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Assessing the Environmental and Economic Footprint of Electronic Toll Collection Lanes: A Simulation Study

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Abstract: Electronic toll collection (ETC) plays, as part of transport demand management (TDM) measures, an important role in preventing traffic congestion and improving the environmental conditions in urban and rural areas. An attempt is made in the framework of this paper to evaluate the overall performance of a toll station when a lane is dedicated to ETC. The case study refers to a toll station in the Thessaloniki Metropolitan Area, Greece. Scenarios considered specific traffic characteristics, variable toll booth setups, and different penetration rates of the ETC tag users for car and heavy vehicles. The tool used in the evaluation process was the PTV Vissim traffic simulation software. The operation of the toll station during a specific peak-hour period was simulated with the aid of the specific software. In total, 39 alternative scenarios were developed and compared to determine the level of penetration rate for which the ETC lane would be effective for different toll booth setups. Results showed that when the right lane of the toll station is converted to ETC lane, the penetration rate of this lane must be greater the 15% for the private vehicles and 20% for the heavy goods vehicles (HGV) to reduce traffic congestion and to improve environmental conditions. It was also found that when an additional ETC lane was introduced to the existing toll station set up, traffic congestion and the associated environmental conditions were much improved even for low penetration rates. It must be noticed that the results from the use of discounted cash flow methods like internal rate of return (IRR), net present value (NPV) and benefit–cost ratio (BCR) showed that all economic indicators converge as penetration rate increases in all toll booth setups. Therefore, there is a specific penetration rate threshold above which the economic viability of the investment is secured. These findings can assist the design of an effective policy in terms of the optimized operation of a toll station and sustainable mobility planning.

Keywords: electronic toll collection; transport demand management; traffic simulation; traffic congestion; environmental conditions; financial assessment; sustainable mobility

1. Introduction

Road pricing is a direct charge imposed on motorists for using a certain part of a highway or a certain area and include road tolls, distance based charges, congestion pricing, cordon (area) pricing, charges for certain vehicle types, High Occupancy Toll (HOT) lanes etc. [1]. Toll systems are divided in three main categories: open (toll stations on various locations in the highway, with or without electronic collection), closed (toll stations on every entry and exit of the highway) and open road (only electronic tolling on entries and exits or on various locations on the highway) [2]. When considering the best tolling technology to implement, many factors need to be considered. The two main factors are the scale of the road network and the fee complexity [3].

Toll plazas are one of the most crucial components of a roadway system and have been used to raise revenue and recently as a counter measure to reduce congestion [4,5]. Toll stations are bottlenecks on highways causing quite often long delays to drivers while contributing to environmental pollution and other externalities. Numerous tolling collection methods have been applied to reduce the drawbacks of manual toll collection. The implementation of electronic tolling has contributed to improving the traffic conditions on toll stations. The main systems of automatic vehicle identification rely on dedicated short-range communication technology (on one or multiple lanes), radio-frequency identification (RFID) tags, barcodes, infrared technology, and automatic number-plate recognition [6]. Recently, there is an increase in payments conducted using smartphones or contactless cards. Such smart technologies are currently used or proposed in many countries for transportation ticketing [7,8]. The use of net present value (NFC) technology and smartphones in toll collection has been proposed in recent years but there is a need for further research before it is implemented [9,10]. Smart applications are proved to have multiple economic and ecological side effects in urban and rural areas [11–14], not only in road transport but also in other modes of transport such as rail [15,16].

In this paper, we tried to evaluate the overall performance of a toll station when a lane is dedicated to ETC installation and then performed a financial evaluation of the implementation of ETC on an existing toll station. An attempt was made to determine the penetration rate threshold of the ETC lanes above which the viability of the investment is ensured. To investigate our hypothesis, we explored the case of a toll station, located nearby the Thessaloniki Metropolitan Area in Greece. High congestion, long queues, and delays often occur during peak hours. To meet our objective, we used PTV Vissim, a microsimulation software to model the operation of the toll station under investigation, along with the proposed modifications of the implementation of electronic toll collection. Our aim was to point out the scenarios that have reduced queues, lower delay times, and lower emissions. Subsequently, the benefits were converted to financial gains, so as to perform the financial evaluation of each scenario.

The purpose of the paper is to shed light on some of the vital questions that are related with highway management: what is the optimal penetration level of ETC tag users in which the whole investment has positive returns; how many conventional toll lanes should be converted to ETC lanes in order to achieve system optimization (e.g., environmental, traffic, and social balance for both operators and users)? The analysis presented in the paper can help policy makers, transportation planners, as well as transport infrastructure operators and future investors to better understand the impact that a transmission from conventional to ETC system will have. This in turn will help them estimate major economic and financial indicators, such as the Operating and Capital Expenses (OPEX and CAPEX indices), which will guide them to decide if and when the planned intervention should be installed.

