Traffic accidents with casualties	10,625	**Output**
	Fatalities occurred in traffic accidents (no)	70	-
	Crime according to surveys, share of persons that report delinquency and vandalism problems (%)	54.2	-
Pollution	Average air concentration of: NO_x ($\mu g/m^3$)	76	-
	Particles ($\mu g/m^3$)	22	-
	Total emissions of: NO_x (t)	50,749	Only emissions of NO_x and PM due to the urban daily mobility of the population are an **output** of the MARS model
	Particles-PM (t)	88,308	
	Emissions in relevant sectors: Transport NO_x (t)	40,838	
	Transport PM (t)	5146	
	Industry NO_x (t)	4421	-
	Industry PM (t)	1118	-
	Noise intensity levels (LAeq dBA)	62.8	-
Climate Change	Greenhouse gases emissions (GHG) (Thousands of Ton of CO_2 eq)	18,857	Only GGE emissions due to the urban daily mobility of the population are an **output** of MARS
	GHG by main sectors: Transport (Thousands of CO_2 eq)	8477	
	Industry(Thousands of CO_2 eq)	3085	-
Demographic decline	Share of active population (%)	53.2	Only the initial population per zone and its growth per aggregated region is an **input** of MARS
	Share of population over 60 years (%)	20.4	
	Share of population under 25 years (%)	25.3	
	Share of skilled workers (%)	51.8	
Education/culture	Drop-out rates from secondary education (%)	21.5	-
	Cultural offer (no. of cinemas and cultural offer)	222	-

Table 4. Efficiency challenges: Indicators for Madrid and their role in the MARS model.

City Challenges	No of Validated Indicators [1]	Madrid (2012)	Role in the Mars MODEL
Economic activity	Household available budget (€ per household/year)	34,770	**Input**
	GDP per capita (€ per inhabitant (inhab)/year)	30,446	**Input**
	Employment (% of the active population)	64.2	**Input**
	Job creation (No. of workplaces)	2,529,262	**Output**
	Land prices (€/m^2)	2181	**Input**
Efficient use of resources (i.e., time)	Unoccupied flats or buildings (No.)	436,977	-
	Congestion, increase of travel time at peak hours (%)	11.8	**Output**
	Total time spent commuting by all inhab (total hours/day)	1,441,325	**Output**

Table 4. *Cont*.

City Challenges	No of Validated Indicators [1]	Madrid (2012)	Role in the Mars MODEL
Energy efficient	Energy consumption (ktoe/year)	10,192	Only energy consumption due to the urban daily mobility of the population are an **output** of the MARS model
	Energy consumption in relevant sectors: Transport (ktoe/year) [1]	5176	
	Housing (ktoe/year)	2396	-
	Industry (ktoe/year)	869	-
	Fuel dependence (energy coming from petrol and carbon sources) (%)	55.8	Only energy fuel dependence of the urban daily mobility of the population is an **output** of the MARS model
	Fuel dependence in relevant sectors: Transport (%)	96.2	
	Housing (%)	16.2	-
	Industry (%)	15.4	-
	Share of energy consumption from renewable sources (%)	1.9	-
Urban sprawl	Urban density (inhabitants/km^2)	6277	**Input** (the urban surface and the population growth are part of the external scenarios of the MARS model)
	Urbanised surface (km^2)	1037	
	Share of the population living in the Central City (%)	49.7	**Output**

[1] toe: Tonnes Oil Equivalent.

2.3. Policies Design and Implementation: Defining the Policy Scenarios

Three policies were assessed in this study: two transport policies, viz. cordon toll and teleworking, and one land use policy, viz. re-densification. These policy measures were selected for the various reasons. Firstly, for their potential to address some city challenges, essentially those that are related to the excessive car use, such as congestion, pollution or climate change. Secondly, for their diverse nature, such as one pricing policy, one behavioural policy and one structural policy, which would broaden the scope of the study and enrich the comparative assessment. Thirdly, because all policies are aligned with some trends, which are really happening in cities, such as car pricing policies [60], flexible working arrangements [61] and regeneration and revitalisation of inner city centres to avoid the migration of the population to the suburbs [62]. Finally, the limitations of the MARS model to simulate policy measures needed to be considered, since it is an aggregated model. Besides, the three policy measures were discussed and agreed by INSIGHT consortium with the assessment of the experts of the project [63]. In order to analyse the effects of the policies, we had to build one scenario for each policy, in addition to the base scenario. This reference scenario is called the do-nothing scenario.

2.3.1. Do Nothing

The Do-nothing scenario is defined and executed in the model in order to compare the effects of implementing the three policy measures with not taking any particular action. However, in this subsection, we present the most important inputs to be implemented in the model for the long term assessment: economic and demographic growths. In order to input the economic growth, we implied the OECD database [57], which provides economic projections (Figure 3). The model considers an economic growth rate for the whole Region, and then redistributes workplaces and residents in the different zones. This economic growth is the same in the four policy scenarios.

Data on demographic growth were provided by Madrid City Council database [54], which gives the population projections until 2023 for Madrid City, and by the National Spanish Statistical database (INE) [55], which gives the population projections for the whole Madrid Region until 2031. There are no official projections of the population in Madrid beyond 2031. For this reason, we have limited the study and the analysis of this paper to 2031. Regarding the demographic growth, the model considers six different population growth rates for the following aggregated regions: Madrid City, Metropolitan North, Metropolitan East, Metropolitan South, Metropolitan West and Regional Crown (Figure 2). For this study, the growth rates of each zone were calculated on the basis of the projections for the city and the whole Madrid Region. The internal distribution of the population between the different aggregated regions was performed by adopting a similar methodology to that adopted by INE [55] for

Madrid Region, which can be consulted in [64], and is based on the socioeconomic features of each zone (Table 5). Logically, the zones where the population is younger and the average birth rate is higher, show higher growth rates, i.e., Metropolitan North or West and Regional Ring. Conversely, the population of Madrid City is expected to decrease [54], being characterised by the highest death rate and a negative migration balance. These social characteristics of the different zones draw part of the urban sprawl picture, e.g., young families move out of the city centres, looking for better environments and more affordable houses [19]. The final growth rates fed in the model are shown in Figure 4, and are the same in the cordon toll + PT and the teleworking scenarios. The re-densification scenario consists of changing the redistribution between the city and the outside rings, and therefore considers a different internal distribution of the population.
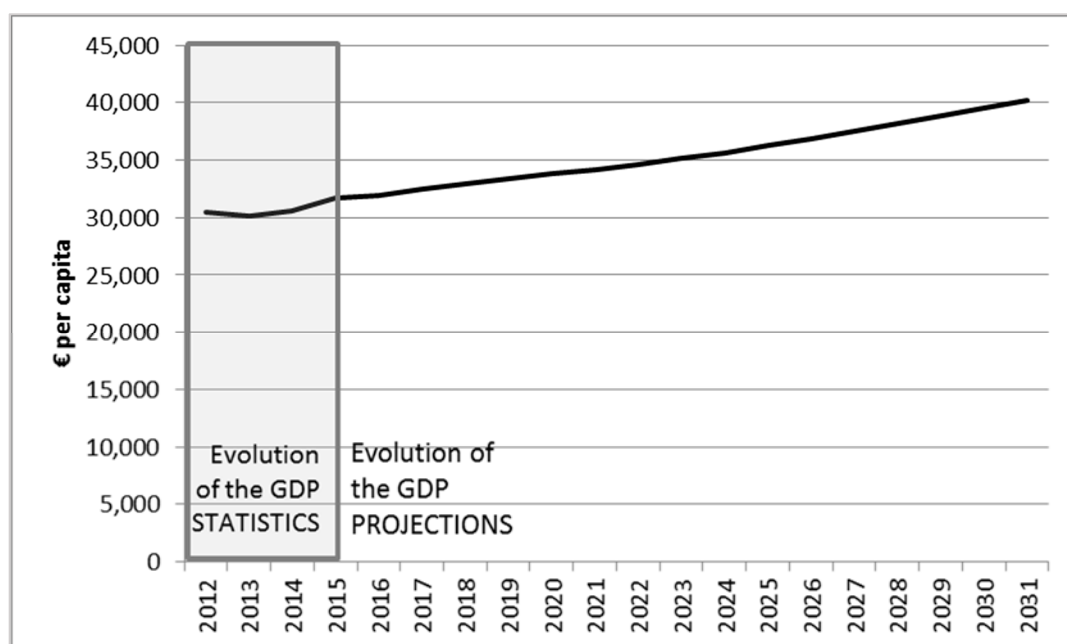

Figure 3. Economic growth. Projections for the whole Madrid Region. Data sources: (INE) [55] for real data, and (OECD) [57] for projections.

