

10 CONCLUSIONS AND FUTURE RESEARCH

This chapter presents a general discussion of the main findings of this thesis. It describes how each publication of this document contributes to fulfilling the research objectives and answering the research questions. Likewise, recommendations for transportation planners and policy makers are proposed. Finally, future research avenues that would complement the results of this dissertation are identified.

10.1 Fulfillment of research objectives

Chapter 3 of this thesis *Objectives and research questions* presented the main objective of this research, which is **to gain a deeper insight into the real acceptance of a variety of TDM measures in suburban environments with both free and toll highway alternatives.**

This general objective has been divided into five more specific objectives. Below, the specific objectives are detailed again, and an explanation is given on how they have been fulfilled:

- 1) To study empirically the acceptance of both push and pull measures in parallel.

Regarding the **first objective**, a great effort has been made during the course of the research to obtain large empirical databases that make it possible to ascertain the real behavior of travelers when facing TDM actions already implemented. To determine the acceptance of those measures that are not currently implemented, a questionnaire was distributed among travelers on a specific transport corridor. Surveyed people were not asked about their support for these measures (acceptability) but about their willingness to use them (acceptance). Two of the proposed initiatives are monetary-related, which made it possible to examine travelers' willingness to pay for them.

- 2) To analyze to what extent different TDM initiatives induce a route or modal shift in suburban trips.

This **second objective** has been achieved mainly through the estimation of discrete choice models (DCM). In the models developed in Papers I, III, and IV, the dependent variable consisted of different transport modes or route alternatives chosen, and the TDM action to be analyzed is the main independent variable. In paper II, the dependent variable is travelers' willingness to adopt the new measure in their trips to Madrid City. A DCM framework is also employed for that purpose. However, in this case, it was also possible to estimate modal shift since the mode of transport currently used by the traveler was included in the model as one of the independent variables.

- 3) To explore empirically the influence of real-time information on route choice when alternative toll roads are available.

The **third objective** pursues to base the results of this thesis on empirical traveler behavior as much as possible. To that end, Papers III and IV have explored changes in route choice at the grouped level (traffic flows) and the

individual level (drivers) respectively, when different real messages have been displayed on VMS panels.

- 4) To explore opportunities to make better use of the capacity of the highway network when there is a toll expressway with excess capacity.

Concerning the **fourth objective**, this thesis has explored two different types of measures that could potentially improve the underutilization of toll expressways competing with parallel high-capacity highways experiencing congestion. First, Paper II has proposed two ad hoc monetary incentives designed to incentivize the use of the toll road among suburban residents. Second, Paper III explored the role that ATIS can play in enhancing the performance of the road network in that context.

- 5) To provide a set of recommendations on the implementation and assessment of TDM measures in suburban areas addressed to transportation planners and policy makers.

The **fifth objective** is a cross-cutting goal. Based on the findings derived from this research work, this thesis proposes a set of practice-oriented recommendations -see Section 10.3 below. These suggestions aim to guide policy makers in the evaluation of TDM and to advise them when they face situations or scenarios similar to those addressed in this thesis.

10.2 Research findings and contribution of each article to the thesis' goals

As noted above, the literature has concluded that there is a need to study the acceptance of various mobility strategies in parallel. This stems from the fact that the combined implementation of TDM measures of different nature is the most effective policy when it comes to orienting travelers' behavior. Therefore, it makes sense to explore the acceptance towards three different TDM strategies within the context of this dissertation.

To fulfill the objectives of this thesis, one general research question (GR0: *How do different TDM measures affect suburban mobility?*) and four specific research questions (RQ1-RQ4) have been formulated. The general question is addressed by answering the specific questions. Below, **Table 10.1** summarizes the contribution of each article of this thesis in answering the proposed research questions.

Table 10.1 Contribution of each article to the achievement of the objectives

			Paper I	Paper II	Paper III	Paper IV
MAIN OBJECTIVE	To gain a deeper insight into the real acceptance of a variety of TDM measures in suburban environments with both free and toll highway alternatives	GRQ0	X			
		RQ1				
		RQ2		X		
		RQ3		X		
		RQ4		X	X	X

In the following paragraphs, the main results of this thesis are explained by answering each of the specific research questions.