2. Literature Review

2.1. Tolls

The implementation of toll managed lanes (High Occupancy Toll—HOT and High Occupancy Vehicle—HOV lanes) was studied by Schwimmer et al. (2019) who summarized the main factors that lead to the utilization of toll managed lanes in five US states. These factors are the population growth, the urban congestion, and the lack of taxes for transportation projects [17].

Another important aspect when toll operators consider the implementation of ETC on stations is the user willingness to acquire the on-board unit necessary to use the ETC lanes. Jou et al. (2013)

investigated drivers' willingness to pay for on-board unit and suggested that as the users are willing to pay less than the actual unit value, incentives should be offered by the toll operator, to increase the percentage of ETC usage [18]. They also tried to estimate the maximum toll rate that the drivers are willing to pay for a distance-based toll system, concluding that a varied toll rate system could be implemented for different periods (weekdays and weekends; peak hours and off-peak hours) and distances (short trips and long trips) [19]. Imposing differentiating toll rates was also proposed by Lin et al. (2018) to encourage drivers to use ETC lanes especially on days of great congestion such as days before major holidays [20]. Holguín-Veras et al. (2020) investigated the user perception of fairness of time-of-day pricing, concluding that commuters perceive the varied toll rates differently depending on their gender, age, and education level [21].

The toll rate is an important parameter that toll operators should compute, as too high a rate could lead drivers to reroute to avoid paying a toll and a too low rate would decrease the toll revenue which is needed to cover the operational and maintenance costs. Panou (2020) developed a model to calculate the minimum toll rate per kilometer needed to cover these costs and be acceptable by the users [22].

A very important factor when it comes to traffic infrastructure is safety. Toll plazas are a critical component when it comes to safety assessment of a highway project, as drivers have to make multiple rapid decisions when they approach a station [23]. Abuzwidah et al. (2015), using before-and-after data, compared the safety effects of upgrading from a traditional station with Manual Toll Collection (MTC) only lanes to a hybrid station (both MTC and ETC available) or an all-electronic toll station. Their findings suggest that ETC only stations increased safety by as much as 90% compared to the traditional all-MTC stations [24]. Saad et al. (2017) performed similar research using a driving simulator, evaluating the safety of various toll setups on hybrid stations (both MTC and ETC available), suggesting that the conversion of a hybrid toll plaza to an open-tolling system where no stop would be necessary (all-ETC lanes or managed lanes), would lead to less risky driving behavior by drivers [25].

2.2. Traffic Impacts

To the best of our knowledge, relatively limited number of papers have evaluated the economic impacts of the implementation of electronic toll collection. Most papers focus on assessing the influence of electronic tolling on traffic conditions. Zarrillo et al. (1997), using queueing theory, modeled the operation of a toll station where three types of toll collection were available (MTC, automatic payment with coin machines, and ETC), in order to determine the queue lengths and delay times for different traffic volumes [26]. Their research did not compare any results but was the basis for future research.

Van Dijk et al. (1999) performed a hybrid approach with a combination of queuing theory and microsimulation in its early stages. Their aim was to determine the optimal number of toll gates and payment technologies on a toll plaza [27]. Ozbay et al. (2005), using the microsimulation software, Paramics, estimated that the implementation of ETC on a toll plaza in New Jersey has reduced the delay times by 89% [28]. A similar study was performed in Japan by Ito (2002) to investigate a toll station in three different setups (MTC on all four lanes, MTC on three lanes and ETC on the fourth, and MTC on three lanes and combined use on the fourth lane). The study concluded that when the traffic volume exceeds 800 vehicles, it is the appropriate time to converse the right gate from ETC-only to a combination gate (both MTC and ETC available) [29]. Poon et al. (2005) tried to evaluate the performance of a Brisbane-based toll station. Their research concluded that the current situation with MTC gates only was not capable of supporting the projected traffic volume for the year 2011, as the drivers may experience delays five times greater than those of 2005. The results were impressive when it comes to ETC though, as with only a four ETC-only lanes, the station could handle the expected volume compared to the nine MTC lanes that would be necessary [30].

Hamid (2011) using Vissim created a chart that determines the necessary number of booths and the number of ETC gates, depending on the traffic volume and composition [31]. Tables of toll booths gate assignments for different traffic volumes were also created by Pratelli and Schoen [32].

Abdelwahab modeled a toll station in Alexandria, Egypt using VB.Net programming language and created tables for different station setups (both MTC and ETC available) and traffic volumes to define the optimal toll design. His research concluded that using MTC exclusively would require more than 14 toll booths for a traffic volume of 4000 vehicles per hour, thus making the implementation of ETC imperative [33]. Chen et al. (2014) introduced a similar study to evaluate an existing toll station for the projected traffic volumes on different target years and concluded that the implementation of at least one ETC lane is necessary to avoid long queues and delay times [34].