Table 5. Socioeconomic features influencing population projections (Year 2012) [1].

| Feature	Unit	City	North	East	South	West	Regional
Population	No. inhab	3,233,527	320,307	652,437	1,292,240	472,043	538,454
Average age	Years	42.4	37.2	37.1	38.3	36.7	37.1
Birth rate	No./1000 inhab	9.9	11.2	11.3	11.6	10.3	11.7
Death rate	No./1000 inhab	8.4	4.5	4.2	5.0	4.1	5.6
Emigration rate	No./1000 inhab	30.5	21.6	19.3	21.5	20.4	19.5
Immigrants from other countries or Spanish regions	No.	98,552	6913	12,597	27,799	9613	10,294
Migration balance with other zones of Madrid	No.	−10,950	1638	2166	466	1720	4960

[1] Data sources: [33].
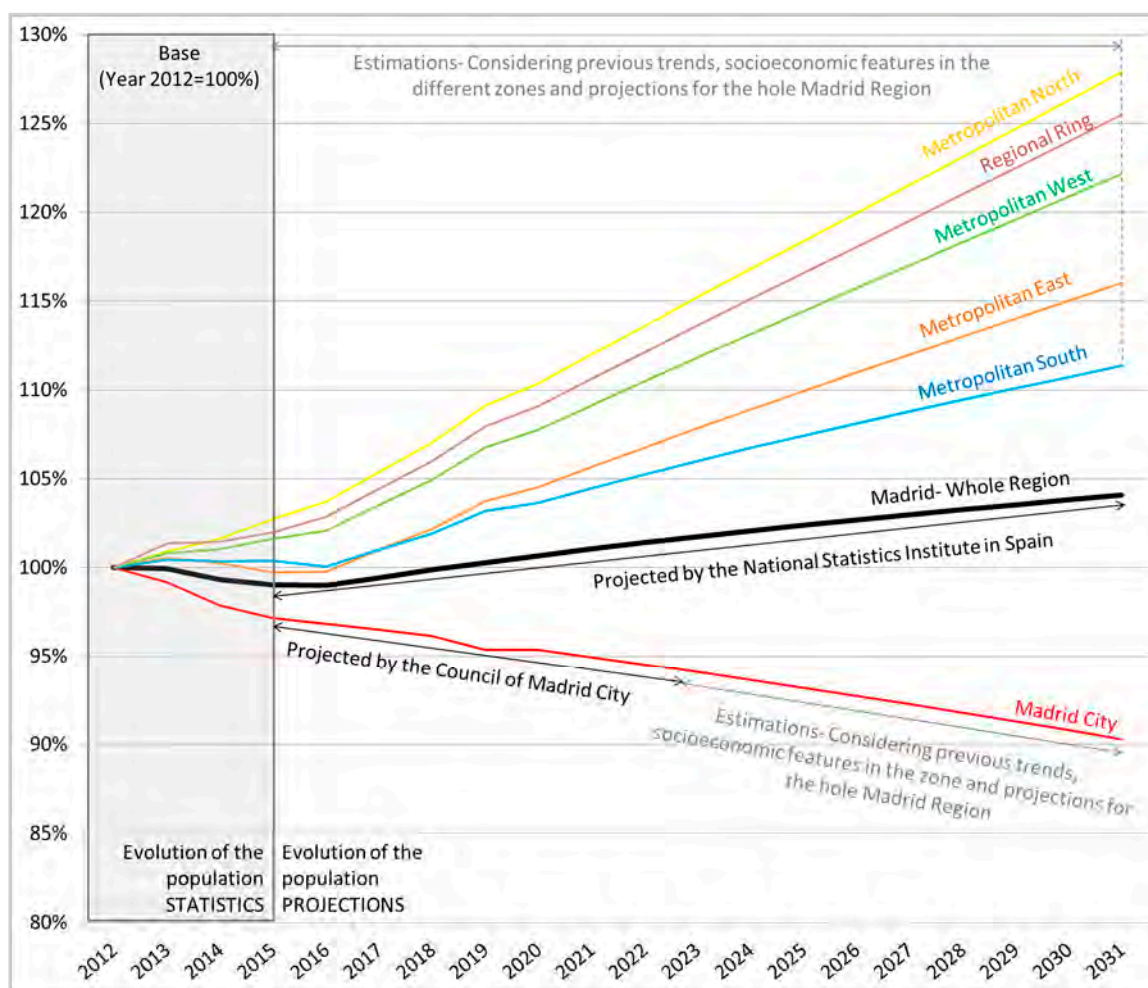
Figure 4. Population growth in the different zones of Madrid Region. The input for the MARS model. Data sources: [33] for real data, [54] for projections in the case of the Madrid city and [55] for projections in the whole Madrid Region.

With regard to the transport sub-model and the data inputs, Table 6 and Figure 5 provide some aggregated data on the daily trips made in Madrid Region. These data were retrieved from the household mobility survey carried out by CRTM [36], and employed to calibrate the model. In Madrid Region, almost 13 million trips are made per day. One-third of these trips are Commuting trips, which are characterised by their dependence on motorised modes and their longer distances. For this reason, many mobility management strategies focus on commuting mobility [65]. On the other hand, we can observe that the trips made in the city are based more on public transport and walking than the trips made in the suburbs, which are more car-dependent. This is one of the reasons why urban sprawl follows an unsustainable growth pattern [19].

Table 6. Daily trips in Madrid Region: The number and distribution by zones and purposes [1].

| Heading	No. of Trips Per Day	Within the City	Between the City and the Metropolitan & Regional Rings	Within the Metropolitan & Regional Trips
Commuting trips	4.3 million	45.4%	28.9%	25.7%
Non-Commuting trips	9.2 million	49.1%	13.2%	37.7%

[1] Data source: The mobility survey carried out by CRTM [36] in 2014.
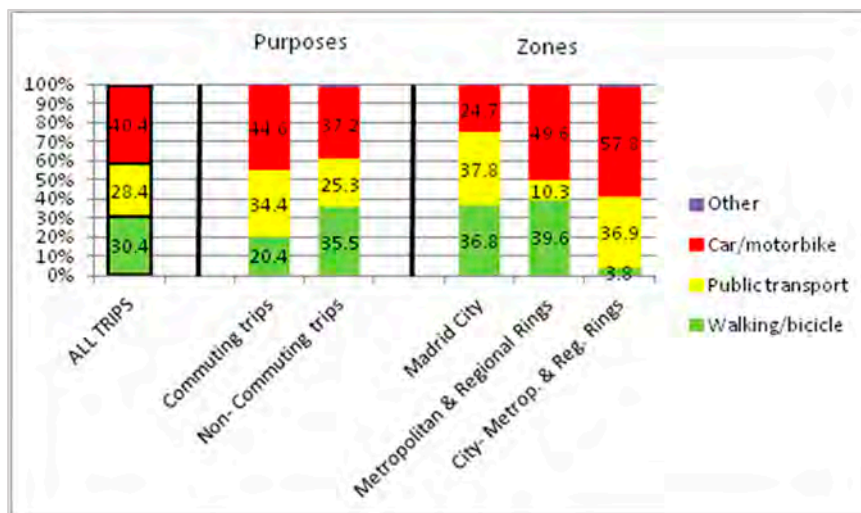
Figure 5. Modal share of daily trips in Madrid Region by purposes and zones. Data source: [36].