RQ1 What is the real acceptance of “push policies” implemented in the core of metropolitan areas for travelers making suburban trips? Are these measures effective in promoting a modal shift towards more sustainable transport alternatives?

This research question has been answered in Paper I. Multinomial logit models have been developed to estimate the effect of two measures arising from the activation of the Madrid NO₂ protocol: reduction of speed limits in the highways accessing Madrid city and on-street parking restrictions in the most central area of the city. These measures have significant effects on mode choice in the expected direction, at least in the case of the Eastern Corridor. It is observed that modal shift is slightly higher in the municipality closer to Madrid (Rivas), which may be due to its greater public transport supply and shorter trip distance. Nevertheless, the effect size is quite low in both towns (Rivas and Arganda), implying that the changes in mode shares are very low. There seems to be a larger effect with driving restrictions that are more difficult to circumvent, although this measure has been activated only a handful of days and this does not make it possible to confirm this result. Finally, an examination of the use of different types of public transport tickets suggests that drivers who normally use their car to get to Madrid do not shift to public transport when the NO₂ protocol scenarios are activated.

Although these measures fall within the group of push policies, they cannot be considered overly restrictive. Drivers may circumvent the general ban on on-street parking without shifting to another mode of transport in several ways -e.g., by choosing off-street parking or by parking their vehicles just near the border of the restricted area. The latter is in line with the findings reported by Borge et al., (2018) for the case of Madrid. These authors observed a drop in pollutants in the area where on-street parking was forbidden but an increase in NO₂ concentration outside that area. Therefore, when designing restrictive measures, it is important to explore how drivers may circumvent them and to look at potential side effects.

RQ2: What is the level of acceptance of congestion-calming measures? What is the difference in the acceptance of commuters of a metropolitan corridor towards public transport improvements, compared to incentives to use an underutilized toll expressway?

This question has been answered by the results of Paper II. Although in this context both measures are pull policies, there are notable differences in the acceptance of both approaches. Based on a SP questionnaire carried out among drivers in the Madrid Eastern Corridor (Case Study 1), it is observed that they are more willing to use the two proposed transit improvements (the implementation of express bus services and the removal of a transfer in the metro service) compared to toll road incentives (discounts for carpoolers and flat-monthly fee pass). In fact, the combination of measures receiving the highest support is the acceptance of the two transit-related initiatives and the disregard of the two toll-related measures.

This difference implies that public transport measures would be more effective in mitigating congestion on the free highway as they would encourage a higher proportion of drivers to use alternative options.

Interestingly, the acceptance of carpool-related discounts is low. Several results of the study point out that the reason is not only low willingness to pay but also low willingness to share a vehicle with a stranger. For example, up to 21% of respondents rejected this discount measure but would adopt the alternative monetary incentive proposed in the SP experiment.

RQ3: Which factors influence the acceptance of TDM policies aimed at mitigating congestion and encouraging travelers to adopt more sustainable behaviors in suburban trips?

This research question is addressed in Paper II. With regard to the factors influencing the level of adoption of pull policies, the main conclusion obtained from this analysis is that trip-related attributes play a greater role than socioeconomic characteristics of travelers. In particular, there are significant differences in travelers' responses depending on the current mode of transport used and the trip frequency. This outcome makes sense given that the mode the traveler use regularly influences the mode she/he would choose in a hypothetical election. In this line, the group of respondents who state that they would not adopt any of the measures proposed are predominantly composed of motorists who drive their own vehicle regularly.

Concerning toll-road incentives, their low acceptance may be due to the fact that travelers reject any measure that implies an extra monetary payment when a free alternative is available. Previous knowledge of toll rates is negatively related to the

willingness to purchase monthly passes. However, this aspect requires further study to understand the causes of this relationship.