The optimal layout of a toll station was determined by Aksoy et al. (2014) using a combination of microsimulation and queuing theory, comparing the total delay time caused by the toll station. The remarkable finding in this study was that the increase of available toll gates caused a bottleneck effect on the exit of the station, even though it reduced delay times [35]. Obelheiro et al. (2011) proposed a method to determine level of service at toll plazas based on drivers' perception of quality of service. They used Vissim to simulate and evaluate various scenarios with different number of toll booths [36].

2.3. Environmental Impacts

Transport accounts for one third of energy consumption in the EU, which mostly comes from oil, thus being a major contributor to greenhouse emissions [37]. Therefore, one of the main objectives of traffic engineers is the reduction of the environmental impact of traffic infrastructure. Such efforts were reviewed from Gharehbaghi et al. (2019) for the planning, construction, and operation of Sydney Metro, concluding that the optimization of logistics and planning play an important role in project's emissions mitigation [38]. Recently, various studies have been conducted to evaluate the environmental burden of the toll stations.

Weng et al. (2015), using queueing theory and sample vehicles, calculated the reduction in fuel consumption caused by the implementation of ETC lanes in toll stations in Beijing. Their research estimated that the monetization value of the environmental benefits arising from the ETC lanes is about 18.52 million US dollars during the years 2009–2013 [39]. Tseng et al. (2014) used data from previous surveys to perform a comparative analysis of the existing situation in four toll stations in Taiwan and a scenario when all four would be converted into ETC only stations [40]. Li et al. (2018) proposed two different toll pricing models to mitigate the environmental impact. The results of their research showed that the increase of toll revenue leads to a greater congestion and therefore environmental impact [41].

Perera et al. (2020) compared four different toll pricing schemes considering the total toll revenue, the operational cost, the travel time, and the environmental benefit. Their study concluded that the reduction of toll revenue leads to a reduction in operational cost, total travel time, and emissions, which is beneficial for some stakeholders [42]. A similar research by Mileknovic et al. (2020) concluded that a shift from manual to electronic toll collection with the multi lane free flow system can reduce CO2 and NOx emissions by as much as 45% and 98%, respectively. An important conclusion of their study was that the differences in emissions occur due to the reduction of service times and vehicles stops while on queue [43].

The survey by Wang et al. (2019) proposed the implementation of a policy for tolling trucks by weight similar to the German HGV toll policy. Their research concluded that imposing an environmental pollution cost on heavy trucks would reduce pollutant emissions and encourage the adoption of additional measures for more environmental friendly highways [44].

2.4. Financial Evaluation

It is clear that the implementation cost of ETC on an existing or a new toll station is an important factor when assessing the viability of the intervention. Thus, it is crucial to financially evaluate the interventions before implementing them, as an inaccuracy of forecast may lead to great losses.

James Odeck et al. (2017) used an econometric method to forecast the traffic for toll projects in Norway. They compared them with those of other countries, concluding that the Norwegian toll road traffic forecasts are unbiased and close to accurate as the mean error is 4% while for other countries it is more than 20% [45]. Additionally, James Odeck proposed an econometric procedure that could be used for future toll projects to estimate the operational cost. This model estimated that the increase of traffic volume leads to a reduction of operational cost as scale economies exist [46].

The research of Regan et al. (2017), selected six toll roads in three largest cities of eastern Australia, to evaluate the viability of these projects. The review of the six case studies concluded that four out of six projects failed commercially, which leads to the assumption that the risk should be allocated more evenly between the private and public sector, as the current situation may discourage private financiers to support future toll projects [47]. A similar study was conducted by Mao et al. (2019), which calculated the total debt risk levels of toll freeways in Mainland China. Using grey approach, as the information they had was limited, they concluded that 6 of the provinces (20.7%) have low debt risk, 10 of them (34.5%) have medium debt risk, and 13 of them have high debt risk, while the debt risk for the whole Mainland China is increasing especially since 2010 [48].

Levinson et al. (2003) tried to monetize the social benefit caused from the implementation of ETC lanes to an existing toll station and find the best combination of ETC lanes and total discount for ETC users so that the monetized social welfare is maximum. They summarized that the sooner the drivers switch to ETC, the greater the overall social benefit would be over the 20 years, while many of the gains are achieved even after only 2 years. Two significant findings were that if the operator allocates too many lanes for ETC usage only, this decision will cause excessive delays for MTC users. A very high discount for the ETC users would encourage more users to acquire an on-board-unit, but would decrease the operator's revenue [49].

Based on the literature review presented above, the current study aims to provide an answer to the following main research question: what is the optimum ETC tag penetration rate combination for private and HGV users, in order to have traffic, environmental, and financial gains?