2.3.2. Cordon Toll and Public Transport Improvement

It is well known that optimal road pricing may yield a social and environmental surplus [66]. Furthermore, in some cases, the added value of the measure to the economy and efficiency has been demonstrated through gains in the value of time and reduced congestion [67]. In this case, for the design of the cordon toll, we decided to follow a similar scheme of the cordon toll implemented in Stockholm, which is usually considered as a successful case study [68] (Table 7). The MARS model simulates the cordon toll policies by increasing the cost of making certain trips, in this case, the area proposed for the cordon toll simulation includes zones 1 to 7 (Figures 2 and 6), and all trips entering in these zones are affected. In addition, and following the Stockholm cordon toll scheme, we implemented improvements in PT service frequencies, which were increased by seven per cent. On the other hand, the acceptability of pricing policies potentially increases along the time, and this can change the effectiveness of the policies [69]. To avoid this effect, it is sometimes recommended to increase the price over time. In the case of Stockholm, the initial price in 2006 was 20 SEK at peak hours, and the price increased to 35 SEK in 2016 [70]. We followed a similar approach for a 15-year simulation, from 2016, which is the initial year of the policy implementation, to 2031, which is the end year of the simulation process. Other authors have also carried out analysis of cordon toll policies using the MARS model before [12,13], where more details about the implementation process can be consulted. Some features about the cordon toll implementation are presented in Table 7.
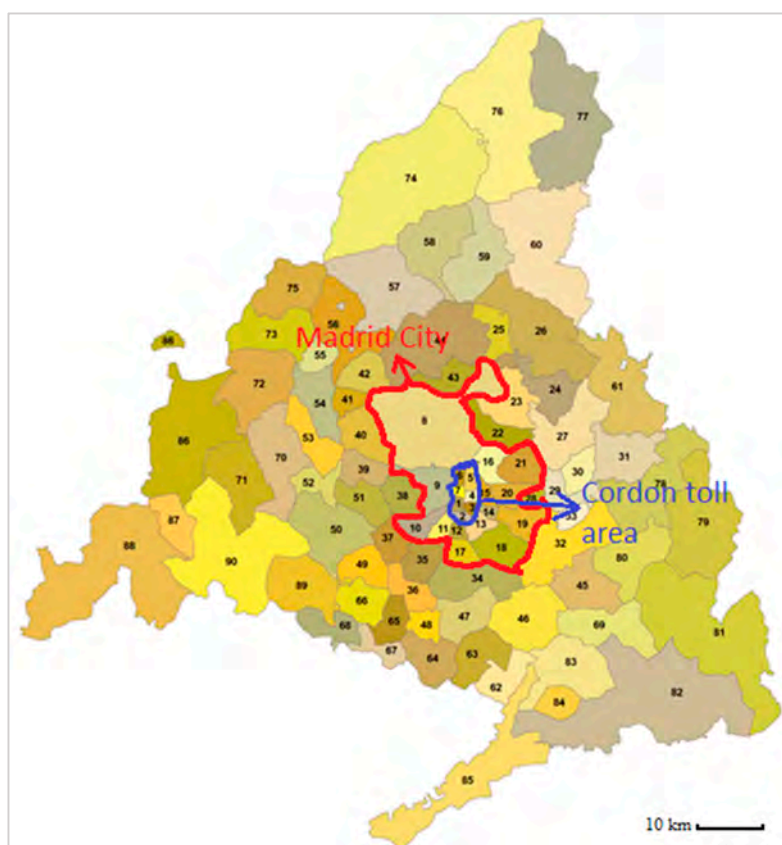
Figure 6. Cordon toll area proposed. Input for the MARS model in the cordon toll policy.

Table 7. Main features of the cordon toll policy. Input for the MARS model in the cordon toll policy [1].

Heading	Stockholm (2 Million Inhabitants)	Madrid (6.4 Million Inhabitants)
	Real Data	Input Data for the Simulation
Toll area: limitation	CBD, physically separated by channels	CBD, physically separated by the M-30 (ring road)
Share of the population living inside the toll area	15.6%	15.4%
Initial Price peak (KRN)/ GDP per capita (KRN)	20 SEK in 2006 (~€2.12 in 2006) 418,099 SEK in 2006 (~€44,421 in 2006)	€2 in 2016/ €30,446 in 2015 (considering the GDP and the city size)
Initial Price off peak (€)/ GDP per capita (€)	10 SEK in 2006 (~€1.06 in 2006) 418,099 SEK in 2006 (~€44,421 in 2006)	€1 in 2016/ €30,446 in 2015
Public transport services extension	7% increase in PT frequencies	7% increase in PT frequencies
Increase of the peak price	75% in 10 years	112.5% in 15 years (accompanied by an increase of the PT frequencies: up to 14% in 2031)
Increase of the off-peak price	10% in 10 years	15 % in 15 years

[1] Data sources: Information of Stockholm taken from [68,70].

2.3.3. Teleworking

Practices such as teleworking or flexible working hours are increasingly gaining importance at a global level, and are predicted to grow continuously [61]. This prediction might also be extended in the case of Spain, where such practices emerged later than in other countries, but are showing an upward trend [71]. Flexible work arrangements are often helpful in transport management solutions, since they are assumed to lessen the number and length of traffic jams at peak hours [72]. However, teleworking practices have some other side effects that should be considered. They often result in the growth of non-work related trips during the day, and this may negatively affect the global energy and increase emissions [73].

According to Census surveys carried out by the INE [55], in Madrid Region, the number of people working at home has grown from 2.4% in 2001 to 8% in 2011. In view of this growth, and considering feasibility studies on this topic [73–75], we considered that teleworking encouragement policies could achieve a reduction of a 10 per cent in trips to work by 2031. Teleworking practices could be part of the workplace mobility plans that the public authorities of Madrid Region intend to establish [36,37]. For the implementation of teleworking in the model, this reduction is assumed to be linear. It is supposed to increase from 2016, where there is still no reduction, to 2031, where a 10 per cent reduction on the commuting trips will be achieved. Teleworking policy measures have also been assessed earlier with the MARS model by other authors [50].

2.3.4. Re-Densification

In the on-going search for guidelines and strategic intervention, the need for the re-densification and the restoration of degraded zones in the city centres has emerged at various levels [76]. However, very few studies have quantified the potential effects of re-densification policies over emissions, energy or social inclusion [77]. Only a few studies have analysed the benefits of Transit Oriented Developments [78] through transport models [15].

For the design of the re-densification policy, we firstly assumed that the net population growth in the whole Region keeps constant in all scenarios. What changes in the re-densification scenario is the internal distribution of the population between the aggregated regions. In the re-densification scenario, the city of Madrid loses less population than in the previous scenarios, due to the regeneration of some zones. There is a zone in Madrid that has recently gone through a process of improvement and regeneration. In this zone, which is called Arganzuela (zone 2 in the model), the so-called Operación Madrid Rio [54] has improved the environment, and expanded green areas, public spaces and sports facilities. In this zone, the population movements to the suburbs are lower than in most of the zones in Madrid City. Considering this case as a successful regeneration process, we assume that similar regeneration processes took place in various zones of the city. Madrid city comprises zones 1–21 (Figure 2). Out of these zones, we have selected those which are considered more degraded and where the population movements to the suburbs have been higher during the last few years: 8 (Fuencarral), 9 (Moncloa), 10 (Latina), 11 (Carabanchel), 12 (Usera), 13 (Vallecas), 14 (Moratalaz), 17 (Villaverde), 20 (San Blas) and 21 (Barajas). For building the re-densification scenario, it is assumed that these zones would behave similarly to zone 2, and would have lower population loses. Under these assumptions, the resulting population growths are represented in Figure 7. These population growth rates were inputted in the model to obtain the re-densification scenario.
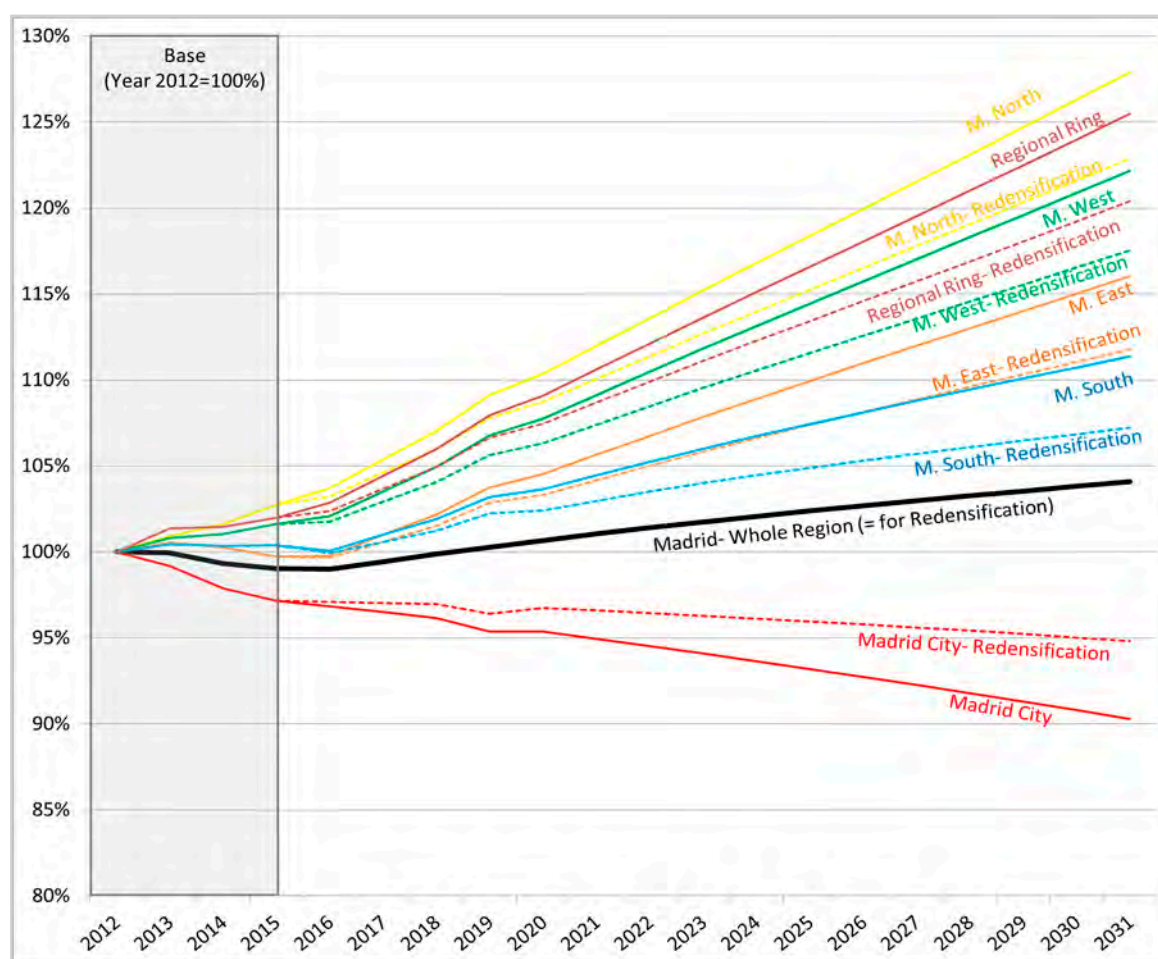
Figure 7. Population growth in the different zones of Madrid Region. Input for the MARS model in the re-densification scenario (compared to the population growth applied in the other policy scenarios).