Finally, certain geographic variables also showed to influence the success of TDM measures, especially with regard to express bus services, where transport accessibility plays an important role. This finding is supported by Guo et al. (2021) and Habibian and Kermanshah (2013). According to the results of this thesis, this service should be designed: i) complementing the current rail mode accessibility, rather than duplicating it, and ii) allowing its terminal bus stop within the main city to reach the maximum number of destinations of the corridor's passengers in the fastest way.

RQ4: Is it possible to promote a more balanced distribution of traffic flows between a highway congested at peak hours and a parallel toll expressway with excess capacity via transport demand management policies? Which role could real-time information play in this distribution?

The measures analyzed in this thesis to mitigate congestion and achieve a more efficient distribution are incentives to increase toll road demand (addressed in Paper II) and the provision of real-time information (covered in Papers III and IV).

On the one hand, the acceptance (i.e., willingness to use) of monetary toll-road incentives is not particularly high (<40%) taking into account that they are toll discounts and that respondents were free to set a level of discount considered appealing. Although, as mentioned above, they are not the most effective policy to reduce congestion on the free highway, these incentives may contribute to increasing traffic demand for toll roads, at least in the specific case of Madrid.

On the other hand, the impact of real-time information has been analyzed by using messages displayed on a VMS panel to drivers in two different case studies (Case Study 1 and Case Study 2). Route choice has then been studied through the use of binary logit models with fixed parameters and random parameters.

According to the modeling results, real-time information can influence drivers' choices between two high-capacity roads even when one of the alternatives is charged. One of the most notable findings of Paper III is that the impact of traffic conditions messages on route choice depends on the day of the week. This means that the same message has different effects depending on whether it is displayed on weekdays or weekends. These variations may be due to the different types of drivers in the corridor. Commuters are more frequent on weekdays while motorists driving for recreational purposes may be prevalent in Sunday trips. Lastly, adding quantitative information (travel time estimates) to qualitative information on

delays on the free highway seems to increase diversion to the toll road compared to only displaying qualitative information.

Based on individual data, Paper IV also concludes that travel time estimates influence route choice but in a different scenario. In this case, drivers can choose between a high-capacity toll highway and a two-lane road. However, unlike Paper III, qualitative information does not seem to have an influence on the route choice. This may be due to the fact that in Case Study 2 there is a greater difference between the travel times of the two alternatives. Finally, there is heterogeneity in the way drivers perceive the travel time estimates displayed in a VMS panel. This supports the idea of displaying information customized to each driver (e.g., through in-vehicle devices).

The fact that the results of Papers III and IV are not fully equivalent is not necessarily a discrepancy. This may be due to the differences between the two case studies explored in this thesis. Therefore, it can be concluded that the context in which real-time information is provided to drivers is an aspect that should be considered in the design of the format and content of the messages.

10.3 Policy implications and recommendations

Understanding how travelers behave before and after implementing transportation measures and knowing the most effective tools in managing transport demand are highly valuable insights for transportation planners and policy makers. Therefore, based on the results of this thesis and the research process, the document discusses and proposes a series of lessons and policy recommendations, which are presented in the following paragraphs.

The **first policy implication** concerns the allocation of public funds with the aim of reducing congestion. In view of the findings of the thesis, **it seems more efficient to allocate public resources to metropolitan transit improvements** than to subsidize discounts on toll roads in terms of congestion mitigation.

As previously mentioned, an existing transport corridor in Madrid already has a HOV lane in operation for more than 25 years and has proven to be a successful measure. Nowadays, a HOV lane in the A-2 corridor using ITS is in the design and implementation phase. The **results of this thesis support the need to invest in bus lanes or HOT lanes on highways** accessing the city of Madrid (and similar cities). This turns the bus more attractive, and it makes it possible to create express metropolitan services that have a high willingness to be used.

The **second policy lesson** is related to road planning and design. Some results of this thesis support the importance of estimating travel time savings and forecasting trip origins and destinations when designing new roads, especially when it comes to toll highways. It has been found that, at least in the case of the Madrid Eastern Corridor, travel times on the two road alternatives are not different enough in off-peak periods to encourage drivers to use the tolled alternative. Even for some origin-destination routes, the travel time offered by the toll road is higher. This may explain why the measures proposed to improve traffic distribution between the two roads—real-time information and toll road incentives—have shown modest effectiveness. The above mentioned findings evidence **the importance of investing money wisely in feasibility studies based on technical and objective criteria** when building new transport infrastructure.