After the introductory section and the current section of literature review, the paper is structured as follows; in the third section, a detailed description about the study area, the on-field data collection approach, as well as the development of the microsimulation scenarios is given. The fourth section presents the traffic and environmental impact analysis of the 39 scenarios tested, as well as the financial assessment of the alternative ETC schemes examined. The last discussion section of the paper pinpoints the main outcomes of the study together with potential policy implication and highlights limitations as well future extensions of the current work.

3. Materials and Methods

3.1. Study Site

The study site is the Malgara Toll Station in Thessaloniki Metropolitan area, Greece. Located on E75-Highway, which connects Athens and Thessaloniki (the two largest Greek cities), Malgara Toll Station (40.602301N, 22.699011E) consists of 12 payment booths, that are distributed in both directions depending on the demand direction. Electronic tolling was implemented in the past but was not active during the traffic count observations made within the framework of the study.

The traffic volume during the peak-hours is making the toll station operate at over capacity conditions frequently. In this respect, the need to investigate smart solutions to reduce congestion on the toll station is vital. Figure 1 presents on the left a map of the E75-Highway; a photo of the Malgara Toll Station is given at the right.

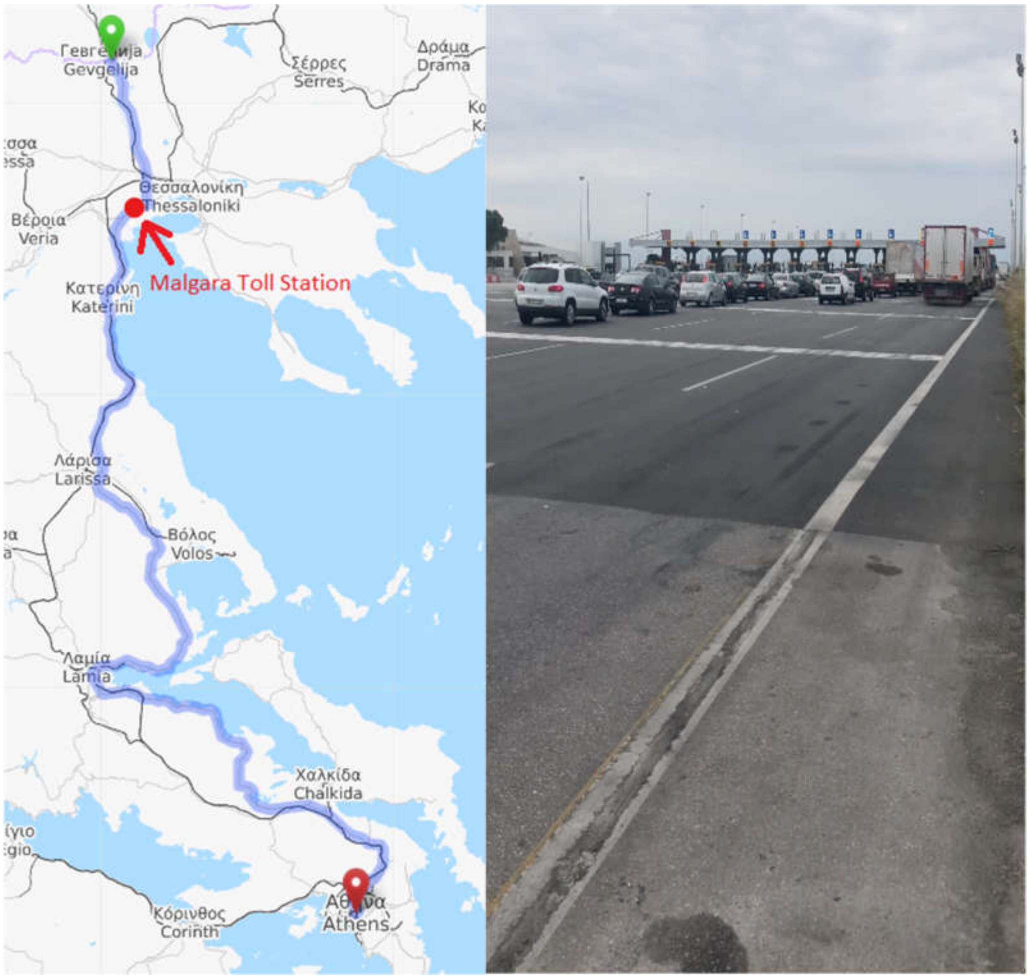

Figure 1. Map of E75 [50]—Location and photograph of the Malgara Toll Station.

3.2. Data Collection

Traffic volumes were collected for one day (25th October 2018). The Malgara Toll Station is located near Thessaloniki Metropolitan Area and is congested especially during the days before major holidays. The 26th October is a public holiday for the city of Thessaloniki, so the 25th October was one of the days with the highest demand along the whole year. The vehicles were classified in four toll categories (classes) based on the method that the toll plaza operator is using and are presented in Table 1 [51].