3. Results

The results of the four simulations corresponding to the four scenarios defined are presented in Figures 8–13. The figures show the variables with the greatest influence in the policy assessment results, which are based on the values of the indicators associated with the different city challenges (Tables 3 and 4). The figures cover each year of the simulation period, from 2012 (Year 0) to 2031 (Year 19): time travelling, passenger-km, car speed and CO_2 COs emissions. In addition, Figures A1–A3 in Appendix A show the causal loop diagrams for the calculation of these variables in the MARS model. Figures 8 and 9 show the time travelling per person. The three policies achieved time savings in commuting trips and reduced the traffic at peak hours. In the cordon toll and teleworking scenarios, the car speed increases due to the improved traffic flow. This is translated into an economic value, and is good in terms of efficiency and reduces congestion. However, the time budget per person and day is more or less constant, and in the three scenarios, people travelled more during nonpeak hours and for not for work reasons. In some scenarios, this resulted in an increase in the total vehicles-km travelled, also increasing the total emissions and energy. This is especially the case of the teleworking scenario, where the trips to work keep decreasing over the years. In fact, the only scenario which achieved a reduction in the total km travelled by car was the re-densification scenario, through a reduction of distances and increasing the trips within the city, which are based more on walking and PT. In the first year of the simulation process (2012–2013), the growth of the economy and the population are still negative, due to the economic crisis that hit European Continent in 2007 [79]. This results in a

reduction of trips and emissions from 2012 to 2013. From 2014 to 2015, the economic indicators start to recover and positive growths for the economy and the population are expected in the upcoming years [54,55,57].
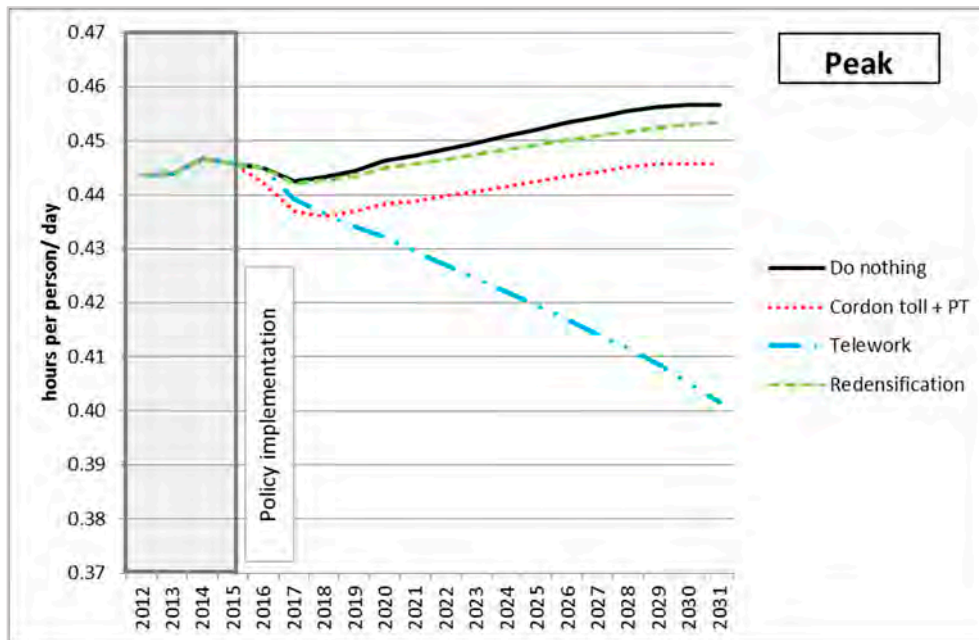

Figure 8. Evolution of time travelling at peak hours in the three policy scenarios, MARS output.
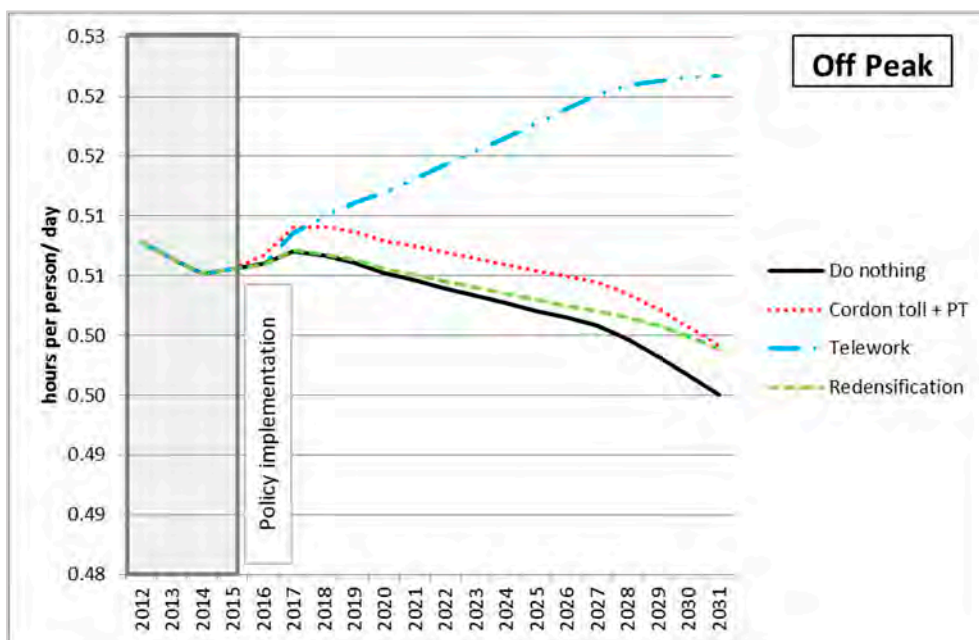