Once the toll road is already built, the issue of low demand should be addressed through the pricing scheme. At the time the data were collected in Case Study 1, two different levels of toll rates—peak and off-peak—were applied following a predetermined time-dependent schedule. Currently, these highways are toll-free at night and have a fixed rate during the day. To enhance the market share of tolled infrastructure, **the implementation of a demand-responsive scheme should be explored**. This dynamic pricing system is applied in many HOT facilities in the US (de Palma and Lindsey, 2011). It is based on rates that vary dynamically according to the level of service on the free alternative. This scheme would require providing drivers with information on variable fares (either through VMS or in-vehicle devices) before they choose their route.

The **third policy recommendation** addresses one of the major culprits of congestion: the low occupancy of private vehicles. Besides the low willingness to pay tolls, this thesis also identifies the low willingness to share a vehicle with a stranger. Since the 1970s different initiatives with more or less success have appeared to promote carpooling (Chan and Shaheen, 2012). For instance, HOV lanes gave rise to casual carpooling or slugging in some American cities (Washington D.C., San Francisco, and Houston). This practice involves single drivers increasing the occupancy of their vehicles by picking up passengers at transit stops and thus meeting the criteria for using HOV lanes. Carpooling web-based platforms such as BlaBlaCar have been successful in recent years in the intercity context. However, in urban or metropolitan trips in Spain (as well as in other countries), drivers do not tend to share their vehicles with non-household carpoolers. For instance, the car occupancy rate was estimated in Madrid City to range from 1.1 to 1.35 (Ayuntamiento de Madrid, 2014). In response to this problem, some start-up companies have emerged (e.g., HOOP Carpool) offering the opportunity to match

travelers who wish to share their private car rides in the urban or metropolitan context. This could increase support for carpooling and reduce the initial reluctance of many drivers. **Local and regional authorities should support these entrepreneurial ventures on the grounds of the societal benefits coming from a higher vehicle occupancy.**

Additionally, the literature review has pointed out that monetary savings are the main motivation that prompts travelers to opt for ridesharing (Abrahamse and Keall, 2012; Delhomme and Gheorghiu, 2016). Therefore, it can be assumed that carpoolers would seek a discount of 100% on the toll rate to use the road. In this sense, **other monetary incentives than those proposed in this thesis may be more effective in promoting the use of carpooling**, such as discounts on parking rates, as shown by Javid et al. (2017).

The **fourth policy recommendation** deals with the provision of real-time information to drivers. Based on the results of the thesis, **messages displayed to drivers** on either roadside panels or in-vehicle devices **should be differentiated according to the day of the week, the type of driver, or the nature of the alternatives** (a toll-highway, a toll-free highway, a two-lane road). Drivers who are less familiar with the road network respond differently to traffic information and travel time estimates. This result is supported by e.g. Ben-Elia and Shiftan (2010) and Wardman et al. (1997). Since these drivers are less aware of the average travel time on the road, a better practice would be to provide them with delay estimates rather than travel time estimates.

The **fifth policy lesson** concerns push policies. Measures that can be easily circumvented may involve moving the problem to another location. If a modal shift towards more sustainable alternatives is really pursued, **these measures should be designed in such a way that they are not easy to circumvent**, as is the case with on-street parking restrictions.

The **last recommendation** is addressed to traffic authorities and departments of transportation. As previously noted, this thesis has sought to gain insight into the actual response of travelers to various TDM measures. To this end, the analyses have been based on empirical data whenever possible. Two of the papers included in this thesis have made use of loop detector data to explore dynamics of actual traffic flows. This data source was useful since it provided real drivers' behavior at a grouped level. However, in this case, data availability depends heavily on the condition of these devices. During the course of the research, some time periods had to be discarded due to operational failures of the sensors. **In order to obtain high-quality and continuous data sets enabling to measure the actual efficiency of**

different TDM measures, road administrations and traffic authorities should carry out regular maintenance of these devices. In addition, this practice would benefit traffic control and management.