Table 1. Vehicle classification.

Vehicle Class	Code	Class Name	Class Description
1	KAT 1	Bicycles, tricycles	Bicycles, tricycles
2	KAT 2	Light vehicles	Vehicles with or without a trailer and a height of up to 2.70 m
3	KAT 3	Trucks, buses, and other vehicles with less than four axles	Vehicles with or without a trailer, with two or three axles and a height of more than 2.70 m
4	KAT 4	Trucks and other vehicles with four or more axles	Vehicles with or without a trailer, with four or more axles and a height of more than 2.70 m

Based on historical data, it was found that the busiest time period at the 25th October, usually occurs between 18.00 and 20.00. This was the period preselected to perform on-field traffic measurements. The traffic volume derived during the on-site observation is presented in Table 2 in 10-min intervals.

Table 2. Traffic volumes in study site during evening peak-hour (per 10 min interval).

Time Intervals	Class 1	Class 2	Class 3	Class 4	Total
18.30–18.39	0	196	17	30	243
18.40–18.49	3	329	15	34	381
18.50–18.59	0	331	4	58	393
19.00–19.09	1	299	10	67	377
19.10–19.19	1	203	5	40	249
19.20–19.29	0	169	9	29	207
19.30–19.39	0	177	9	34	220
19.40–19.49	2	194	12	25	233
19.50–19.59	0	171	12	25	208
Sum	7	2069	93	342	2511

In order to test our research hypothesis, we used Vissim, a microsimulation software to model the toll plaza operation. For our study it was important to test the behavior of each vehicle individually and the interaction between the vehicles in the network. The detailed level of behavior modeling is an important benefit of microscopic simulation and it was an important factor for choosing microscopic simulation over macroscopic or mesoscopic [52]. A microsimulation software is used to study the operation of a transport network before its construction or modification. Thus, it is possible to evaluate the proposed interventions safely and with low cost. The results are represented using 3D graphics so they are easier conceivable [53].

There are numerous microscopic simulation software packages, but Vissim was used as its interface is user friendly and the user manual is very detailed so even an inexperienced user could use it to model a network.

Vissim (Verkehr In Städten—SIMulationsmodell) is a multi-modal microscopic simulation software that belongs to the German software company PTV Planung Transport Verkehr AG. Its operation is based on the psycho-physical driver behavior model, which was developed by Wiedemann in 1974. The basic concept behind the car-following model that Wiedemann developed is the driver of a vehicle starts to decelerate when he reaches a certain distance from the leading, slower moving vehicle that he considers to be not safe. The fact that the driver of the faster moving vehicle does not know the exact speed of the leading vehicle results in his speed falling below the speed of the leading vehicle and then accelerating again after reaching a certain distance that he perceives as safe [53].

3.3. Scenario Development

An important parameter to model with accuracy for the operation of a toll plaza is the service time for every vehicle class. The cumulative frequency curves that occurred after processing the measured service times are presented in Figures 2–4, as they were exported from Vissim. On the x-axis, the time needed for the vehicles to pay the toll fee was placed, and on the y-axis the percentage distribution of traffic volume of each class is also given. For vehicle class 2 and 3, the lowest service time was set to 3 s while the higher to 25 s. For class 4, the lower and upper values were set to 4 and 38 s, respectively. For vehicles of class 1, the traffic volume was too low and the service times almost the same for each vehicle, so we used the mean service time of 7 s with a deviation of ±1 s.

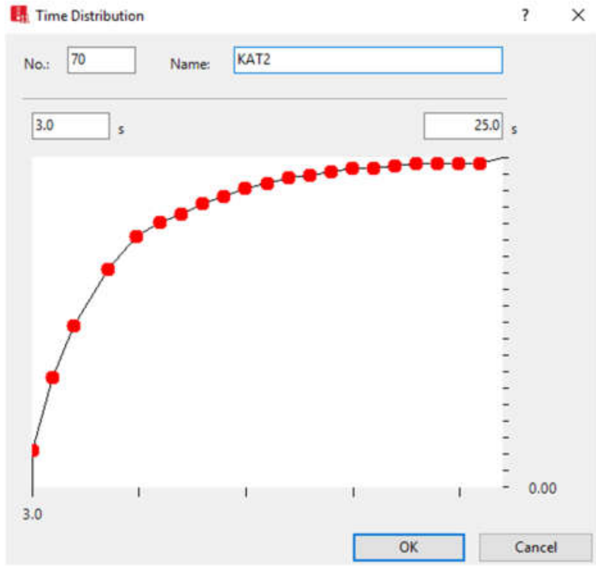

Figure 2. Cumulative frequency graph of service times for vehicles of Class 2.