Figure 9. Evolution of time travelling at off peak hours in the three policy scenarios, the MARS output.
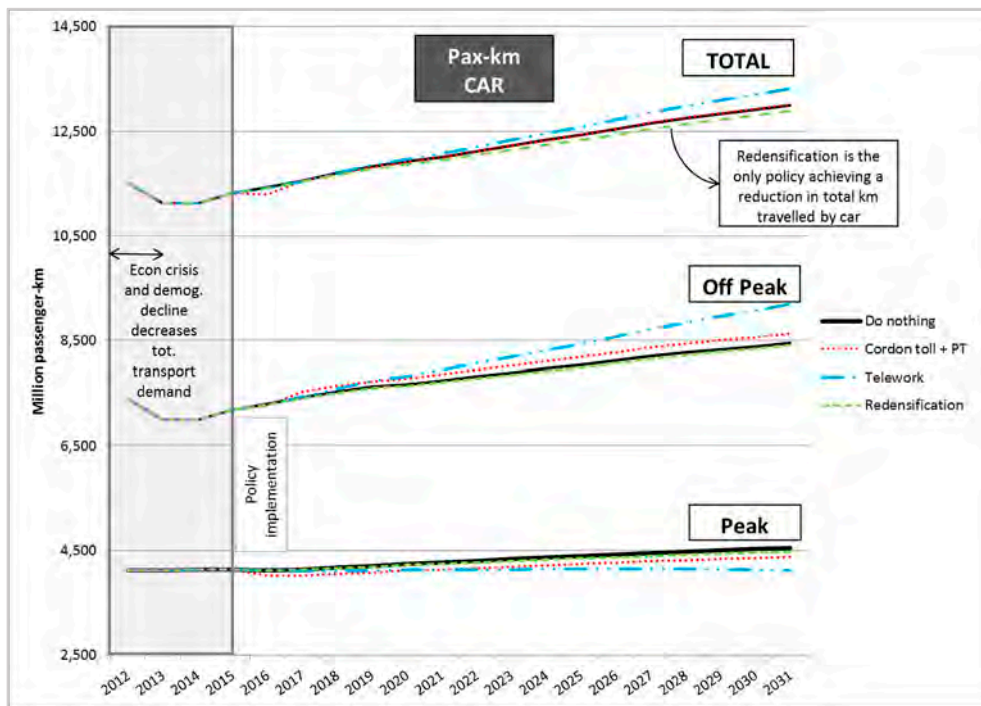
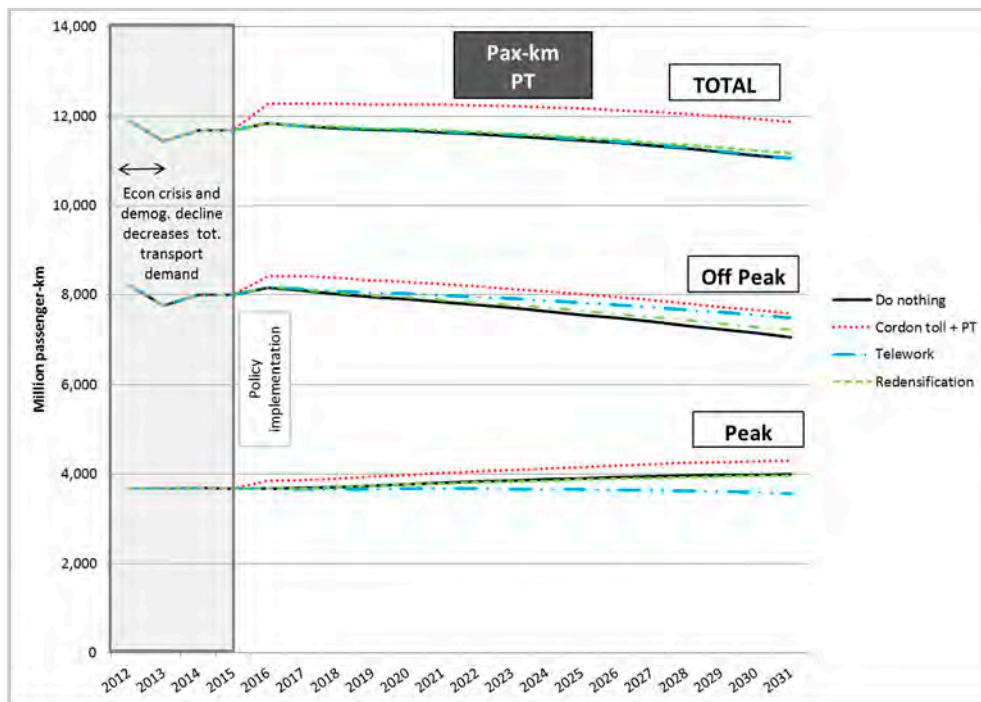**Figure 10.** Evolution of passenger-km travelled by car in the three policy scenarios, the MARS output.

Figure 11. Evolution of passenger-km travelled by public transport in the three policy scenarios, the MARS output.
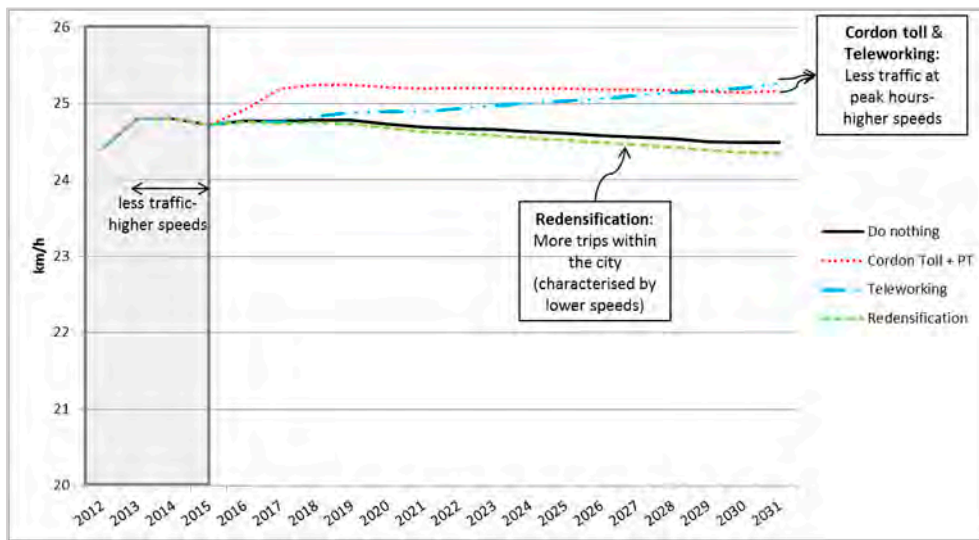
Figure 12. Evolution of average car speed in the three policy scenarios, the MARS output.
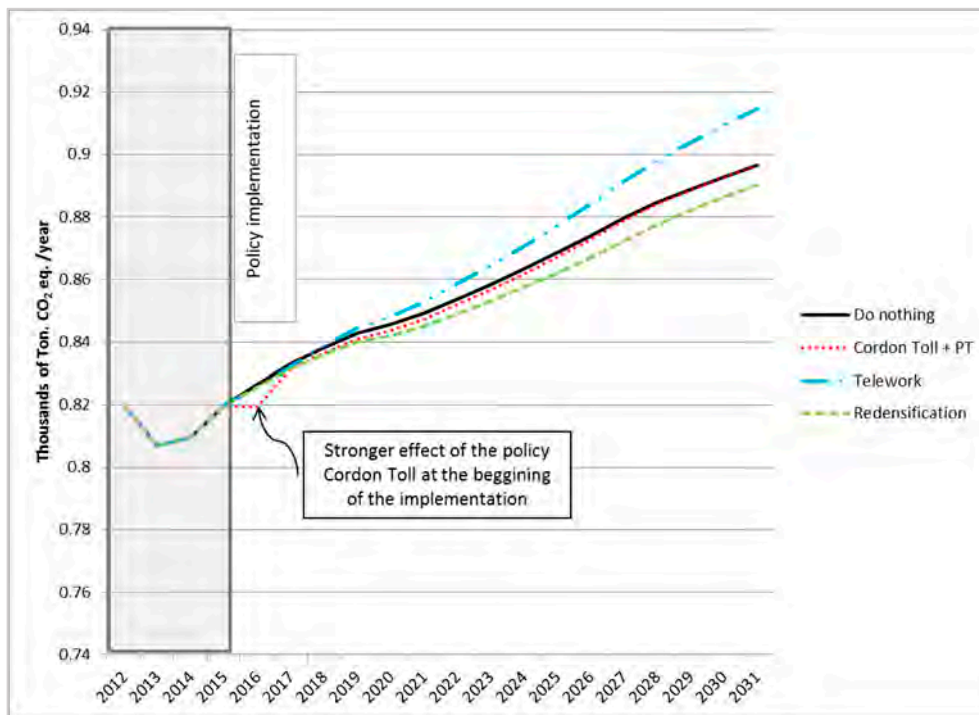

Figure 13. Evolution of CO_2 emissions per person due to urban transport in the three policy scenarios, the MARS output.

The results of the policy assessment are presented in the terms of the indicators related to the city challenges, as shown in Tables 3 and 4. For measuring the contribution of the three policies to meet the city challenges, we have used only those indicators which are given as an output in the MARS model. The simulation results for the four policies are presented in Tables 8 and 9.

Table 8. Contribution of the three policy measures to efficiency challenge [1].

