sustainability

MDPI

Article

A Model to Evaluate the Effect of Urban Road Pricing on Traffic Speed and Congestion in Madrid City Center and Its Surrounding

Juan Pedro Muñoz Miguel [1,*], Ana Elizabeth García Sipols [2], Clara Simón de Blas [3] and Francisca Anguita Rodríguez [1]

1 Department of Business Economics, Faculty of Social Sciences, Rey Juan Carlos University, 28933 Madrid, Spain; francisca.anguita@urjc.es
2 Department of Applied Mathematics, Science and Engineering of Materials and Electronic Technology, Rey Juan Carlos University, 28933 Madrid, Spain; anaelizabeth.garcia@urjc.es
3 Department of Statistics and Computer Science, Technical School of Computer Engineering, Rey Juan Carlos University, 28933 Madrid, Spain; clara.simon@urjc.es
* Correspondence: juanpedro.munoz@urjc.es

Abstract: Currently, traffic intensity in large cities and their surroundings constitute the main unsustainability factor associated with urban transport, leading to significant traffic speed reduction due to high levels of congestion. Road pricing seems to be a measure of transport policy capable of improving efficiency and sustainability in urban transport, reducing traffic intensity and increasing traffic speed, as reflected in the main road pricing indicators currently in operation (Singapore, London, Stockholm, Milan . . .). Based on the data obtained through a mobility survey applied to a theoretical design of road pricing for the city of Madrid, we developed a traffic speed forecast model using time series analysis, to which we applied the mobility survey results. The research results show that theoretical urban road pricing could imply very significant positive effects in traffic speed increase and congestion reduction, fundamentally in the city center and metropolitan crown, as well as demonstrating positive effects in the improvement of traffic speed in those municipalities furthest from the urban center. Moreover, our findings reveal that road pricing would allow an average traffic speed increase in the protected area of the city center during the operating hours of between 10% and 32.5%: 15.9% in the metropolitan crown, 10% in M-30, and 32.5% in the case of Madrid's city center.

Keywords: road pricing; mobility behaviour; urban transport; traffic speed model; traffic congestion reduction

Citation: Muñoz Miguel, J.P.; García Sipols, A.E.; Simón de Blas, C.; Anguita Rodríguez, F. A Model to Evaluate the Effect of Urban Road Pricing on Traffic Speed and Congestion in Madrid City Center and Its Surrounding. *Sustainability* **2021**, *13*, 8415. https://doi.org/10.3390/su13158415

Academic Editors: Elżbieta Macioszek and Ralf Risser

Received: 10 May 2021
Accepted: 25 July 2021
Published: 28 July 2021

1. Introduction

Traffic density around large cities is one of the main problems associated with urban land use, transport and social well-being; therefore, it is necessary to seek an adequate balance between the land distribution and tolerance of congestion [1] that ensures greater efficiency in urban transport systems so that the social costs of transportation are equivalent to the social benefits that this system must provide to all citizens, thus allowing more sustainable urban development.

The high level of urban congestion resulting from urban transportation is a consequence of the growing phenomenon of suburbanization and decentralization of employment that affects most large cities [2]. This phenomenon multiplies the amount of displacement and contributes to imposing urban mobility behavior fundamentally based on the massive use of automobiles in the absence of competitive and accessible urban public transportation alternatives that are much more sustainable. This urban congestion, which we can call structural and difficult to solve in the short and medium terms, given the high supply of existing roads [3], has become the main focus of attention for the implementation of policies and measures by urban transport authorities in order to seek to ensure a proper balance between urban transport and sustainable land use. These measures, when applied with adequate social and political support, can form a high-quality and sustainable urban transport system [4]. These policies include urban road pricing, which is a measure with a high level of effectiveness in reducing the problems of traffic congestion and its externalities that improves the efficiency of urban transportation, as revealed by a large number of studies on the main congestion charging systems currently in operation [5–8]. Most of these investigations have attempted to study both the high capacity of these toll systems to promote a sustainable behavioral change in mobility and the possible adverse effects derived from the captivity that this measure may impose on certain travelers.

Urban road pricing makes it possible to achieve certain objectives as a consequence of traffic reduction such as environmental improvements, revenue generation, efficient urban transport and equity effects [9]. Furthermore, we must emphasize that in accordance with the sustainable development goals set out in the 2030 Agenda, specifically, goal 11 on "Sustainable Cities and Communities" aimed at achieving cities that are more inclusive, safe, resilient and sustainable [10], urban road pricing can contribute significantly to the fulfilment of this goal.0 These aspects and implications regarding road pricing have been the subject of a large number of studies focused on the main urban tolls in operation, such as the most traditional system in Singapore, the ALS and ERP system [11–13]; the congestion charge in London [14–16]; Stockholm road pricing [7,17,18]; and, more recently, Milan [19].

Despite a large number of studies on current urban road pricing systems in operation, these studies have not yet been able to offer exhaustive conclusions on the benefits that these systems provide, since they depend on multiple factors and variables (e.g., the design of the toll, the typology of each city, the application scope, tariffs, and the variability of the affected social groups). Nevertheless, it seems to be generally demonstrated that the social benefits due to increased traffic speed are higher than the payment of tariff tolls supported by drivers [20], as has been revealed after their implementation. Singapore's ALS system increased the average speed from 19 to 36 km per hour [21], and an additional increase of 22% was observed with the implementation of the ERP system in 1999 [22], the congestion charge of London increased the average traffic speed by between 14% and 21% [23], and the Stockholm congestion charge increased traffic speeds by approximately 32% measured in terms of reducing travel delays [7].

Studies on the acceptable average travel speed that is specified or should be specified in a road pricing system to reduce congestion in terms of increased travel speed are still scarce, despite its importance in practice. In most cases, these studies analyse traffic conditions and only consider the traffic speed variable as a measure of the performance provided by the system [24]. The case of the Singapore ALS and ERP system, whose priority objective is to set the average speed of vehicles, where initially the target speed range was defined as 45–65 km/h for expressways and 20–30 km/h for arterials and roads crossing the restricted zone cordon [25], has given rise to a set of studies on average traffic speed as a measurement variable of congestion. Examples include the model based on the elasticity of demand that assesses the response of car drivers to variable prices in the peak period based on the traffic intensity before and after the introduction of the ERP [26], the modelling methodology for the estimation and forecasting of the short-term impacts of traffic speed rate adjustments on peak period traffic volumes [27], and mathematical programming with equilibrium constraints (MPEC) models to maintain the average travel speed within a satisfactory range [24]. Likewise, some studies whose objective was to find the optimal toll tax based on traffic speeds and travel times stand out. Research on the monocentric toll system model proposed by De Lara et al. [28] for the Paris region concluded that the application of an optimal toll tax could reduce the level of congestion and increase traffic speeds in terms of the distance reduction of average travel by 34% and 15%, respectively.

Traffic intensity reduction as a priority objective of a road pricing system—a goal that is certainly easy to communicate—requires the use of models that make it possible to relate reduced traffic intensity with increased travel speeds [17]. The average travel speed is an ideal measure of traffic conditions in the study of road pricing. The measure is easier to appreciate than the traffic intensity and better represents the benefits obtained by car drivers in their travel times as a consequence of the road pricing system [29]. Increased travel speeds and reduced travel times are highly sensitive variables. Research on revealed preferences conducted by Abulibdeh [30] concluded that car drivers show a high degree of congestion tax acceptance if they obtain reduced travel times depending on the urgency of their trips as a benefit. In this sense, the purpose of our research has been to evaluate the average increase in traffic speeds due to a change in mobility behavior—reduced traffic intensity—as a consequence of the implementation of a theoretical pricing mechanism for urban roads in Spain and, more specifically, in the city of Madrid by applying a basic socially accepted toll tax as recommended by certain international pronouncements for the implementation of these toll systems (EUR 1.5 per access) [9].

Traffic intensity in Madrid is strongly linked to the phenomenon of residential and business dispersion towards suburban areas; furthermore, the city center continues to be the main center of attraction for journeys. This creates multiple spaces of mobility that constitute a complex, confusing and diverse structure [31], which is largely caused by the high number of both radial and orbital roads and increases the traffic density around the city center during peak hours [1]. Likewise, the lack of an adequate interurban public transportation policy has considerably increased the use of automobiles over time [3], fundamentally creating “inverse commuting” between the city center and suburban areas [32]. This context means that the traffic intensity and the traffic speed reduction in the urban center and metropolitan area constitute a progressive and unacceptable level of congestion because urban form changes have intensified journeys by automobiles, since public transportation is not competitive, which means that Madrid has a mobility situation far removed from sustainable urban development models, despite having achieved a certain balance between car use and public transportation [33,34]. A study of the road infrastructures available in Madrid reveals that only approximately 3% of roads experience 84% of the daily congestion during periods with the most congestion with average speeds below 40 km/h, mainly due to suburban trips through orbital roads and secondary roads bound for the city center as the main attraction center of journeys [35,36].

However, the opening of high occupancy lanes on radial roads would allow an effective modal shift towards public transportation, but this investment has been paralyzed by the lack of public funds [37] that, coupled with the mobility culture of Madrid citizens based on the use of the automobiles due to autonomy, prestige, and status [38], significantly aggravates the problem of congestion in the urban center. Given this situation, a recent study by A.T. Kearney [39] raised the need to apply a road pricing model to the orbital roads of Madrid for road maintenance given the current budget deficit of the state, which would also mean a significant increase in traffic speeds by between 33% and 53%. Likewise, research related to a simulation of urban road pricing applied to the case of Madrid for the 2012–2031 period by Alonso et al. [40] concluded that this measure can contribute to improving time efficiency, providing time savings in trips, reducing congestion, improving traffic flows at peak hours and increasing public transportation.

The situation described above for Madrid regarding current mobility behavior constitutes the main research argument of this article. Our research consists of analyzing and evaluating the possible effects and consequences that the implementation of urban road pricing could have on traffic intensity reductions and traffic speed increases in the city of Madrid. The research encompasses two main components. First, we designed a theoretical basic urban road pricing model, and we conducted a survey of Madrid citizens who travel using available urban transportation methods under the assumption of having to pay a toll tax to access the city center for their trips when automobiles are used as the transportation method. Second, we developed a prediction model through time series analysis, which allowed us to explain traffic speeds with respect to the variables of the traffic intensity, average level of occupation of public transportation and average level of atmospheric humidity. The model, thus defined, was used to predict the effects on traffic speeds both outside and inside of the proposed cordon toll in the city center by applying the data from the mobility survey. Likewise, it is important to highlight that regarding the design and application of the proposed urban road pricing model, we did not consider important issues in this research, such as those related to the problem of social acceptability or the accessibility of road infrastructures.