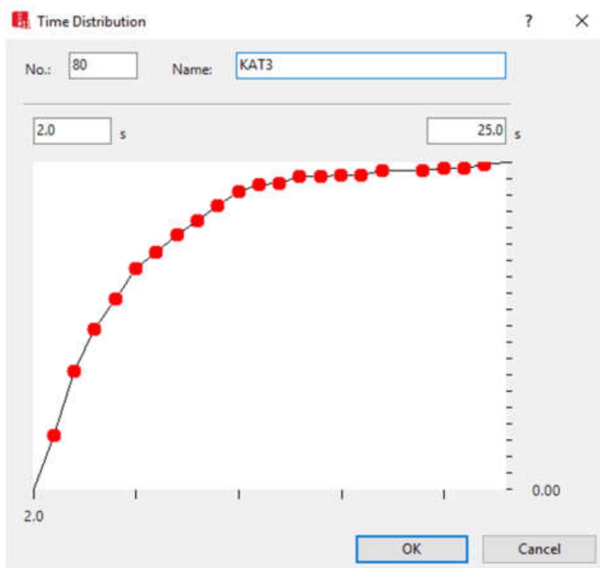

Figure 3. Cumulative frequency graph of service times for vehicles of Class 3.

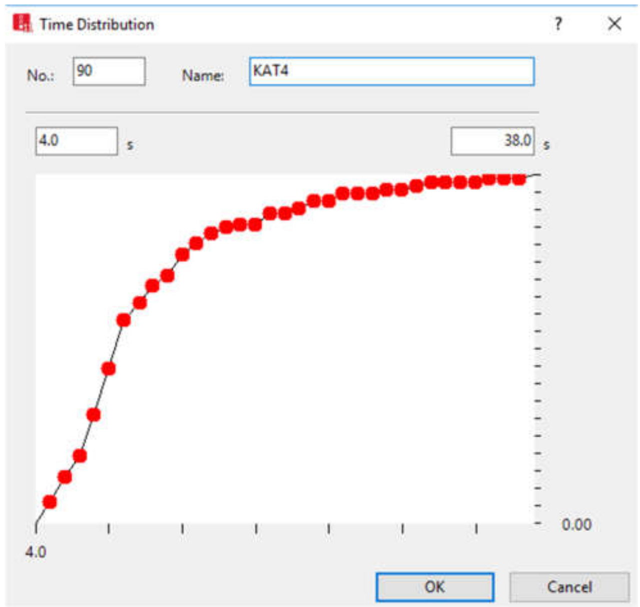

Figure 4. Cumulative frequency graph of service times for vehicles of Class 4.

3.3.1. Base Scenario

This scenario simulates the real traffic conditions that occur in the study site during the evening peak-hour. The toll station consists of seven toll booths where only the manual toll collection (MTC) option is provided. Data from Table 1 were used as input for the vehicle volumes. The toll booths were simulated using stop signs with variable dwell time for each vehicle (Figures 2–4 presented the cumulative frequency curves of dwell times for all vehicle classes). Figure 5 provides a representative screenshot of the base scenario simulation conditions.

Figure 5. Base scenario modeling screenshot: queue formation.

The traffic volumes and vehicles' queue length were derived from 10 simulation runs, and the average values were calculated for each of the 9 time intervals. Figure 6 shows the difference between the actual and the modeled queue lengths, which were used to calibrate the simulation model for the base scenario.