Challenges	Indicator	2012	Policy Scenario	2020 (Model)	2031 (Model)	Total Savings (2012–2031)
Economic activity	Workplaces (no. of jobs)	2,529,262	Do-nothing	2,665,996	2,854,384	Base scenario
			Toll + PT	**2,667,759**	**2,870,712**	n.a. [2]
			Telework	2,665,936	2,852,071	n.a.
			Redensific.	2,665,996	2,855,003	n.a.
Time efficiency	Congestion, increase in travel time at peak hours (%)	11.8	Do-nothing	12.0	12.7	Base scenario
			Toll + PT	11.5	12.0	n.a.
			Telework	**11.7**	**11.5**	n.a.
			Redensific.	11.9	12.5	n.a.
	Total time spent commuting by all inhab. (hours/day)	1,441,325	Do-nothing	1,459,921	1,544,282	Base scenario
			Toll + PT	1,433,810	1,506,929	114 mill. hrs saved
			Telework	**1,413,901**	**1,358,071**	357 mill. hrs saved
			Redensific.	1,455,872	1,533,569	29 mill. hrs saved
Energy efficiency	Energy consumption in daily urban mobility (ktoe/year)	1961	Do-nothing	2038	2222	Base scenario
			Toll + PT	2029	2239	3 ktoe saved
			Telework	2049	2296	498 ktoe extra
			Redensific.	**2027**	**2199**	249 ktoe saved
	Fuel energy dependency (%)	94.4	Do-nothing	94.5	95.0	Base scenario
			Toll + PT	94.5	94.9	n.a
			Telework	94.6	95.2	n.a
			Redensific.	94.5	95.0	n.a
Sprawl	Share of the metropolitan population living in the main city (%)	49.7	Do-nothing	47.0	43.4	Base scenario
			Toll + PT	47.2	43.5	n.a
			Telework	47.2	43.4	n.a
			Redensific.	**47.7**	**45.3**	n.a

[1] Bold letters highlight the policy with the best results; [2] n.a: not applicable.

Table 9. Contribution of the three policy measures to social and environmental challenge.

Challenges	Indicator	2012	Policy Scenario	2020 (Model)	2031 (Model)	Total Savings (2012–2031)
Safety	Traffic accidents (No./year)	10,625	Do-nothing	11,667	12,027	Base scenario
			Cordon toll	11,255	12,052	4504 accid. less
			Telework	11,157	12,445	3483 accid. less
			Redensific.	**10,966**	**11,561**	10,076 accid. less
Accessibility	PT use (million Pax-km/year)	11,836	Do-nothing	11,678	11,048	Base scenario
			Cordon toll	**12,267**	**11,881**	n.a
			Telework	11,696	11,053	n.a
			Redensific.	11,718	11,173	n.a
	Cost of mobility to work or study per person (€/day)	1.25	Do-nothing	1.31	1.43	Base scenario
			Cordon toll	1.53	1.74	n.a
			Telework	**1.27**	**1.29**	n.a
			Redensific.	1.30	1.40	n.a
Climate change	GGE from urban transport (Thousands of Ton CO_2 eq./year)	5458	Do-nothing	5531	6064	Base scenario
			Cordon toll	5518	6062	177 t of CO_2 saved
			Telework	5548	6185	776 t of CO_2 extra
			Redensific.	**5509**	**6022**	519 t of CO_2 saved
Air pollution	NO_x emissions from urban transport (t/year)	14,677	Do-nothing	16,494	18,725	Base scenario
			Cordon toll	16,583	18,925	1879 t extra
			Telework	16,564	19,190	3078 t extra
			Redensific.	**16,428**	**18,598**	1540 t less
	PM emissions from urban transport (t/year)	1088	Do-nothing	1569	1926	Base scenario
			Cordon toll	1563	1914	162 t saved
			Telework	1573	1958	195 t extra
			Redensific.	**1560**	**1912**	170 t saved

[1] Bold letters highlight the policy with the best results; [2] n.a: not applicable.

4. Discussion

The following paragraphs clarify and discuss the results shown in Tables 8 and 9.

Economic activity: In both cordon toll and re-densification scenarios, the number of workplaces increased with regards to the reference scenario. This was due to the different allocation of residents and workplaces. On the one hand, the cordon toll policy measure allocated more workplaces outside the city, balancing the equilibrium between the residents and workplaces outside the city and reducing unsatisfied demand. On the other hand, in the re-densification scenario more workplaces were allocated in the city, balancing the equilibrium between the residents and workplaces inside the city and reducing slightly the unsatisfied demand. Conversely to the cordon toll and re-densification measures, the teleworking policy measure reduced slightly the total number of workplaces, due to the reduction of supply.

Time efficiency: The three policy measures reduced the time spent on commuting, especially teleworking, which reduced the need to travel to work. On the other hand, the total time budget per person tends to be constant. On this basis, the time spent travelling for other reasons increased in the three policy scenarios. However, these time losses do not necessarily affect the economic efficiency. Regarding the congestion, the three policy measures improved the traffic flow, but the most effective was the teleworking.

Energy efficiency: Only the re-densification policy measure really contributed to save energy. In the teleworking scenario, the increased demand for non-commuting mobility led to increase the total energy consumption. In the cordon toll scenario, the increase of PT services caused a moderate increase in the total energy consumed in the last years.

Safety: The three policy measures reduced the total number of traffic accidents along the period, especially the re-densification, due to a mobility based more on slow modes and PT. At the end of the period, the traffic accidents increased in the teleworking and re-densification scenarios, due to the increases in car speed at peak hours (improved traffic flow) and the increase in the number of trips at non-peak hours.

Accessibility: The three policy measures encourage PT use. Especially the cordon toll, due to the improvement in PT services and the higher costs of travelling by car. In the teleworking scenario, the trips done by PT increased (slightly) due to the increased demand at non-peak hours. In the re-densification scenario, the trips within the city gained significance. This increased the PT use since the mobility inside the city is more based on PT. Regarding the cost of commuting mobility, the more effective measure to reduce the costs of the obligatory mobility is the teleworking, which reduces the need to travel. On the other hand, the only policy measure that increases the cost of mobility to work or study is the cordon toll, due to the increased costs of travelling by car.

Climate change: Both cordon toll and re-densification policy measures contribute to reduce GGE, especially the re-densification policy, by reducing travel distances and encouraging mobility more based more on PT and slow modes. The GGE reduction in the cordon toll scenario is due to the reduction in the total number of trips by car. In the teleworking scenario, the GGE increase due to the increased demand for non-commuting mobility.

Air pollution: Regarding emissions, only the re-densification policy measure contributed to reduce both NO_x and PM emissions. In the teleworking scenario, emissions increased due to the growth of traffic at non-peak hours. In the cordon toll scenario, only the PM emissions decreased due to the reduced car traffic, but the emissions of NO_x increased, due to the increased bus services.

5. Conclusions

In this paper, we compared three land use and transport policy measures to determine their contribution in addressing different city challenges. The three policies, cordon toll, teleworking and re-densification, are aligned with some trends which are really happening in cities and have a high potential to address some city challenges, essentially those related to the excessive car use, e.g., congestion, pollution or climate change. The policy assessment required a long-term simulation tool,

able to consider the interactions between the land use and transport systems. For this, we employed the MARS model applied to Madrid Region. This LUTI model, created by Pfaffenbichler [32] for the city of Vienna, was developed by Guzmán [51] for the city of Madrid, and latter improved by Wang [52]. In the framework of INSIGHT project, the model was updated and re-developed [80,81], and this last version of the model was used to simulate and assess the three policy measures. The simulations were executed for the period 2012–2031.

The contribution of the policy measures to address the city challenges in Madrid Region was measured through indicators, validated and assessed by stakeholders during the project. The results indicate that the three policy measures contribute to the time efficiency challenge, and yield commuting time savings, reducing congestion and improving traffic flow at peak hours. The most effective policy in this regard is the teleworking measure. Another positive effect of the three policies is an increase in the PT use, especially in the cordon toll scenario, which includes PT improvements. This effect is positive for the social inclusion and accessibility for all.

On the other hand, commuting time savings have some side effects: people travel more at nonpeak hours and for not working purposes. This results in increasing the total passengers-km at non-peak hours and, in some scenarios, also in the total energy and emissions. This is especially the case of the teleworking measure. The cordon toll measure produces energy and emissions savings at the beginning of the implementation, but loses efficiency over time due to the acceptability. The only policy that really contributes to the city challenges such as energy, emissions and pollution in the long term is the re-densification measure, which reduces travel distances and encourages a mobility based more on PT and slow modes. The containment of urban sprawl in Madrid should be a priority policy objective, especially considering the dispersion of the population that has occurred during the last years in the region [7,31,39].