In addition, further efforts should be made to put these data publicly available as it would make it easier and faster for researchers to analyze the real acceptance of transport policies, with clear benefits for the scientific knowledge and the society.

10.4 Summary of contributions

This thesis sheds additional light on the acceptance of various TDM measures and their potential to promote more sustainable behaviors among travelers in the metropolitan context. It has focused on trips within the metropolitan ring (metropolitan area excluding the main city) and trips from suburbs to the city center. These types of trips are worth exploring since they show lower sustainable mobility patterns, present higher levels of congestion, and have been paid less specific attention in the TDM literature compared to e.g., urban or intra-city trips.

As regards methodology, this thesis has been based as much as possible on empirical data, which is a novel approach for some of the TDM measures considered. This procedure reduces or removes potential bias in modeling estimates compared to e.g., stated preference experiments, and leads to a real-world picture of the effectiveness of TDM measures.

In addition, this dissertation aims to identify solutions to the inefficient distribution of traffic between roads within transportation corridors that include toll highways. To this end, two alternatives have been considered, both of which are a novelty in the TDM literature. First, monetary incentives for tolls are analyzed and their acceptability is compared with transit improvements. And second, this thesis empirically explores the role of real-time information in traffic distribution within these corridors.

10.5 Further research avenues

The results of this thesis are relevant and add insight to the research gaps identified in the literature review. Nevertheless, due to scope or methodological limitations, some issues arise which deserve further research. The areas for further work to expand the current research are proposed below:

- 1) First, it is necessary to be cautious in extrapolating the findings of this thesis to other different locations. The results of this thesis are influenced by context-related factors of the selected case studies such as the supply of

public transport and its share in the modal split, the familiarity of paying (or not) tolls when driving, and the level of existing congestion in the metropolitan area. Though the Madrid Metropolitan Area experienced congestion in the period analyzed in this dissertation, congestion levels were less severe compared to other cities worldwide. One might expect that the acceptance of congestion-calming measures may be higher in cities where congestion problems are much worse.

Furthermore, the low willingness to pay observed among the citizens of the MMA, and consequently the low acceptance of toll-road incentives, could be due to the limited habit of drivers from Madrid to pay tolls in the urban area. Therefore, it may be expected that the acceptance results would be different in cities without free high-quality alternatives or with an extensive road pricing system.

The results are likely to be similar for other European cities as they have comparable mobility patterns. However, it is worthwhile to replicate this analysis in metropolitan areas with different mobility characteristics. This might be the case of American cities where the share of transit use is much lower and metropolitan toll facilities are more usual compared to the European context.

- 2) Using only real-world data makes it more difficult to analyze the effect of the joint implementation of pull and push measures. The joint analysis would require empirical data from three different periods of time: when no measure is implemented, when one type of measure is implemented, and when both types of measures are implemented. This problem has been approached in several studies by conducting stated preference surveys (see e.g., Habibian and Kermanshah, 2013; O'Fallon et al., 2004). Therefore, this research avenue is still pending.
- 3) To explore the acceptance of hypothetical pull measures, a SP survey was conducted among travelers. The results show a strong acceptance of the measures, especially for transit-related measures. A good approach would be to complement these results with a pilot experiment in collaboration with public transport administrations and traffic authorities. This would make it possible to validate the results of this study.
- 4) Regarding real-time information, this thesis has only addressed its influence on the private vehicle mode. Other studies have looked at the impact of real-time information provided to users of public transport through e.g. mobile applications (see e.g., Romero et al., 2021). In this sense, this research avenue

can be pursued by analyzing the role of ATIS within a multimodal approach (e.g., messages to drivers about the occupancy of park and ride facilities) based on real-world data.

- 5) All the analyses performed in this thesis are based on data prior to the COVID-19. However, the pandemic has strongly impacted urban mobility patterns. It can be expected that travelers' perceptions on using public transport or sharing a ride may have been affected (Dong et al., 2021; Przybylowski et al., 2021). Once the health crisis stabilizes, it would be interesting to assess whether the findings of different TDM studies, in particular those explored in this thesis, have been affected.