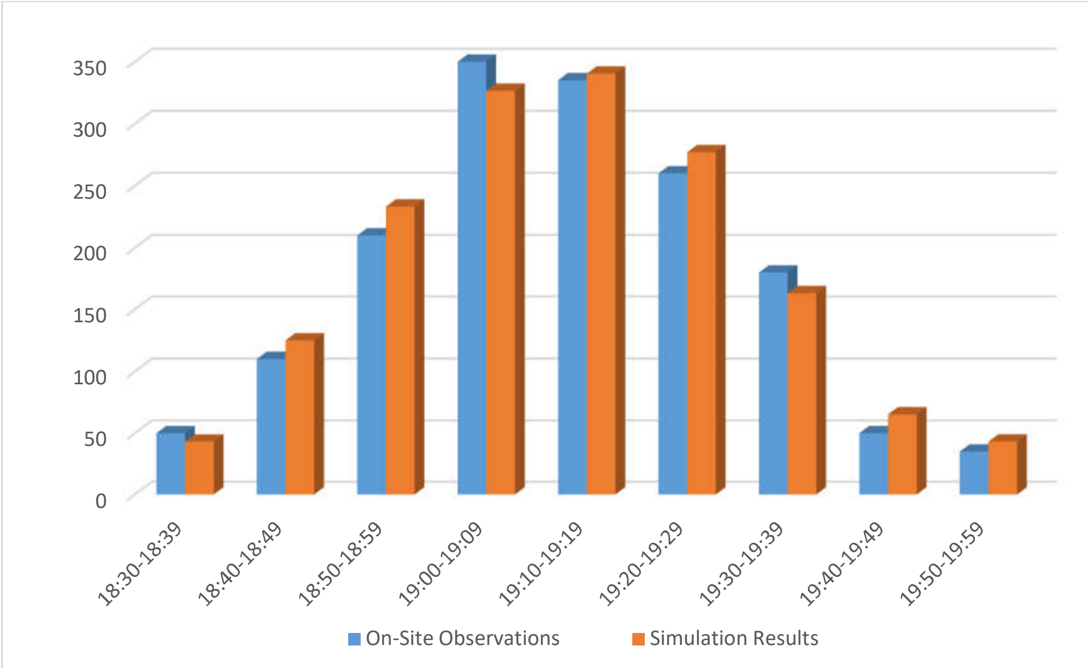

Figure 6. Comparison of average queue length (m).

The Spearman's correlation coefficient (ϱ) was calculated to determine the degree of correlation between the modeled and the actual queue lengths. Spearman's correlation coefficient (ϱ) takes values from −1 to +1. It is obvious that the closer the coefficient gets to 0, the lower the degree of correlation is, while the values −1 and +1 occur when each variable is a perfect monotone function of the other. In our case, the coefficient has a value of $\varrho = 0.95$; therefore, the correlation is significant. It is obvious from both Figure 6 and the Spearman's correlation coefficient that the model developed on VISSIM is a reliable representation of the actual operation of the toll plaza and it can be used for the evaluation of the proposed scenarios.

The paper presents the calibration levels only on queues without giving more details about other examined factors such as the traffic converge (e.g., GEH index) and the travel time representation. This is selected since the network is simplistic and such information falls out of the objective of the paper.

3.3.2. Scenarios Summary

The traffic conditions that were observed during the on-site counts and was highlighted by the simulation results was problematic with long queues averaging up to 340 m during the busiest interval. Thus, solutions were sought to reduce delays and queue lengths with the addition of manual toll collection (MTC) lanes or the implementation of electronic toll collection (ETC) lanes on the existing toll station. The scenarios developed were divided in three categories. The first category (Scenarios 1.x) contained scenarios created with the consecutive addition of MTC lanes on the existing station setup, with the total lane number reaching up to ten lanes. The second category (Scenarios 2.x) consisted of scenarios created with the conversion of the right lane to a lane used only for ETC, with a total number of seven booths, as it was observed. The third category (Scenarios 3.x) was modeled using the existing toll station setup by adding one extra lane for ETC only.

For vehicle classes 3 and 4, three alternative penetration rates were examined (starting from 10% and reaching up to 30%). For vehicle classes 1 and 2, the examined penetration rates ranged from 5% to 30%. For the former vehicle categories, only three penetration levels were assumed (10%, 20%, and 30%), whereas for the latter two categories, the total levels were assumed to be six (5%, 10%, 15%, 20%, 25%, and 30%).

Table 2 summarizes the structure of Scenario 1.x, Scenario 2.x, and Scenario 3.x subcases, respectively. The total traffic volume remains the same for all scenarios tested and equal to 2511 vehicles per hour, as it was observed during the data collection period, in order to have comparable traffic conditions. The table shows also the number of total booths (electronic toll collection and manual toll collection booths) for each setup. The percentage of traffic volume (penetration rate) of each class is presented in the sixth and seventh columns. It was assumed that all vehicles equipped with the ETC unit chose the electronic toll collection lane.

Scenarios Without ETC (Scenarios 1.x)

Three different scenarios were developed with the addition of one MTC lane on each scenario. Figures 7–9 provide representative screenshots of Scenarios 1.x simulations.

Figure 7. Scenario 1.1 modeling screenshot: queue formation.

Figure 8. Scenario 1.2 modeling screenshot: queue formation.

Figure 9. Scenario 1.3 modeling screenshot: queue formation.

Scenarios with ETC (Scenarios 2.x and 3.x)

Two sets of scenarios were tested in order to define the optimal toll station setup depending on the penetration rate of the ETC lane. These scenarios were modeled based on the conversion of the right toll lane to an exclusive lane for ETC. Scenarios 2.x consisted of seven lanes in total with the right lane used only by vehicles equipped with ETC On-Board-Units. Scenarios 3.x were based on the model created for Scenario 1.1. The total number of lanes was eight with the right lane being used exclusively for ETC. Figures 10–13 provide representative screenshots of Scenarios 2.x and 3.x simulations, for the upper x.1 and lower x.18 scenario examined.

Figure 10. Scenario 2.1 modeling screenshot: queue formation.