Three main contributions of this research are revealed. First, we assess the impact of the application of urban road pricing in Madrid on mobility behavior, a necessary measure that has not been previously addressed in the case of Spain and whose application is not foreseen by competent authorities due to the political implications of social acceptance that the measure would entail. Second, the research assesses the impact of urban road pricing with respect to traffic speed increases on reducing congestion. This aspect that we consider has not yet been sufficiently addressed by the literature. Third, we present a novel procedure based on the transfer function model that allows us to design alternative scenarios with respect to changes in predictable mobility demand. Furthermore, the model allows us to forecast the behavior of explanatory variables in the short term, providing useful information for early decision making on mobility behavior. Transfer function models are more efficient in predicting the long-term effects, and are an alternative to simple models that are not always the most suitable for forecasting, especially when additional information is available.

2. Survey: Methodology and Results

2.1. The Survey and Questionnaire

The methodology applied to the survey as the basis of our research is contained in Muñoz ([3], pp. 176–181, 186–189), and the results of the same are found in previous research by Muñoz et al. [37]. The survey was applied to a sample of 1298 citizens of the community of Madrid (see Appendix A) who made regular urban trips from Monday to Friday, which would be affected by hypothetical urban road pricing. The population studied through the sample was 4.6 million inhabitants. The theoretical operation of the system was established from Monday to Friday for periods with the most congestion (7:00 to 10:00 and 18:00 to 20:00). The items of the questionnaire that allowed us to assess the mobility behavior of those surveyed can be found in Muñoz et al. ([37], pp. 35–36), and show the number of cases surveyed, their percentages and the mobility alternatives chosen by those surveyed in the event that they are affected by the proposed toll tax. Specifically, the items of the questionnaire allow us to obtain information from respondents such as the following: their perceptions of the congestion problem in Madrid, their acceptance of a basic toll tax payment in order to reduce their travel times, current mobility alternatives and mobility alternatives chosen if the toll system is implemented.

The urban transport network in the Madrid region as a basis for proposing our urban road pricing has remained practically stable since 2008, due to the economic crisis. Two priority investments were halted: the creation of high occupancy lines, for the eight roads that connect periphery areas with the city center, and the expansion and intensification of interurban train lines. The urban transport network of the region is currently characterized by urban public transport for the city center, which is presently competitive, accessible and efficient, whereas the interurban transport in peripheral areas is inefficient and difficult to access; a factor that intensifies the use of the automobile for routes between peripheral areas and city center as the most efficient mode of transport, which causes structural congestion [3]. The toll tax applied to our urban road pricing would be a basic toll tax for citizen acceptance based on the pre-existing situation of the urban transport network. Significant changes in the urban transport network, such as the opening of high occupancy lines and the extension of interurban train lines mentioned above, would represent a turning point with respect to the application of a basic toll tax. The improved competitiveness, efficiency and accessibility of interurban public transport would lead to a higher toll tax or, alternatively, variable toll tax by areas depending on congestion levels, since car drivers would have other more efficient alternatives for interurban public transport modes that contribute to reducing their travel time.

Figure 1 shows a map of the region of Madrid where the areas under study in this research are reflected (Area A and Area B), along with the hypothetical cordon toll.

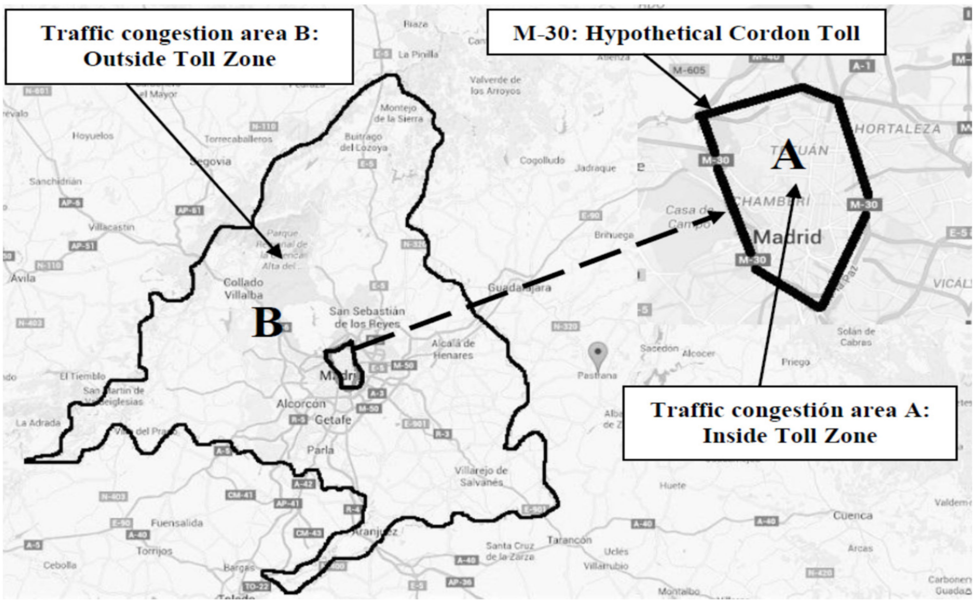

Figure 1. Theoretical road pricing and description of traffic speed areas subject of study by Muñoz et al. ([37], p. 25)] (Reprinted with permission from ref. [37]. Copyright 2021 Copyright Juan Pedro Muñoz). Area A: Average traffic speed associated with displacements with start and end points in A and displacements with start and end points in A and B or vice versa. Area B: Average traffic speed associated with displacements with start and end points in B and displacements with start and end points in A and B or vice versa.

2.2. Survey Results

The survey reveals that a total of 576 car drivers from the 1298 citizens surveyed are likely to increase the traffic intensity because of their urban journeys from Monday to Friday, and thus contribute to reducing the average traffic speed. One hundred and eighty of these drivers make their journeys entirely in zone A, 189 make their journeys with start and end points in zones A and B or vice versa and, finally, 207 drivers make their journeys entirely in zone B. The mobility situation of the car drivers surveyed after implementing the proposed road pricing, the adopted mobility behavior and its effect on reducing the traffic intensity for the areas under study is shown in Table 1.

The reduction in traffic intensity during the working hours of the toll system is shown in Table 2. A total of 60.1% of the car drivers surveyed who made their trips by car would be willing to change to other transportation modes during the operating hours of the proposed road pricing system. Most of these car drivers make their trips inside the city center and would be willing to shift to public transportation or even cycling or walking as a result of the better mobility conditions that road pricing would bring due to the expected decrease in traffic intensity (61.8%) inside the city center as a protected area.

Table 1. Mobility behavior of car drivers surveyed and their effect in traffic intensity reduction in areas A and B.

	Area A [1]		**Area B** [2]	
	Respondents	**%**	**Respondents**	**%**
Car drivers before road pricing	369	100.0%	396	100.0%
Mobility behavior after road pricing 1 = Car drivers	141	38.2%	158	39.9%
2 = Public transportation	130	35.2%	76	19.2%
3 = Non-motorized modes (bicycle or walk)	11	3.0%	0	0.0%
4 = Car drivers in radial displacements to access in area A by public transportation [3]	11	3.0%	26	6.6%
5 = Car drivers that changes to alternative route	0	0.0%	28	7.0%
6 = Car drivers who make their trips out of operating hours of road pricing	76	20.6%	108	27.3%
Traffic congestion reduction in charged periods	−228	−61.8%	−212	−60.1%v

Car drivers with radial displacements (189 users) cause traffic intensity increase in both area A and B. [1] Inside toll area: Car drivers with displacements entirely in area A (180) plus car drivers with radial displacements between areas A and B or vice versa (189). [2] Outside toll area: Car drivers with displacements entirely in area B (207) plus car drivers with radial displacements between areas A and B or vice versa (189). [3] Car drivers with radial displacements that contribute to traffic intensity reduction in area A due to changing to public transport within the cordon toll, but do not reduce traffic intensity in area B.

Table 2. Distribution on traffic congestion reduction in charged periods.

	Inside the Toll Zone		**Outside the Toll Zone**	
	Respondents	**%**	**Respondents**	**%**
Car drivers before road pricing	369	100.0%	396	100.0%
Traffic intensity reduction on charged periods	228	−61.8%	212	−60.1%
Effectively reduced traffic intensity (2+3+4 Table 1) [1]	152	−41.2%	76 [2]	−19.2%
Increase in use of public transport (2 Table 1)	130	35.2%	76	19.2%
Displaced traffic intensity (5+6 Table 1)	76	−20.6%	136	−40.9%

[1] Includes car drivers who change from automobiles to public transportation (130 car drivers in the case of inside the toll zone and 76 car drivers in the case of outside the toll zone), since, in both cases, they contribute to effectively reducing traffic congestion. [2] Those car drivers of radial shifts which access to the inside toll zone by public transport are not included, since they do not reduce traffic congestion outside the toll zone.

The effective reduction in traffic intensity (19.2%) outside the toll cordon area is due to car drivers that decide to shift to public transport, while the effective reduction in traffic intensity inside the toll cordon area (41.2%) is due to car drivers that decide to shift to public transportation and nonmotorized modes and those car drivers that are radially displaced that access the area inside the toll cordon using public transportation. The modal shift to public transportation provided by road pricing should be considered an increase in the level of occupation of public transportation, both interurban (19.2%) outside the toll cordon area and urban (35.2%) inside the toll cordon area.

Displaced traffic intensity as a consequence of those car drivers who choose to advance or postpone their usual trips to time when road pricing is not operating in order to avoid paying the toll tariff stands at 40.9% outside the toll cordon area and 20.6% inside the toll cordon area, respectively. This displaced traffic intensity constitutes a negative effect caused by the toll system and represents a potential risk of edge effects or barrier effects.

3. Estimation and Forecasting Model

3.1. Model Description

Using time series analysis and forecasting techniques, we developed a forecasting model for the congestion behavior due to increased traffic speeds as a consequence of implementing an urban toll system in Madrid and the traffic intensity reduction that would be provided by such a system.

As such, we explain the traffic speed variable (S_t) [41] as a function of the traffic intensity (C_t) [41]; atmospheric humidity (H_t) and average rainfall in Madrid per millimeter, since rain and fog, especially in Madrid, have a large impact on traffic jam increases and traffic speed reductions [42]; and the variable corresponding to the level of occupation of modes of public transportation (T_t)—buses, subways and trains [43]. The traffic speed variable (S_t) will be analyzed in two zones: inside M-30 and outside M-30. M-30 is the first orbital road closest to the urban center and is proposed to be located in the hypothetical toll cordon. Hence, the forecasting model was designed for two congestion zones: inside M-30 and outside M-30.