Policy strategies need to include long-term land-use and urban development measures to achieve more sustainable transport systems. Strategies that limit measures to transport management are not enough to resolve the city challenges [7]. It is necessary to establish the basis of a sustainable transport system that can tackle urban sprawl and encourage investments for improving PT quality, in order to improve accessibility and equity. Regarding flexible working schemes, they are very effective for time efficiency and to reduce congestion, but they could negatively affect the energy and emissions challenges [73].

Future research could focus on the implementation of combined policy actions to design a strategic plan for achieving a sustainable urban development. An effective strategy to address all the city challenges should contain various measures related to land use development and transport management with an objective of bringing together the positive effects of the different measures.

Author Contributions: Andrea Alonso wrote the paper and elaborated tables and figures to compile and present the data and results. Andrés Monzón structured the paper and the presentation of the results and coordinated the whole research process. Yang Wang worked with the tool used (MARS model) in order to improve it and make it able to simulate the policy measures. The three authors decided the type of policies to be implemented. Andrea Alonso elaborated the list of challenges and assessment indicators, designed and implemented the policies in the model, processed and elaborated the results and drawn the main conclusions.

Conflicts of Interest: There is no conflict of interest.

Abbreviations

CBD	Central Business District
CRTM	Consorcio Regional de Transportes de Madrid (Public Transport Authority in Madrid Region)
GHG	Green House Gases
HOH	Home–Others–Home

HWH	Home–Work–Home
INE	Instituto Nacional de Estadística (National Statistical Institute in Spain)
LUTI	Land Use and Transport Interaction
MARS	Metropolitan Activity Relocation Simulator
OD	Origin–Destination
PT	Public Transport
PM	Particulate Matter
TOD	Transyt Oriented Developments

Appendix A

The basic concepts and equations behind the MARS model can be found elsewhere [32]. The main specifications for the case of Madrid are detailed by Guzmán [51] and Wang [52] and the improvements carried out during the INSIGHT project can be found in the studies by Wang et al. [80] and Salas-Olmedo et al. [81]. The main issues are summarised below, following the structure shown in Figure 1.

The **external scenarios** are a necessary input for the MARS model. These include a number of variables in relation to demographic growth, transport data and land use development that can be collected via the local statistic census or mobility surveys. Those variables related to the future growth projections are generally obtained from the institutional data sources. It is not the aim of the model to predict the population or the economic growth but to allocate residents and workplaces depending on the growth scenario and the accessibility provided by the transport sub-model.

The **policy instruments** are policy interventions to be evaluated. They are considered as another input for the MARS model, since they modify the conditions of the land use sub-model or the transport sub-model. Each policy measure needs to be defined in the terms of the implementation period, geographical scale and intensity.

The **transport sub-model** in the MARS model needs to be complemented by another specific transport model, as the model is an aggregated LUTI model and does not include a transport network. The complementary model, representing the road and public transport network, provides the necessary data to build the transport sub-model in the MARS: travel times, distances and speeds between the different zones and for different modes at peak and off-peak hours. The transport sub-model in the MARS contains three stages: trip generation, trip distribution and modal split. The fourth stage, route assignment, which is characteristic of traditional transport models, is not present in the MARS model.

- The **trip generation** stage considers two types of trip purposes: work and others. This stage follows the overall principle of constant time budgets, supported by many studies [82–85]. The work-oriented trips, termed Home–Work–Home (HWH), generated in each zone i depend on the number of employed residents in the zone and on the average trip rate per person (Equation (A1)). The trips related to other purposes, termed Home–Other activities–Home (HOH), depend on the travel time available per person, which is calculated after the trips to work have been generated and distributed. The total travel time per capita and day is assumed to be constant.

$$P_i|_{HWH} = r|_{HWH} * E_i \qquad (A1)$$

where $P_i|_{HWH}$ is the production of trips at zone i for tours HWH; $r|_{HWH}$ is the average trip rate per person for tours HWH, and E_i is the number of employed residents living in zone i.

- The **trip distribution** and **modal split** take place simultaneously in the transport sub-model, using a combination of the analogy to the law of gravity and Kirchoff's law from electrical engineering [32]. The trip attraction and mode choice is divided into HWH and HOH trips. The attraction of each zone, j, as a destination is given by the land use sub-model and depends on the activity for which the destination is chosen. For the trips HWH, the attraction depends on the number of workplaces in the destination zone. For the trips HOH, the attraction depends on the population living in the destination zone, and the existence of activities such as retail. Travel times and travel costs per mode and Origin-Destination (OD) pair give the different friction factors. Equation (A2) describes these simultaneous stages.

$$T_{ij}^{m,p} = \left[P_i * \frac{A_j/f\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)}{\sum_{mj} A_j/f\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)} \right]_{HWH} + \left[P_i * \frac{A_j/f\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)}{\sum_{mj} A_j/f\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)} \right]_{HOH} \qquad (A2)$$

where $T_{ij}^{m,p}$ is the number of trips by mode m from zone i to destination j during the p period (peak or off peak hours); P_i is the production of trips at zone i, A_j is the attraction of zone j as a destination; and $f\left(t_{ij}^{m,p}, c_{ij}^{m,p}\right)$ is the friction factor for a trip by mode m from zone i to destination j during the period p, including travel time $t_{ij}^{m,p}$ and travel costs $c_{ij}^{m,p}$ (which are calculated iteratively for the mode car, depending on the speed and the traffic flow).

The generation, distribution and modal split influence the **accessibility**, which is an input for the land use sub-model (Equation (A3)). One of the most important improvements in the model carried out during INSIGHT

project was the development of the accessibility measure. The accessibility indicator in the current version contemplates not only the accessibility-to-jobs but also the accessibility to schools and shops. These improvements in the MARS model are described in more detail in [80,81].

$$
\begin{aligned}
Acc_j(t) = \quad & \sum_t \sum_{j,m,P} \left[a_j * W_j^m(t) * F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right)_{\text{Work}} + b_j * Edu_j^m(t) \right. \\
& * F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right)_{\text{edu}} + c_j * Hea_j^m(t) * F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right)_{\text{health}} + d_j \\
& \left. * Park_j^m(t) * F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right)_{\text{Park}} + e_j * Shop_j^m(t) * F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right)_{\text{Shop}} \right]
\end{aligned}
\tag{A3}
$$

where $Acc_j(t)$ is the aggregated accessibility to workplaces and services; $W_j^m(t)$ is the number of jobs in the destination zone j by mode m in the year t; $Edu_j^m(t)$ is the number of schools in the destination zone j by mode m in the year t; $Hea_j^m(t)$ is the number of hospitals and health centres in the destination zone j by mode m in year t; $Park_j^m(t)$ is the number of parks in the destination zone j by mode m in year t; and $F\left(t_{ij}^{m,P}, c_{ij}^{m,P}\right) = Exp\left[-0.0163 * (c_{ij}^{m,P}(t) + t_{ij}^{m,P}(t) * Time\ value^P\right]$ is the generalised cost to reach jobs or the respective public service from i to j in the mode m and in the period p, calibrating the value of time on the basis of the mobility surveys.

The **land use sub-model** comprises a module for the location of residents and another for the location of workplaces. The sub-model allocates residents and workplaces in the different zones considering the willingness to move in and out of each zone and the supply-demand balance. Equations (A4) and (A5) represent the calculation for the residents moving out and intending to move in.

$$
N_j^{mv} = P^{mv}(t) * \frac{a^{mv} * e^{b^{mv} * Acc_j(t) + c^{mv} ShGr_j(t) + d^{mv} * R_j^D(t)}}{\sum_j a^{mv} * e^{b^{mv} * Acc_j(t) + c^{mv} ShGr_j(t) + d^{mv} * R_j^D(t)}}
\tag{A4}
$$

where N_j^{mv} is the number of residents demanding a living place in zone j in the year t; $P^{mv}(t) = \frac{N^R(t)}{\Delta T^{mv}}$ is the potential number of residents moving out, which depends on the total number of residents in the study area ($N^R(t)$) and the average time living at the same residence (T^{mv}); $Acc_j(t)$ is the aggregated accessibility to different activities in zone j in the year t; $ShGr(t)$ is the share of Greenland in zone j in the year t; $R_j^D(t)$ is the monthly rent for a domicile in zone j in the year t; and a^{mv}, b^{mv}, c^{mv}, and d^{mv} are parameters derived from a regression analysis using observed data and calibration.

$$
\begin{aligned}
N_j^{in} &= P^{in}(t) * \frac{\frac{A_j^{in}(t)}{f\left(Z_j^{in}(t)\right)}}{\frac{\sum_j A_j^{in}(t)}{f\left(Z_j^{in}(t)\right)}} \\
&= P^{in}(t) * \frac{a^{in} * e^{b^{in} * Acc_j(t) + ShGr_j(t) * (c^{in} * ShGr_j(t) + d^{in}) + e^{in} * R_j^D(t)}}{\sum_j a^{in} * e^{b^{in} * Acc_j(t) + ShGr_j(t) * (c^{in} * ShGr_j(t) + d^{in}) + e^{in} * R_j^D(t)}}
\end{aligned}
\tag{A5}
$$

where $N_j^{in}(t)$ is the number of residents demanding a living place in zone j in the year t; $P^{in}(t)$ is the total demand for living places which can be satisfied in the year t; $A_j^{in}(t)$ is the attraction to move into zone *j* in the year t; and $f(Z_j^{in}(t))$ is the friction factor, a^{in}, b^{in}, c^{in}, d^{in}, and e^{in} are parameters derived from a regression analysis using observed data and calibration.