The explanatory power of some of the discrete choice models estimated in this thesis is not as high as that found in other previous studies also using this technique. This is partially due to the employment of empirical data. In any case, values similar to those achieved by the models developed in this thesis can be found in other transportation papers (Börjesson et al., 2015; Bueno et al., 2017b). Odeck and Kjekreit (2010) point out that values between 5% and 10% may be acceptable. Furthermore, some authors place limits on the importance of the different pseudo R^2 measures (likelihood ratio measures) when the regressand is categorical (Gujarati and Porter, 2009; Train, 2009). Additional research avenues aimed at improving the explanatory power of the models are presented below.

- 6) One of the sub-objectives of this thesis is to elicit actual traveler behaviors by employing empirical data, as much as possible. This has often required the use of information from e.g., sensor or count databases, which typically only collect information at an aggregated level. By opting for this approach, it has not been possible to incorporate information at the individual level, such as socioeconomic characteristics of the travelers. Therefore, an effort should be made to combine these real-world data sources so as to capture true behaviors at the macro level, with other databases that can provide more detailed information at the individual level, such as characteristics of vehicles and travelers. It is expected that these new sources can increase the explanatory power of the models. Among the data sources that could be used, smart transit cards and information on vehicles held by the traffic authority present a higher potential given that they can provide detailed input on e.g., residential location, car make and model, type of vehicle. At this point, special care should be taken with data privacy.
- 7) The literature review has shown the importance of attitudinal factors in explaining both the acceptability and acceptance of different TDM strategies.

To this end, empirical data should be complemented with additional questionnaires addressing these types of variables. In this case, the analyses could be complemented with more complex econometric specifications such as latent class models and structural equation models, so as to incorporate individuals' preferences, beliefs, and psychological variables in the modeling. These variables are expected to significantly increase the explanatory power of the analysis given their importance in other areas of transportation research.

ACRONYMS AND ABBREVIATIONS

AADT:	Average annual daily traffic
ATIS:	Advanced Traveler Information System
CRTM:	Consortio Regional de Transportes de Madrid (Public Transport Authority of Madrid Region)
DCM:	Discrete Choice Models
DGT:	Dirección General de Tráfico (Spanish Traffic Authority)
EU:	European Union
HOT:	High Occupancy Toll
HOV:	High Occupancy Vehicle
ITS:	Intelligent Transportation Systems
LPR:	License Plate Recognition
LEZ:	Low Emission Zone
MMA:	Madrid Metropolitan Area
PM:	Particulate matter
RP:	Revealed preferences
SDG:	Sustainable Development Goals
SP:	Stated preferences
TDM:	Transportation Demand Management
UN:	United Nations
VMS:	Variable Message Sign
VMT	Vehicle miles traveled
WHO:	World Health Organization
WTP:	Willingness To Pay

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ANNEX I DISSEMINATION OF RESULTS

In addition to the three publications in high-impact journals, the content of the doctoral thesis has also been presented at international academic conferences:

- (1) Romero, F., Gómez, J., Rangel, T., Vassallo, J.M., Jurado-Piña, R., 2019. The impact of real-time information on route choice between a toll highway and a free competing alternative. *Transportation Research Board 98th Annual Meeting*, January 13th-17th, 2019, Washington D.C., US.
- (2) Romero, F., Gómez, J., Rangel, T., Vassallo, J.M., 2020. Is there a modal shift due to transport restrictions aimed at mitigating NO₂ episodes? Case study of a commuting corridor in Madrid Metropolitan Area. *8th Transportation Research Arena*, April 27th-30th, 2020, Helsinki, Finland (Cancelled).
- (3) Romero, F., Gómez, J., Páez, A., Vassallo, J.M., 2021. Comparing solutions to relieve congestion in metropolitan areas: road pricing or transit improvements? A case study in Madrid. *Transportation Research Board 100th Annual Meeting*, January 21st-29th, 2021.