The proposed estimation and forecasting model follows the steps depicted in Figure 2.

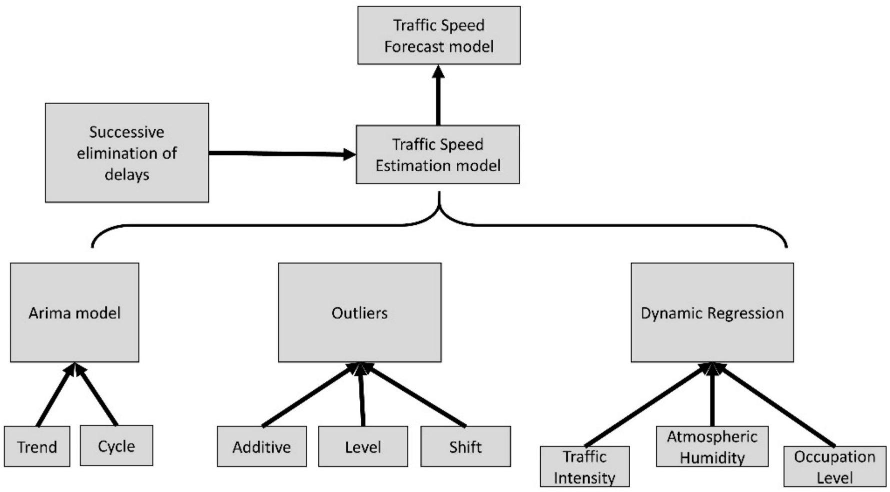

Figure 2. Estimation and forecasting model steps.

3.2. Dynamic Modelling

ARIMA is a modelization technique that allows the construction of models that collect observations of a phenomenon over time from a data set. These models are capable of capturing the trends and the cyclical seasonality of the data frame over the time period in the study. These models are usually represented as ARIMA(A,B,C), where A is the order of the autoregressive model (number of time periods the variable of interest is dependent on in previous occurrences), B is the necessary number of times the variable of interest must be differentially designed as a backshift operator (number of times the data have had past values subtracted) and C is the order of the moving average (number of time periods the errors of the model are a linear combination of the current error value). When seasonality is considered for these models, i.e., patterns observed in the same time periods over time, these models are extended as ARIMA(A,B,C) $\times$ (AS,BS,CS), where (AS,BS,CS) represents the seasonality parts of the model.

To validate the assumptions of the underlying model, the residuals, i.e., the differences between the predicted and real values, must follow a random process known as white noise, characterized by signal values at two different times not being statistically correlated.

3.3. Outliers

Time series analysis methods require the identification of outstanding data with respect to the data frame, referred to as outliers. These data in time series structures are considered deterministic, as they affect only the mean level of the series. It is common to classify perturbations as additive outliers (AOs), level shift (LS) outliers or transitory changes (TCs). Let y_t be the time series of interest. Assuming the observed data contain k outliers, their combined effect can be expressed as:

$$y_t = \sum_{i=1}^{k} \gamma_i(B) w_i I_t^{(\tau_i)} + z_t \quad (1)$$

where z_t follows the ARIMA process, w_i is the impact of outliers in the model at time $t = \tau_i$, $I_t^{(\tau_i)}$ is the indicator function that takes a value of 1 for $t = \tau_i$ and 0 otherwise, and $\gamma_i(B)$ is the outlier type according to the following expressions:

Additive outlier:

$$\gamma_i(B) = 1 \quad (2)$$

Level shift outlier:

$$\gamma_i(B) = \frac{1}{1-B} \quad (3)$$

Transitory change outlier:

$$\gamma_i(B) = \frac{1}{(4)1-\delta B}\ 0 < \delta < 1 \quad (4)$$

3.4. Dynamic Regression

Transfer function models have been proven to be useful tools to capture the contributions from current and lagged values of the predictor series that describes the relationship between an output variable Y and one or more input variables X.

We used a transfer function model to forecast the traffic speed variable, since if we model this variable with the ARIMA univariate procedure, a smaller predictive capacity is observed; in contrast, the dynamic regression model presents a lower standard error in the prediction, and therefore, their confidence intervals are more precise [44].

The modelling of series using dynamic regression models is also known as dynamic econometric modelling, which describes how the effects are transmitted between variables and, therefore, is an essential tool for evaluating dynamic responses. If the variable x_t is stochastic, it is necessary to construct a univariate model to predict x_t. Then, it is possible that the improvement provided by the dynamic model using the prediction of the variable x_t with respect to the univariate model for the variable y_t is small according to the cumulative prediction errors of both variables.

We followed the methodology proposed by Gómez and Maravall [45,46] to estimate seasonal trends and cycles based on ARMA processes, evaluate the authenticity of Kalman filters and optimize the estimation of the missing values. Time series regression with ARIMA noise, missing observations and outliers (TRAMO) was used for this purpose, and estimating the models inside M-30 (see 0), and outside M-30 (see 0) was performed with the EViews software. Fair [47] measures of predictive accuracy (RMSE, root mean square error; MAE, mean absolute error; and Theil's inequality coefficient U) have been used to evaluate the accuracy of ex post and ex ante forecasts

3.4.1. Inside M-30 Model

The time series associated with the variables used for the inside M-30 scenario are the following: traffic speed $S(M30\_Ins)_t$, traffic intensity $C(M30\_Ins)_t$, atmospheric humidity $H(M30\_Ins)_t$ and average occupation level in public transport $T(M30\_Ins)_t$ for the period between January 2005 and December 2015.

To predict the traffic speed variable, predictions of the explanatory variables in the selected sample time range are needed. These predicted values of the explanatory variables will be input into the final model with the objective of predicting the traffic speed for the 2016 period. Figure 3 shows the series between January 2005 and December 2015.

Table 3 presents the estimation parameters and the outliers detected in the traffic speed estimation model inside the toll zone.

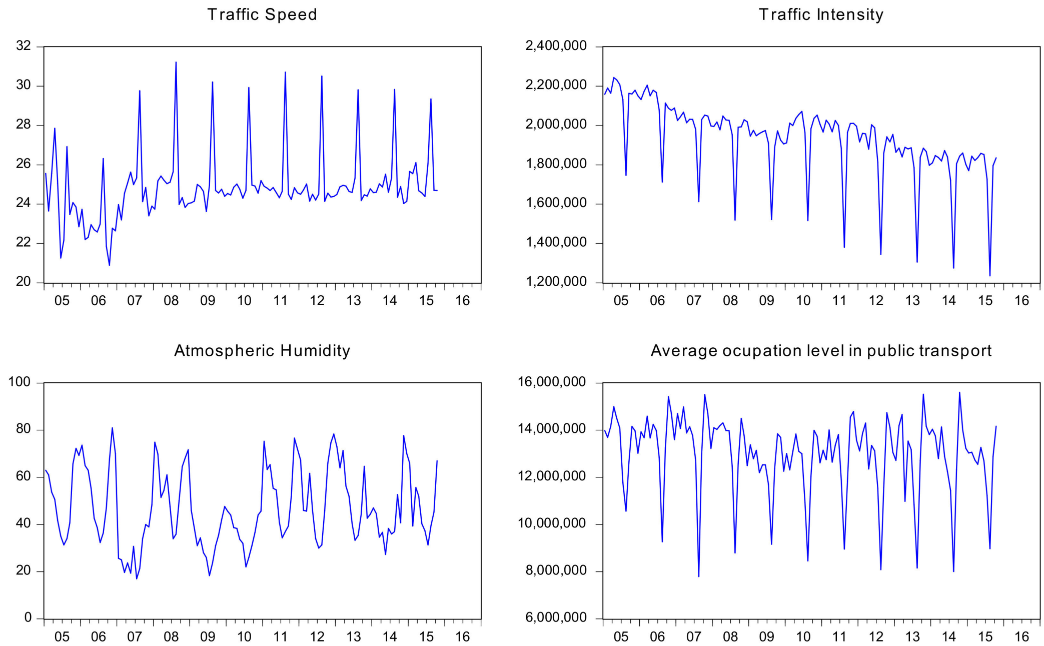

Figure 3. Time series estimation from January 2005 to December 2015.

Table 3. Parameters with ARIMA associated with inside M30 (inside the toll zone).

	Parameters	Estimate	Std Error	T Ratio	Lag
Traffic intensity [1]	TH1	−0.41930	0.084426	−4.97	1
$C(M30\_Ins)_t$	BTH	−0.51595	0.079662	−6.48	12
Atmospheric humidity [2]	PHI1	−0.78346	0.057398	−13.65	1
$H(M30\_Ins)_t$	BTH	−0.95000	0.028840	−32.94	12
Average occupation level in public transport [3]	TH1	−0.75298	0.062359	−12.08	1
$T(M30\_Ins)_t$	BTH	−0.72694	0.065075	−11.17	12

[1] Selected model: ARIMA (1, 1, 0) × (0, 1, 1), without mean. ARMA parameters. [2] Model finally chosen: ARIMA (1, 0, 0) × (0, 1, 1), without mean. Outliers. 25 TC (1 2007) transitory change. 118 AO (10 2014) additive outlier. 30 AO (6 2007) additive outlier. Method of estimation: exact maximum likelihood. [3] Selected model: ARIMA (0, 1, 1) × (0, 1, 1), without mean. Outliers. 100 AO (4 2013) additive outlier. 32 AO (8 2007) additive outlier. Method of estimation: exact maximum likelihood.

The equations resulting from the application of this model for the inside M-30 scenario are expressed in Equations (5)–(7). Table 4 shows the estimation of the different types of outliers detected in the different models.

$$\left(1-B\right)\left(1-B^{12}\right)C\left(M30_{Ins}\right)_t = -0.41930a_{t-1} - 0.51595a_{t-12} + a_t \quad (5)$$

$$\begin{aligned}\left(1-B^{12}\right)H\left(M30_{Ins}\right)_t & \\ &= -0.78346H\left(M30_{Ins}\right)_{t-1} - 0.95a_{t-12} - \left[\frac{0.96536}{1-\delta B}\right]I_t^{25} \\ &\quad -0.55483I_t^{118} + 0.45829I_t^{30} + a_t\end{aligned} \quad (6)$$

where $\delta = 0.7$

$$\begin{aligned}\left(1-B\right)\left(1-B^{12}\right) \quad & T\left(M30_{Ins}\right)_t \\ &= -0.75298a_{t-1} - 0.726945a_{t-12} - 1896I_t^{32} \\ &\quad -2357.4I_t^{100} + a_t\end{aligned} \quad (7)$$

Figure 4 shows the extended series for each of the regressive variables for 2016, and the forecasts are shown in Appendix B (Table A1).