The **location of households and workplaces** is an output from the land use sub-model, which affects to the attraction and generation of trips and to the accessibility of each zone.

The different parameters are obtained in the calibration process. The quality of the input data is essential in this stage. A summary of the different data sources used is provided in Section 2.2.2.

The transport and land use sub-models are executed iteratively over a certain period of years. The results of the simulations in terms of variables and indicators are used for the policy assessment. Figures A1–A3 show some simplified causal loops for calculating some of them.
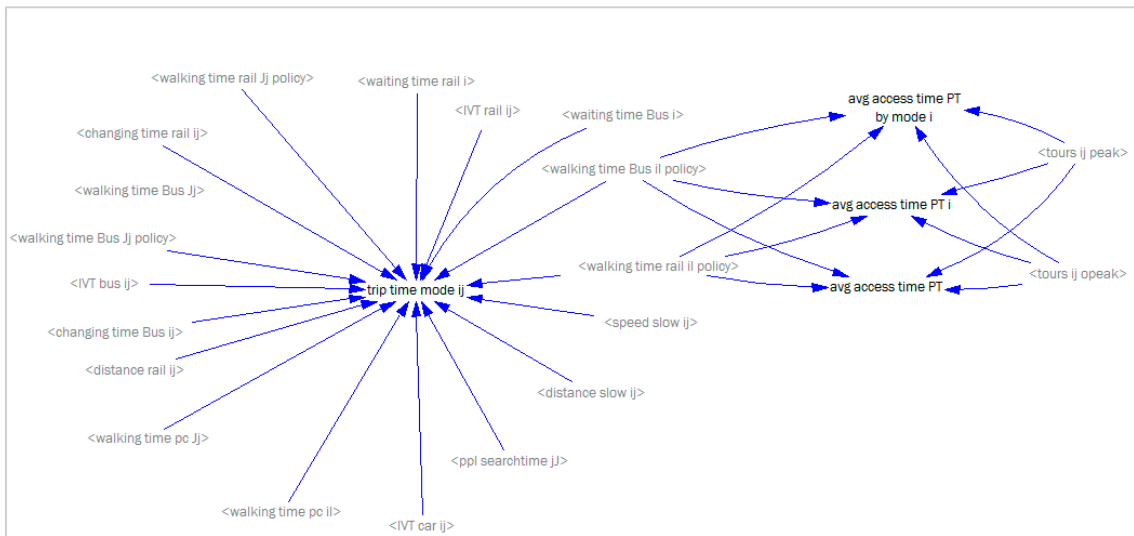
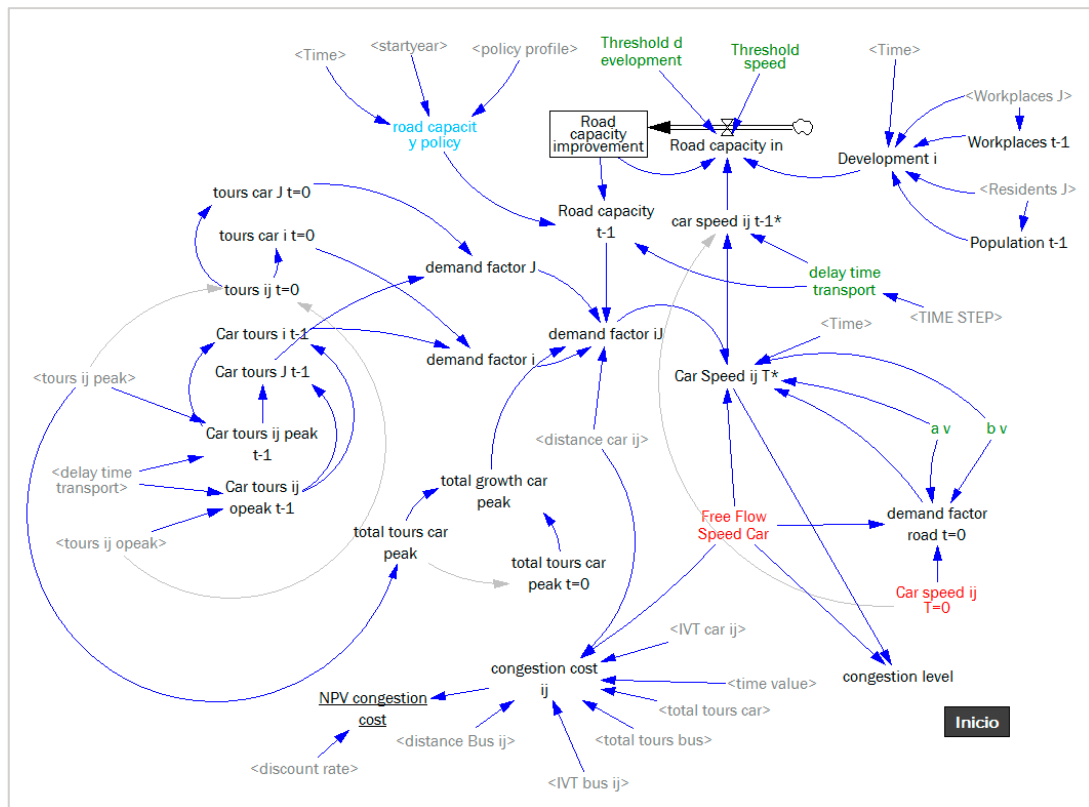**Figure A1.** Simplified causal loop diagram of time calculations in MARS model.

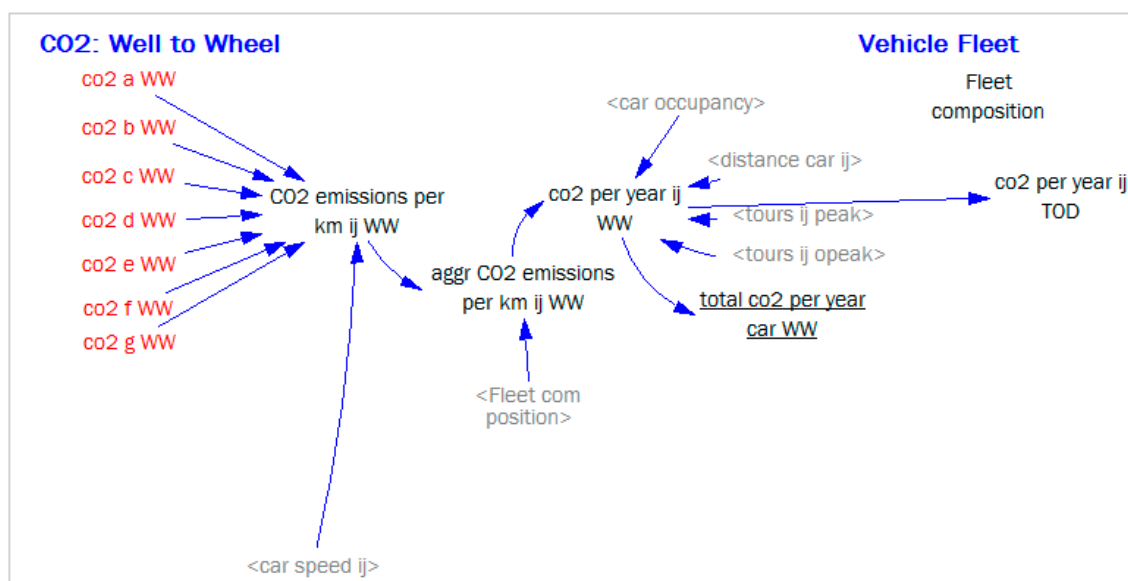**Figure A2.** Simplified causal loop diagram of speed calculations in MARS model.

Figure A3. Simplified causal loop diagram of cars CO_2 calculations in MARS model.

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