In the case of the inside M-30 scenario, once the predictions for the regressive variables that will form part of the transfer function model were obtained, the modelling of the traffic speed $S(M30\_Ins)_t$ variable was conducted by successively eliminating the delays (we will suppose in principle 12 delays for monthly series), which means that the contemporary relation increases and the analysis of the residuals shows structure.

Table 4. Estimation of the different types of outliers in the different models according to Equations (6) and (7).

	Parameters	Value	Std Error	T Value	
Model Equation (6)	OUT 1 (25)	−0.96536	(0.15980)	−6.04	TC (1 2007)
	OUT 2 (118)	−0.55483	(0.12637)	−4.39	AO (10 2014)
	OUT 3 (30)	0.45829	(0.12626)	3.63	AO (6 2007)
Model Equation (7)	OUT 1 (100)	−2357.4	(530.10169)	−4.45	AO (4 2013)
	OUT 2 (32)	−1896.8	(530.10885)	−3.58	AO (8 2007)

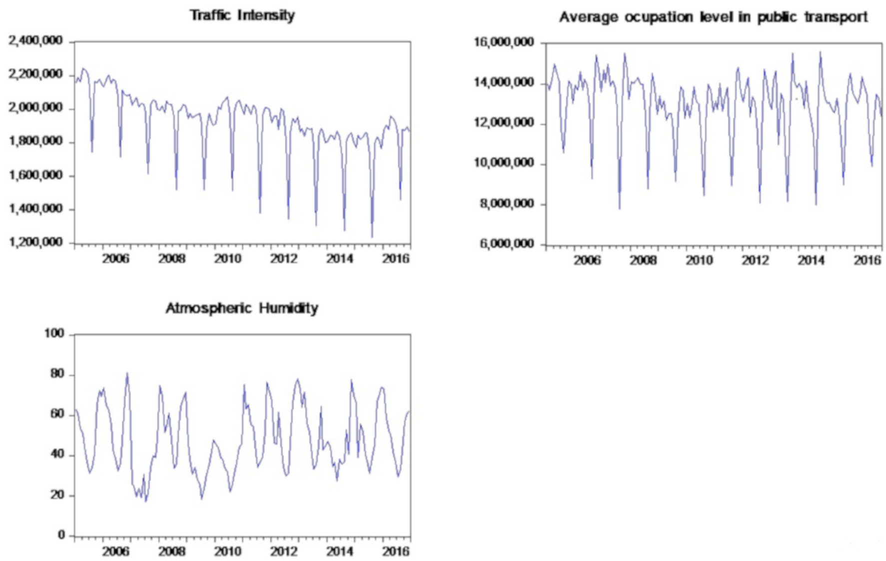

Figure 4. Time series estimation for regressive variables from January 2005 to December 2015 and forecast to 2016.

Therefore, we must reformulate this dynamic until we obtain the model that establishes a significant relationship with a rather complicated structure for the noise model. Table 5 shows the estimation of the model for the $S(M30\_Ins)_t$ variable, and the equation of the model is represented in Equation (8).

$$S(M30_{Ins})_t = \frac{-6.30+(-15.58-1.61B)logC(M30_{Ins})_t-0.003H(M30_{Ins})_t+0.39T(M30_{Ins})_t+(1+0.99B)\left(1-0.87B^{12}\right)a_t}{(1-B)\left(1-B^{12}\right)\left(1-0.32B^{12}\right)} \quad (8)$$

Equation (8) of the inside M30 model shows the negative impacts of the traffic intensity variables $C(M30\_Ins)_t$ and atmospheric humidity $H(M30\_Ins)_t$ with respect to the speed traffic $S(M30\_Ins)_t$ variable, while the average level of occupation of public transportation $T(M30\_Ins)_t$ variable has a positive impact that together with the ARMA structure modelled with the noise effect has allowed us to estimate this model. The residual of the model given by Equation (8) is presented in Figure 5. The model is validated, as the residuals can be assumed to be white noise.

Table 5. Estimation model for the dependent variable $S(M30\_Ins)_t$ [1].

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$C(M30\_Ins)_t$	−6.307622	3.033845	−2.079085	0.0400
$D \log C(M30\_Ins)_t$	−15.58778	0.793129	−19.65353	0.0000
$D \log C(M30\_Ins)_t{}^{(-1)}$	−1.610115	0.785498	−2.049801	0.0429
$H(M30\_Ins)_t$	−0.003430	0.001062	−3.230835	0.0016
$T(M30\_Ins)_t$	0.394695	0.184816	2.135609	0.0350
AR (1)	0.204268	0.097776	2.089146	0.0391
SAR (12)	0.321852	0.068886	4.672235	0.0000
MA (1)	−0.995325	0.009506	−104.7017	0.0000
SMA (12)	0.872228	0.028566	30.53355	0.0000
Parameters				
R-squared	0.940250	Mean dependent var	0.020696	
Adjusted R-squared	0.935740	S.D. dependent var	2.289234	
S.E. of regression	0.580310	Akaike info criterion	1.824519	
Sum squared resid	35.69647	Schwarz criterion	2.039339	
Log likelihood	−95.90981	F-statistic	208.5063	
Durbin-Watson stat	2.072600	Prob (F-statistic)	0.000000	

[1] Method applied for the dependent variables (M30_Ins) t: least Squares, sample (adjusted): 2006M04 2005M10. Included observations: 115 after adjustments. Convergence achieved after 12 iterations. Bakcast: 2005M03 2006M03

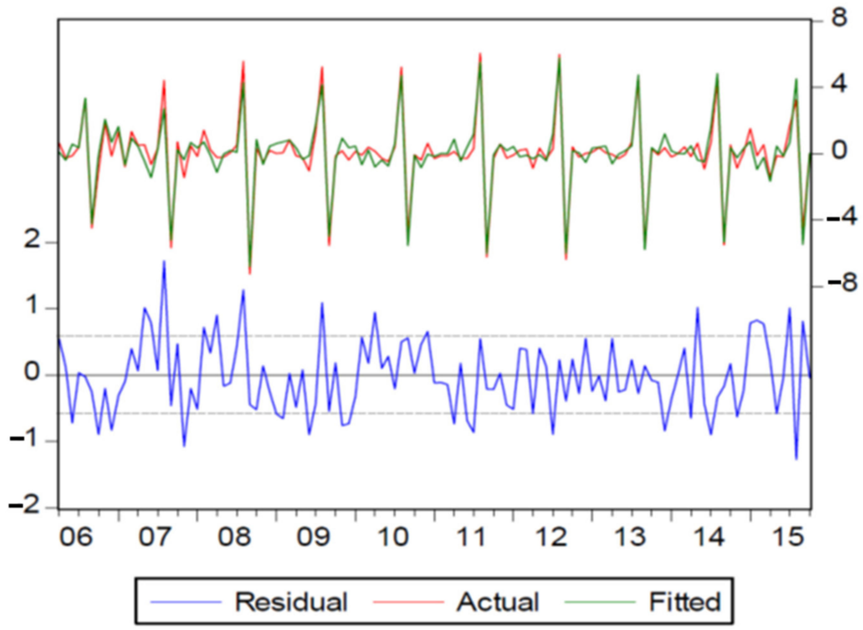

Figure 5. Residuals of the model given by Equation (8). Original and estimated values of the speed traffic by traffic intensity, atmospheric humidity, and average occupation level in public transport in the inside toll zone.

Within-sample forecasting and dynamic forecasting techniques were used, following Muñoz et al. [37]. The results for the estimation of the original time series for $S(M30\_Ins)_t$ from January 2005 to December 2015 as a forecast inside the sample and from January 2016 to December 2016 as a forecast outside the sample are depicted in Figure 6.

Figure 7 presents the speed traffic forecast inside the toll zone, the confidence intervals and the accuracy measures. The adequacy of the model for forecast purposes is confirmed by the Theil inequality coefficient (0.01).

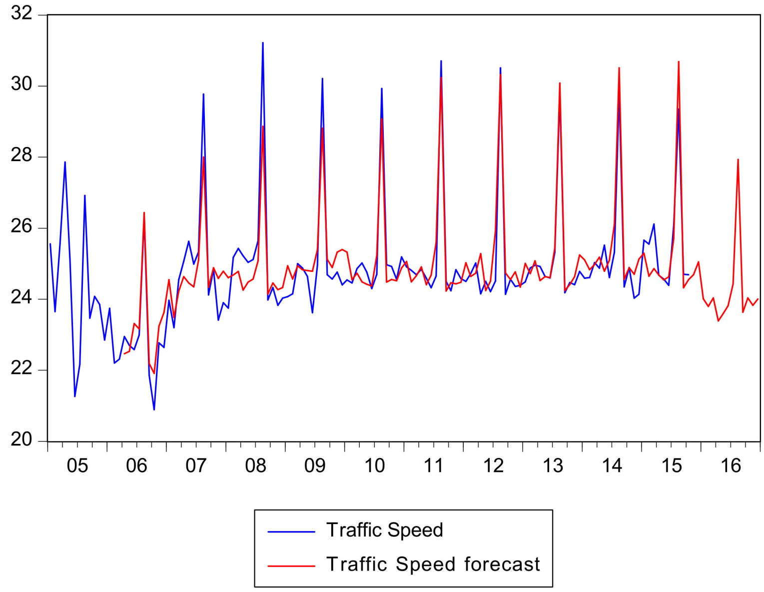

Figure 6. Time series and forecast inside and outside the sample estimations for traffic speed inside the M-30 zone. SPEED = traffic speed, SPEEDF = estimated and forecasted traffic speed.

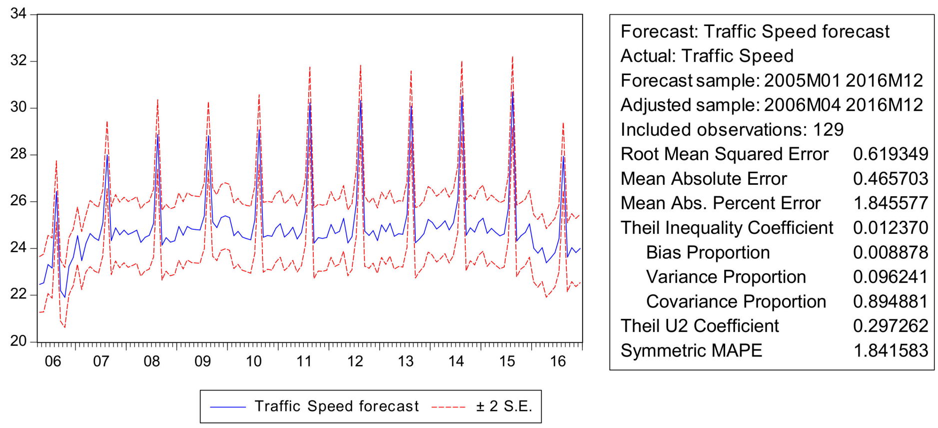

Figure 7. Forecast speed traffic inside the toll zone and the accuracy measures.

3.4.2. Outside M-30 Model

In the same way that we proceeded for the inside M-30 scenario, the time series associated with the variables for the outside M-30 scenario, including the traffic speed $S(M30\_Out)_t$, traffic intensity $C(M30\_Out)_t$, atmospheric humidity $H(M30\_Out)_t$ and average level of occupation of public transport $T(M30\_Out)_t$ for the period between January 2005 and December 2015, were obtained by modelling traffic speeds through a transfer function or dynamic regressive models with the dynamic regressors of the traffic intensity, atmospheric humidity and average level of occupation of public transportation variables. The predicted values of those explanatory variables for the period are shown in Figure 8, which allows us to input them into the model in order to predict the traffic speeds for 2016.

Next, the different selected models that were used to detect outliers for each of the explanatory variables are shown in Table 6. Humidity follows the same model as for the inside M-30 stage.

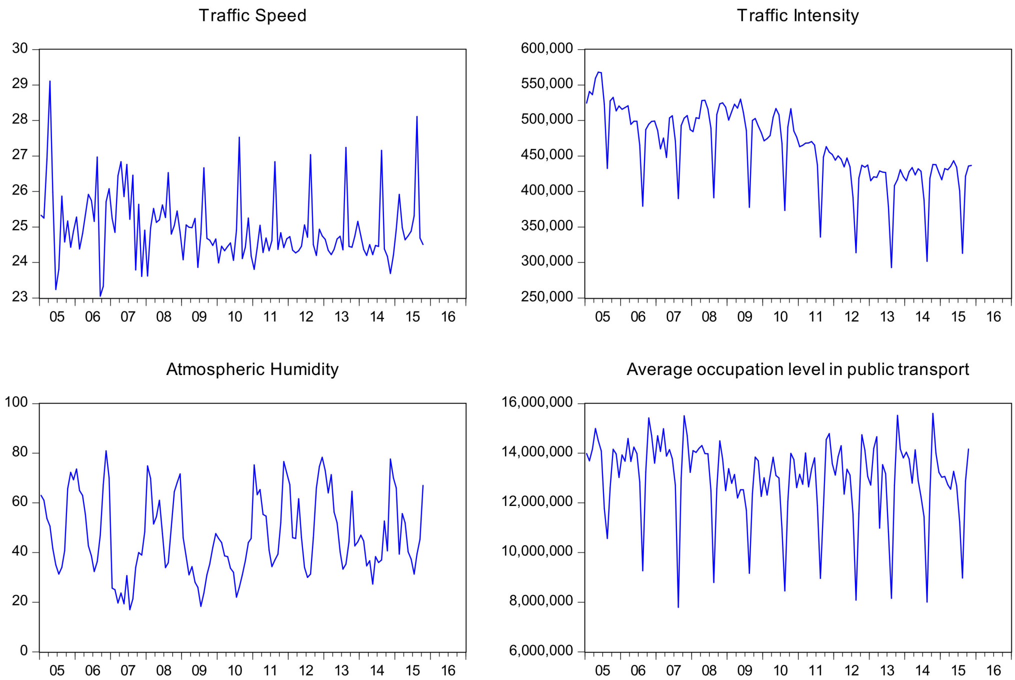

Figure 8. Time series estimation from January 2005 to December 2015.

Table 6. Parameters with ARIMA associated with outside M-30 (outside the toll zone).

	Parameters	Estimate	Std Error	T Ratio	Lag
Traffic intensity [1]	PHI1	−0.30728	0.088182	3.48	1
$C(M30\_Out)_t$	BTH	−0.70590	0.065636	−10.75	12
Average occupation level in public transport [2]	TH1	−0.75255	0.062406	−12.06	1
$T(M30\_Out)_t$	BTH	−0.72707	0.065062	−11.18	12

[1] Selected model: ARIMA (1, 1, 0) × (0, 1, 1), without mean. Outliers. 28 AO (4 2007) additive outlier. 16 LS (4 2006) level shift. 70 AO (10 2010) additive outlier. Method of estimation: exact maximum likelihood. [2] Selected model: ARIMA (0, 1, 1) × (0, 1, 1), without mean. Outliers. 100AO (42013).32 AO (82007). Method of estimation: exact maximum likelihood.

The equations resulting from the application of this model for the outside M30 (outside the toll zone) scenario are shown in Equations (9) and (10). Table 7 shows the estimations of the different types of outliers detected in the different models.

$$\begin{aligned} &(1-B)\left(1-B^{12}\right) C(M30_{Out})_t \\ &= -0.30728C(M30_{Out})_{t-1} - 0.70590a_{t-12} - 46,692I_t^{28} + 23,286I_t^{70} \\ &-39,910S_t^{16} - \left[\frac{37456}{1-\delta B}\right] I_t^{30} \\ &+a_t \end{aligned} \quad (9)$$

where $\delta = 0.7$

$$\begin{aligned} (1-B)\left(1-B^{12}\right) \quad & T(M30_{Out})_t \\ & = -075298a_{t-1} - 0.726945a_{t-12} - 1896.8I_t^{32} - 2357.4I_t^{100} \\ & +a_t \end{aligned} \quad (10)$$

Figure 9 shows the modelled series for each of the regressive variables whose forecasts for 2016 are shown in Appendix B (Table A2).

Table 7. Estimation of the different types of outliers in the different models according to Equations (9) and (10).

	Parameters	Value	Std Error	T Value	
Model Equation (9)	OUT 1 (25)	–46692.	(6189.78871)	–7.54	AO (4 2007)
	OUT 2 (118)	–39910.	(7561.96073)	–5.28	LS (4 2006)
	OUT 3 (30)	–37456.	(7115.29321)	–5.26	TC (2 2007)
	OUT 4 (70)	23286.	(6036.40259)	3.86	AO (10 2010)
Model Equation (10)	OUT 1 (100)	–2357.4	(530.10169)	–4.45	AO (4 2013)
	OUT 2 (32)	–1896.8	(530.10885)	–3.58	AO (8 2007)

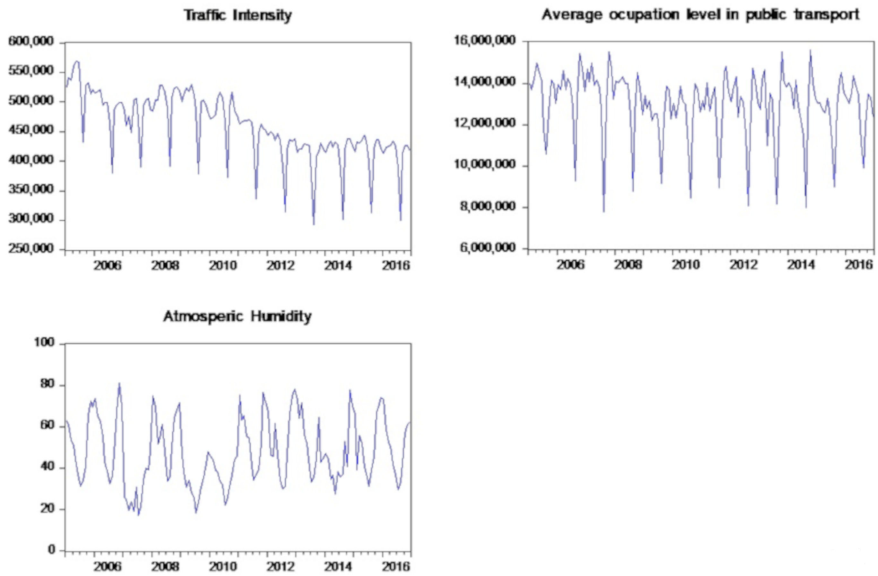

Figure 9. Time series estimation for regressive variables from January 2005 to December 2015 and forecast to 2016.

Once the predictions for the regressive variables that will form part of the transfer function model were obtained, the modelling of the traffic speed variable in the outside M-30 scenario $S(M30\_Out)_t$ was conducted in the same way as in the inside M-30 scenario described in Section 3.4.1 through the successive elimination of delays where the contemporary relationship increases. Table 8 shows the estimations of the model for the $S(M30\_Out)_t$ variable, and the equation of the model is Equation (11).

$$S(M30_{Out})_t = \frac{60.61 - 3.02dlogC(M30_{Out})_t - 0.002H(M30_{Out})_t + 2.16T(M30_{Out})_t + (1+0.5B)\left(1-0.89B^{12}\right)a_t}{(1-0.73B)\left(1-0.41B^{12}\right)} \quad (11)$$

Equation (11) of the outside M30 (outside the toll zone) model again shows the negative impact provided by the traffic intensity $C(M30\_Out)_t$ and atmospheric humidity $H(M30\_Out)_t$ variables with respect to the speed traffic $S(M30\_Out)_t$ variable. In contrast, the average level of occupation of public transportation $T(M30\_Out)_t$ variable has a positive impact. The residuals of the model given by Equation (11) are presented in Figure 10. The model is validated, as the residuals can be assumed to be white noise.

Table 8. Estimation model for the dependent variable S $(M30\_Out)_t$ [1].

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$C(M30\_Out)_t$	60.61926	9.066392	6.686151	0.0000
$D \log C(M30\_Out)_t$	−3.020643	0.610702	−4.946179	0.0000
$H(M30\_Out)_t$	−0.002430	0.002062	−3.240835	0.0013
$T(M30\_Out)_t$	2.164192	0.558603	3.874293	0.0002
AR (1)	0.738075	0.117904	6.259964	0.0000
SAR (12)	0.416938	0.077309	−5.393159	0.0000
MA (1)	−0.515637	0.143140	−3.602322	0.0005
SMA (12)	0.892738	0.026897	33.19153	0.0000
Parameters				
R-squared	0.642619	Mean dependent var		24.93509
Adjusted R-squared	0.619455	S.D. dependent var		0.908153
S.E. of regression	0.560224	Akaike info criterion		1.745513
Sum squared resid	33.89593	Schwarz criterion		1.935416
Log likelihood	−93.23974	F-statistic		27.74262
Durbin-Watson stat	1.898455	Prob (F-statistic)		0.000000

[1] Method applied for the dependent variables (M30_Out) t: least squares, convergence achieved after 18 iterations.

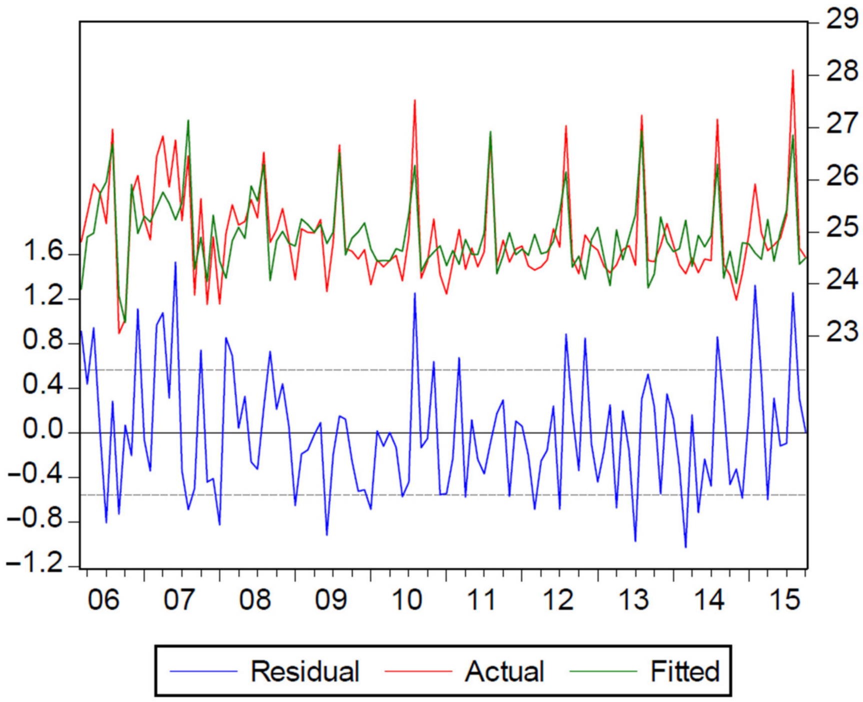

Figure 10. Residuals of the model given by Equation (11). Original and estimated values of the speed traffic by traffic intensity, atmospheric humidity and average occupation level in public transport in the outside toll zone.

Figure 11 presents the estimation model for the original time series for $S(M30\text{-}Out)_t$ from January 2005 to December 2015 as a dynamic forecast inside the sample and from January 2016 to December 2016 as a forecast outside the sample.

The predictive accuracy according to Fair (1986) and Theil's inequality coefficient U is shown in Figure 12. The Theil inequality coefficient (0.01) confirms the adequacy of the model for forecast purposes.

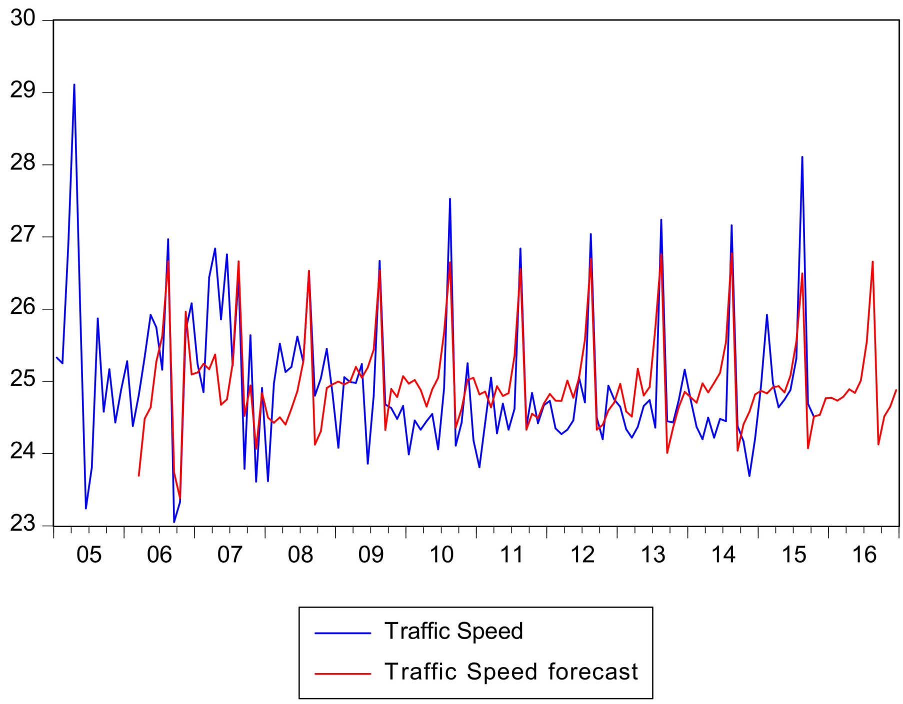

Figure 11. Time series and forecast inside and outside the sample estimations for speed traffic outside the M-30 zone. Notes: SPEED = speed traffic, SPEEDF = estimated and forecast speed traffic.

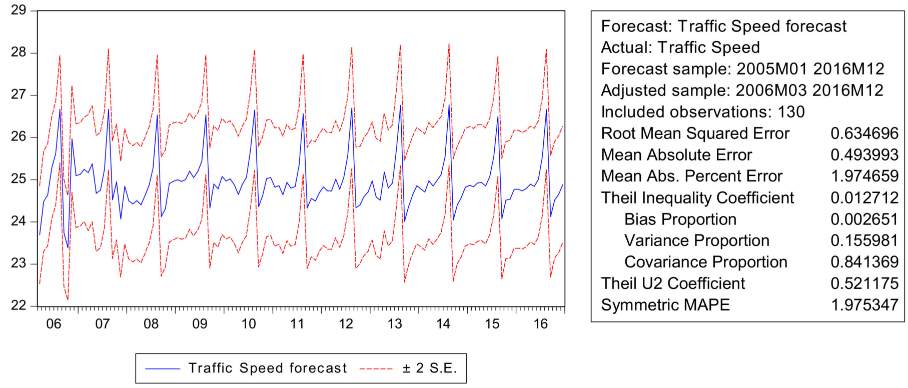

Figure 12. Forecasted speed traffic outside the toll zone and the accuracy measures.

4. Results

Survey data related to the decrease in car drivers (see Table 1) and distribution and analysis of traffic intensity reduction in charge periods (see Table 2), as a consequence of a theoretical urban road pricing scheme for each of the congestion areas, allow us to estimate the expected impact in traffic speed increase by means of Equations (4) and (7) for each forecast model. Table 9 shows the estimated impact in traffic speed increase as a consequence of road pricing.

In order to perform a more complete analysis of the effects on traffic speed due to the impacts provided by the forecast model as shown in Table 9, a set of reference traffic speeds for each area under study are provided, as reflected below in the Appendix C (Table A3). The analysis of the results obtained will be carried out, considering that the area inside the toll cordon includes the traffic speed corresponding to the metropolitan crown, M-30 and city center sub-area, while the area outside the toll cordon includes the traffic speed corresponding to M-40 and the external subareas from M-40.

Table 9. Effects on traffic speed increase due to applying theoretical road pricing for each study area.

	Effects by Study Area (Expressed in Km/h)	
	Inside Area of Cordon Toll	**Outside Area of Cordon Toll**
Increase in traffic speed due to traffic intensity reduction on charged periods	6.5	1.2
Increase in traffic speed due to effective traffic intensity reduction because of road pricing	3.6	0.3
Increase in traffic speed due to average occupation of public transport increase because of urban road pricing	0.5	2.6
Reduction in traffic speed due to displaced traffic intensity out to operating time of road pricing	–1.3	–0.4

5. Discussion

5.1. Traffic Speed Increase during the Urban Road Pricing Working Time

The traffic speed increases during the working time of the urban road pricing scheme (7:00–10:00 and 18:00–20.00); the periods with the highest daily congestion have traffic speed increases of 6.5 km/h and 1.2 km/h in the areas inside and outside of the toll cordon, respectively. The traffic speed increase of 6.5 km/h inside the toll cordon area reflects the road pricing scheme's high capacity and efficacy for increasing traffic speeds due to a significant traffic intensity reduction as a consequence of car drivers choosing to make their trips by interurban public transportation, postponing their trips, changing routes to avoid road pricing, or shifting to public transportation and nonmotorized transportation modes (bicycling or walking) in the city center due to the traffic intensity reduction that would improve their habitability and accessibility. Such changes to more sustainable transportation modes are influenced by improvements in mobility conditions that impose road pricing systems in the city center and are not due to tariff payments, since these types of internal displacements would be exempt.

The traffic speed increase is 15.9% in the metropolitan crown, where the average traffic speed would be 47.5 km/h, compared to the existing 41 km/h, 10% in M-30, where the average traffic speed would be at 71.5 km/h, compared to the existing 65 km/h, and 32.5% in the city center, where the average traffic speed would be 26.5 km/h, compared to the existing 20 km/h.

The traffic speed increase outside of the toll cordon area would be 1.2 km/h, and only represents a traffic speed increase of 1.7% and 1.3% in the road network belonging to M-40 (second orbital road) and subareas outside of M-40, respectively. These most distant subareas of linear road infrastructures present lower levels of congestion, and traffic flows are still more fluid. The average traffic speed would be 72.2 km/h compared to the existing 70 km/h in M-40 and 96.2 km/h compared to the existing 95 km/h in subareas outside of M-40.

5.2. Effective Traffic Speed Increase

An effective average traffic speed increase should be considered as the average traffic speed that allows us to ensure urban road pricing continuously throughout a typical day (Monday to Friday); that is, the urban road pricing scheme's capacity to discourage using automobiles permanently. The effective average traffic speed increase should therefore be less than the average traffic speed during the working time of the urban road pricing scheme. This effective traffic speed emerges as a consequence of those car drivers who would choose to postpone their trips to nontariff time periods or change routes to avoid tariff payments and constitute displaced traffic intensity. The effective average traffic speed increase as a consequence of the urban road pricing scheme is 0.3 and 3.6 km/h outside and inside the toll cordon area, respectively.

The effective average traffic speed increase that the urban road pricing scheme provided in areas outside of toll cordons of 0.3 km/h is not large and only represents an increase of 0.4% and 0.3% in M-40 and subareas outside of M-40, respectively. This limited impact corresponds to a set of linear and long-distance road infrastructures with low levels of congestion. The effective average traffic speed would be 71.4 km/h compared to the existing 71 km/h in M-40 and 95.3 km/h compared to the existing 95 km/h in subareas outside of M-40.

The effective average traffic speed increase inside the toll cordon area is 3.6 km/h. This represents average traffic speed increases of 8.8%, 5.5% and 18% in the metropolitan crown, M-30 and city center, respectively. Urban road pricing allows continuous traffic throughout a typical day (Monday to Friday) to reach average traffic speeds of 44.6 km/h in the metropolitan crown, 68.6 km/h in M-30, and 23.6 km/h in the city center. These effects on the average traffic speed increase are very significant, considering that sections of road infrastructures are shorter and concentrated in the case of M-30 and shorter and linear in the case of metropolitan crowns, and in no case do they exceed the legal restrictions on traffic speeds established.

5.3. Traffic Speed Increase due to Increase of Occupation of Public Transport as a Consequence of Urban Road Pricing

The increase in the occupation of public transportation due to urban road pricing during working time periods is 19.2% (see Table 2) outside the toll cordon area as a consequence of car drivers that would choose to change from automobiles to interurban buses and suburban rail and 35.2% (see Table 2) inside the toll cordon area as a consequence of car drivers that would choose to change to the interurban public transportation mentioned above, car drivers that would use automobiles until the toll cordon area and change to urban public transportation to conclude their trips into the city center and resident drivers in the city center that would choose to change from automobiles to urban buses and subways due to improving congestion, habitability and environmental conditions in the city center.

The estimation model establishes that traffic speeds are more elastic with respect to the level of occupation of public transportation in road infrastructures that are outside of the toll cordon area than road infrastructures that are inside the toll cordon area. This elasticity depends on the greater or lesser traffic speeds that can be achieved in each zone legal restrictions on traffic speed established. Therefore, the traffic speed increase due to the level of occupation of public interurban transportation in the area outside of the toll cordon is 2.6 km/h, so the average traffic speed in subareas outside of M-40 and the metropolitan crown would be 98.6 and 43.6 km/h, respectively, instead of the existing average traffic speeds of 95 and 41 km/h, respectively. Similarly, the traffic speed increase due to the increase in the occupation of urban public transportation inside the toll cordon area is only 0.5 km/h, so the average traffic speed in Madrid's city center would only be 20.5 km/h with respect to the existing speed of 20 km/h.

5.4. Traffic Speed Decrease due to Displaced Traffic Intensity to Time Periods in Which Urban Road Pricing Scheme Is Non-Operating

The displaced traffic intensity should be interpreted as the traffic intensity decrease during the periods in which the urban road pricing scheme is operating (7:00–10:00 and 18:00–20:00), in comparison to time periods where road pricing will not be operating.

An analysis and study of displaced traffic intensity highlights the potential barrier or border effect due to traffic speed decreases as a consequence of traffic intensity transferring to time periods in which road pricing is not operating, which represents a negative externality imposed by the system. Our forecast model estimates that the traffic speed reductions that would occur due to displaced traffic intensity moving to time periods in which system is not operating are 0.4 and 1.3 km/h in the areas outside and inside the toll cordon, respectively. These traffic speed reductions would occur mainly in subareas outside of the M-40 subarea within the area outside of the toll cordon 0.4 km/h and in the metropolitan crown subarea within the area inside of the toll cordon 1.3 km/h. These effects would not imply a significant barrier effect caused by the proposed urban toll system.

In summary, road pricing would allow an average traffic speed increase in the city center as a protected area during the operating hours of between 10% and 32.5%—15.9% in the metropolitan crown, 10% in M-30 and 32.5% in the case of Madrid's city center. These indicators of average traffic speed obtained by our prediction model are coherent with those achieved by the main congestion charge systems currently in operation. The congestion charge in London led to an increase in the average traffic speed after its entry into operation of around by 30% with respect to the average traffic speed existing in 2002 [23], while the case of Stockholm provided increases in traffic speed of 32% measured in terms of reduced travel delays [7]. Finally, we highlight the ALS/ERP system of Singapore, which allowed an increase in the average traffic speed from 19 to 36 km per hour [21] as a consequence of high traffic intensity during the morning peak hours, which fell by 45%, while car entries decreased by 70% [48].

6. Conclusions

The predictive model applied in our research has allowed us to identify the potential impacts on the reduction in traffic intensity and therefore the increase in traffic speeds as a consequence of the change in mobility behavior due to the implementation of theoretical urban road pricing in the city of Madrid during the periods considered the most congested or peak hour periods.

The model applied to the survey data reveals that the toll system could provide a significant increase in traffic speeds, especially in the city center, as the main focus of the concentration of traffic congestion coming from areas inside and outside of the toll cordon. The increase in traffic speed in the area outside the toll cordon is also relevant if we consider that these are less concentrated roads with greater linear length and lower levels of congestion, such as M-40 (second orbital road) and the roads that belong to subzones outside of M-40. This increase in the traffic speed in the area outside of the toll cordon is mainly due to a high number of car drivers who would shift towards interurban public transportation modes and those car drivers who would switch to alternative routes or anticipate or delay their journeys in order to avoid the toll tax. These speed increases would not exceed the currently established speed limits.

Traffic intensity reduction in the area outside of the toll cordon significantly induces traffic entry reduction in the area inside the toll cordon. The traffic speed increase in the metropolitan crown subarea and M-30 is very significant, considering that these areas contain greater concentrations of roads with shorter lengths and high levels of congestion during periods with the most congestion. These subareas are characterized by large bottlenecks where the main roads that give access to the city center converge. This traffic intensity reduction would positively improve traffic speeds in the city center as the main area protected by urban road pricing, which would allow a modal shift towards public transportation and nonmotorized modes, since traffic congestion is reduced during the working periods of the toll system.

An effective average traffic speed increase that ensures theoretical road pricing continuously throughout a typical working day is also relevant due to car drivers who would make their trips using public transportation instead of cars, which induces an increase in the level of occupancy of interurban public transportation-buses and railways-which further improves the effective traffic speeds in general.

In the proposed urban road pricing model for Madrid, in conjunction with the derived effect in traffic density reduction and consequently, the traffic speed increases by 6.5 km/h with respect to the circulation of vehicles for the roads that are circumscribed within the cordon toll. Considering this, a significant increase in travelling times is expected, as these roads are highly congested, non-linear, and short-length roads. These expected traffic speed increments guarantee road safety as they are still below the maximum traffic speed established in the majority of the roads circumscribed within the cordon toll. Furthermore, traffic speed increases as a consequence of congestion decrease derived from an urban road pricing model allow the improvement of urban habitability in the city center, resulting in the enhancement of the efficiency of public transport and the encouragement of the use of more sustainable transportation modes.

Future research focused on improving the quality of predictions will consider the inclusion of exogenous variables capable of representing the urban transport economy. Advanced computational techniques such as machine learning and artificial neural networks can be considered to develop on-linear models for urban transport networks with greater dimension in a more dynamic way.

Author Contributions: Conceptualization, J.P.M.M.; Formal analysis, J.P.M.M., A.E.G.S., C.S.d.B. and F.A.R.; Investigation, J.P.M.M., A.E.G.S., C.S.d.B.; Methodology, J.P.M.M., A.E.G.S., C.S.d.B. and F.A.R.; Supervision, J.P.M.M. and C.S.d.B.; Writing—original draft, J.P.M.M., A.E.G.S., C.S.d.B. and F.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by URJC, "Programa propio de ayudas a la investigación: Ayudas a grupos de investigaión", and Spanish Ministry of Science, grant number PRODEBAT PID2019-106254RB-I00.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to the comments and suggestions made by anonymous referees.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Methodology Applied to Selection of Sample for the Mobility Survey

The population used to obtain the sample was divided into two strata: the population resident in the center of Madrid and the population resident in other municipalities of the Community of Madrid, considering a statistically representative sample of 600 subjects for each stratum. The statistical consideration of infinite population allowed us, by means of the equation $n = \frac{p\ (1-p)z^2\alpha}{\varepsilon^2}$, to determine that the proportion of representative sample for each defined stratum must be at least 600 citizens to be surveyed, with a given error of 3% and a significance level of 0.05. Finally, the number of people surveyed rose to 1298 urban transport users, 630 citizens for the center of Madrid stratum and 668 citizens for other municipalities in the Community of Madrid.

Appendix B. Forecast for Each of the Regressive Variables in Each Analyzed Zone

The univariate forecast for each regressive variable used for each analyzed zone—traffic intensity, atmospheric humidity and average occupation level in public transport—is shown below in Tables A1 and A2. This estimate corresponds to the period between January 2016 and December 2016.

Table A1. Forecast inside M-30 (inside cordon toll).

Period (Month/year)	Traffic Intensity	Atmospheric Humidity	Average Occupation Level in Public Transport
01/2016	1872329	73,1284903	13331117
02/2016	1904351	58,6325344	13040076
03/2016	1877874	52,3098851	13512536
04/2016	1957864	50,6977218	14336265
05/2016	1945901	41,870411	13850126
06/2016	1921627	36,830037	13433052
07/2016	1845078	29,7182597	11115917
08/2016	1460778	33,1781532	9910561
09/2016	1877200	42,5958749	11951715

Table A1. *Cont.*

Period (Month/year)	Traffic Intensity	Atmospheric Humidity	Average Occupation Level in Public Transport
10/2016	1874224	56,975613	13498437
11/2016	1893633	61,3141543	13311370
12/2016	1865249	62,3246083	12364391

Table A2. Forecast outside M-30 (outside cordon toll).

Period (Month/year)	Traffic Intensity	Atmospheric Humidity	Average Occupation Level in Public Transport
01/2016	413664,136	73,1284903	13236505
02/2016	423480,918	58,6325344	13172811
03/2016	424781,204	52,3098851	13429291
04/2016	426823,676	50,6977218	12833639
05/2016	433652,501	41,870411	13216471
06/2016	426801,808	36,830037	12927484
07/2016	389074,731	29,7182597	11405382
08/2016	300550,304	33,1781532	8529643
09/2016	412690,956	42,5958749	12270321
10/2016	426296,453	56,975613	14411474
11/2016	426622,108	61,3141543	13995698
12/2016	417586,417	62,3246083	12961358

Appendix C

Table A3. Reference traffic speeds for analysis purposes of each study area.

	Indicators of Traffic Speed		
	Traffic Speed Type in Maximum Daily Congestion Time [1]	Real Average Traffic Speed [2]	Legal Restrictions on Traffic Speed Established
Inside toll zone			
Madrid's city center M-30 (1st orbital road) Metropolitan Crown [3]	<40 km/h	20 km/h 65 km/h 41 km/h	30 km/h 90 km/h 90 km/h
Outside toll zone			
M-40 (2nd orbital road) Outside M-40	40 km/h–80 km/h 40 km/h–80 km/h	71 km/h 95 km/h	120 km/h 120 km/h

[1] Traffic speed ranges according to efficiency in the road network and time segments [35]. [2] Average traffic speed according to information from the Madrid City Council Database [41]. [3] Area that concentrates a high level of traffic intensity in peak hours and where the main access to city center is located. We consider this traffic intensity as inside the area of the toll cordon for analysis purposes.

References

1. Moya-Gómez, B.; García-Palomares, J.C. The impacts of congestion on automobile accessibility. What happens in large European cities? *J. Transp. Geogr.* **2017**, *62*, 148–159. [CrossRef]
2. Giuliano, G.; Small, K.A. The determinants of growth of employment subcenters. *J. Transp. Geogr.* **1999**, *7*, 189–201. [CrossRef]
3. Muñoz, J.P. *Urban Toll Systems: Study and Prediction of the Effects Derived from the Implementation of an Urban Toll System for the City of Madrid*; Rey Juan Carlos University: Madrid, Spain, 2012.

4. Batty, P.; Palacin, R.; González-Gil, A. Challenges and opportunities in developing urban modal shift. *Travel Behav. Soc.* **2015**, *2*, 109–123. [CrossRef]
5. Börjesson, M.; Kristoffersson, I. The Gothenburg Congestion Charge. Effects, Design and Politics. *Transp. Res. Part A Policy Pract.* **2015**, *75*, 134–146. [CrossRef]
6. Buckingham, C.; Doherty, A.R.; Hawkett, D.C.L.; Vitouladiti, S. Central London Congestion Charging: Understanding Its Impacts. *Proceeding Inst. Civ. Eng. Transp.* **2010**, *163*, 73–83. [CrossRef]
7. Eliasson, J.; Hultkrantz, L.; Nerhagen, L.; Rosqvist, L.S. The Stockholm congestion-charging trial 2006: Overview of effects. *Transp. Res. Part A Policy Pract.* **2009**, *43*, 240–250. [CrossRef]
8. Santos, G. The London congestion charging scheme. *Brook. Whart. Pap. Urban Aff.* **2008**, 177–234. [CrossRef]
9. Curacao Project. Promoting Progressive Pricing. Deliverable D2: State of Art Review (Final). Available online: http://www.isis-it.net/curacao/index.asp (accessed on 15 May 2019).
10. United Nations Sustainable Development Goals. 17 Goals to Transform Our World. Available online: https://www.un.org/sustainabledevelopment/ (accessed on 10 April 2019).
11. Holland, E.P.; Watson, P.L. Traffic restraint in Singapore 1: Measuring the effects of the area license scheme. *Traffic Eng. Control* **1978**, *19*, 14–22.
12. Sock-Yong, P.; Rex, T. Road Congestion Pricing in Singapore: 1975 to 2003. *Transp. J.* **2004**, *43*, 16–25.
13. Christainsen, G. Road pricing in Singapore after 30 years. *Cato J.* **2006**, *26*, 71–88.
14. Santos, G.; Shaffer, B. Preliminary results of the London Congestion Charging Scheme. *Public Work. Manag. Policy* **2004**, *9*, 164–181. [CrossRef]
15. Santos, G.; Fraser, G. Road pricing: Lessons from London. *Econ. Policy* **2006**, *21*, 264–310. [CrossRef]
16. Leape, J. The London congestion charge. *J. Econ. Perspect.* **2006**, *20*, 157–176. [CrossRef]
17. Eliasson, J. Lessons from the Stockholm congestion trial. *Transp. Policy* **2008**, *15*, 395–404. [CrossRef]
18. Börjesson, M.; Eliasson, J.; Hugosson, M.B.; Brundell-Freij, K. The Stockholm congestion charges—5 years on. Effects, acceptability and lessons learnt. *Transp. Policy* **2012**, *20*, 1–12. [CrossRef]
19. Rotaris, L.; Danielis, R.; Marcucci, E.; Massiani, J. The urban road pricing scheme to curb pollution in Milan, Italy: Description, impacts and preliminary cost-benefit analysis assessment. *Transp. Res. Part A Policy Pract.* **2010**, *44*, 359–375. [CrossRef]
20. Eliasson, J.; Lundberg, M. Road Pricing in Urban Areas. Swedish Road. Administration Borlager. 2002. Available online: http://www.transportpricing.net/download/swedishreport.pdf (accessed on 20 February 2019).
21. Phang, S.Y.; Toh, R.S. From manual to electronic road congestion pricing: The Singapore experience and experiment. *Transp. Res. Part E Logist. Transp. Rev.* **1997**, *33*, 97–106. [CrossRef]
22. Pozueta, J. International Experience in Urban Tolls. Urban Research Notebooks (Ci [ur] 58). May/June 2008. Available online: http://polired.upm.es/index.php/ciur/article/view/273/268 (accessed on 10 June 2019).
23. Transport for London. Congestion Charging. Update on Scheme Impacts and Operations. Feburary 2004. Available online: http://www.tfl.gov.uk/tfl/downloads/pdf/congestion-charging/cc-12monthson.pdf (accessed on 10 March 2019).
24. Liu, Z.; Meng, Q.; Wang, S. Speed-based toll design for cordon-based congestion pricing scheme. *Transp. Res. Part C Emerg. Technol.* **2013**, *31*, 83–98. [CrossRef]
25. Menon, A. ERP in Singapore—A perspective one year on. *Traffic Eng. Control* **2000**, *41*, 40–45.
26. Olszewski, P.; Xie, L. Modelling the effects of road pricing on traffic in Singapore. *Transp. Res. Part A Policy Pract.* **2005**, *39*, 755–772. [CrossRef]
27. Xie, L.; Olszewski, P. Modelling the effects of road pricing on traffic using ERP traffic data. *Transp. Res. Part A Policy Pract.* **2011**, *45*, 512–522. [CrossRef]
28. De Lara, M.; De Palma, A.; Kilani, M.; Piperno, S. Congestion pricing and long-term urban form: Application to Paris region. *Reg. Sci. Urban Econ.* **2013**, *43*, 282–295. [CrossRef]
29. Li, M.Z.F. The role of speed-flow relationship in congestion pricing implementation with an application to Singapore. *Transp. Res. Part B Methodol.* **2002**, *36*, 731–754. [CrossRef]
30. Abulibdeh, A. Implementing congestión pricing policies in MENA Region City: Analysis of the impact in travel behiviour and equity. *Cities* **2018**, *74*, 196–207. [CrossRef]
31. Nello, O.; Muñoz, F. The urbanization process. In *Human Geography. Processes, Risks and Uncertainties in a Globalized World*; Romero, J., Ed.; Ariel: Barcelona, Spain, 2004; pp. 254–332.
32. Giuliano, G.; Gillespie, A. Research issues regarding societal change and transport. *J. Transp. Geogr.* **1997**, *5*, 165–176. [CrossRef]
33. Garcia-Palomares, J.C. Urban sprawl and travel to work: The case of the metropolitan area of Madrid. *J. Transp. Geogr.* **2010**, *18*, 197–213. [CrossRef]
34. Madrid Regional Transport Consortium. Annual Report 2007. Madrid. Available online: https://www.crtm.es/media/651608/informe_anual.pdf (accessed on 5 October 2019).
35. RACC Foundation. Congestion in the Access Corridors to Madrid. Studies and Publications of the RACC Foundation. January 2009 Madrid. Available online: http://imagenes.racc.es/pub/ficheros/adjuntos/adjuntos_estudio_congestion_webb_jzq_9adadbd7.pdf (accessed on 15 November 2019).
36. Gutiérrez, J.; Garcia-Palomares, J.C. New spatial patterns of mobility within the metropolitan area of Madrid: Towards more complex and dispersed Flow networks. *J. Transp. Geogr.* **2007**, *15*, 18–30. [CrossRef]

37. Muñoz, J.P.; Simón, C.; García, A.E. A forecast air pollution model applied to a hypothetical urban road pricing scheme: An empirical study in Madrid. *Transp. Res. Part D Transp. Environ.* **2017**, *55*, 21–38. [CrossRef]
38. Thomson, I.; Bull, A. Urban traffic congestion: Economic and social causes and consequences. *J. CEPAL* **2002**, *76*, 109–121. Available online: http://www.cepal.org/es/node/30737 (accessed on 15 November 2019). [CrossRef]
39. Kearney, A.T. Towards a Social and Sustainable Model of Road Infrastructures in Spain. September 2018. Available online: http://www.atkearney.es/documents/3900187/6315418/AT+KEARNEY_Hacia+un+modelo+social+y+sostenible+de+infraestructuras+viarias+en+Espa%C3%B1a.pdf/c0c7635f-e81c-d954-25d5-159feda88d39 (accessed on 5 December 2019).
40. Alonso, A.; Monzón, A.; Wang, Y. Modelling Land Use and Transport Policies to Measure Their Contribution to Urban Challenges: The Case of Madrid. *Sustainability* **2017**, *9*, 378. [CrossRef]
41. Madrid Council. Environmental and Mobility Government Area. Sustainability General Authority. Statistical information. Available online: http://www-2.munimadrid.es/CSE6/control/seleccionDatos?numSerie=15010000012 (accessed on 15 March 2019).
42. AEMET. State Meteorological Agency. Ministry for Ecological Transition. Available online: http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos?k=mad (accessed on 15 April 2019).
43. Madrid Council. Environmental and Mobility Government Area. Sustainability General Authority. Statistical information. Available online: http://www-2.munimadrid.es/CSE6/control/menuCSE?filtro=NS&tablaSerie=SERIES (accessed on 15 March 2019).
44. Box, G.E.; Jenkins, G.M. *Time Series Analysis: Forecasting and Control*; Holden-Day: Ann Arbor, MI, USA, 1976.
45. Gómez, V.; Maravall, A.; Peña, D. *Missing Observations in ARIMA Models. Working Paper 9701*; Bank of Spain: Madrid, Spain, 1997.
46. Gómez, V.; Maravall, A.; Peña, D. Missing observations in ARIMA models: Skipping approach versus, additive outlier approach. *J. Econom.* **1999**, *88*, 341–363. [CrossRef]
47. Fair, R.C. Evaluating the predictive accuracy of models. *Handb. Econom.* **1986**, *3*, 1979–1995. [CrossRef]
48. Willoughby, C. Singapore's Experience in Managing Motorization and Its Relevance to Other Countries. New York: World Bank. Discussion Paper TWU-43, 2000. 2000. Available online: http://www.worldbank.org/transport/publicat/twu_43.pdf (accessed on 10 June 2019).