Figure 11. Scenario 2.18 modeling screenshot: queue formation.

Figure 12. Scenario 3.1 modeling screenshot: queue formation.

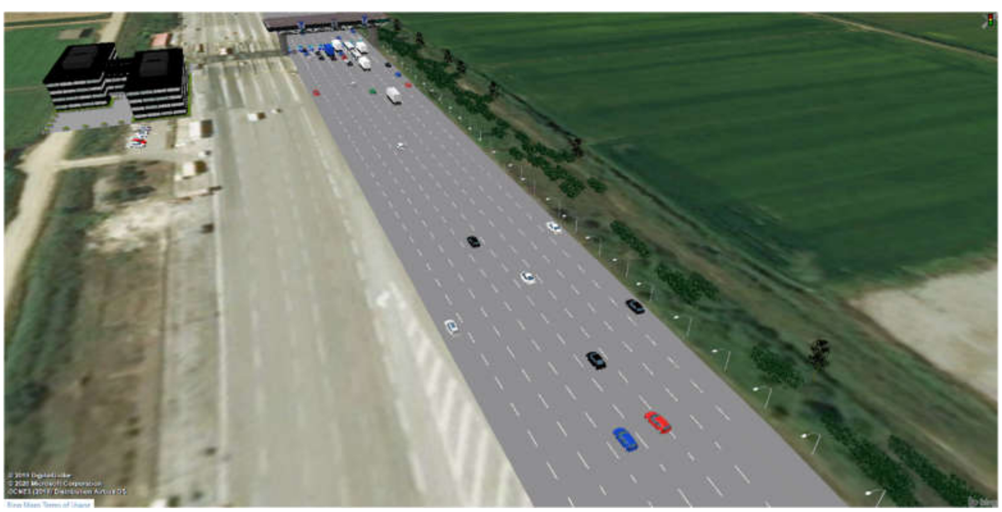

Figure 13. Scenario 3.18 modeling screenshot: queue formation.

4. Results

The results obtained from Vissim are compared to those of the base scenario and are presented in the sections below in three subchapters.

4.1. Traffic Results

To evaluate the effect of the proposed interventions on the traffic conditions of the station, we used the average queue length and the average delay time of each scenario, which we compared to those values derived from the base scenario. Figures 14 and 15 compare the average queue lengths (in meters) and delays (in seconds per vehicle) of vehicles in the study site between all the simulation scenarios and the base scenario.

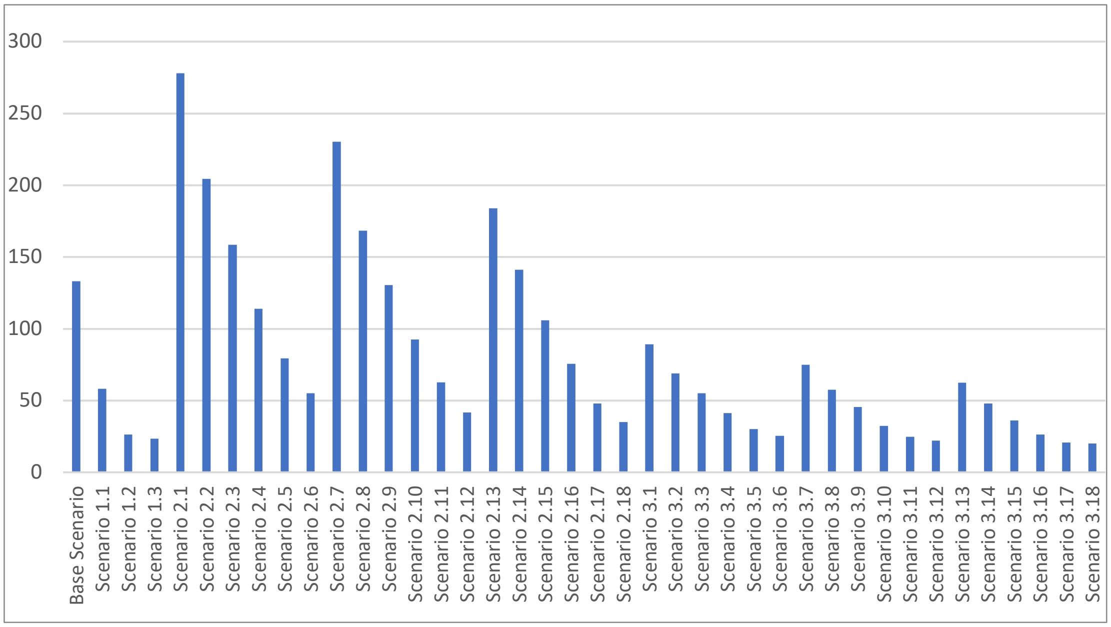

Figure 14. Average queue length (m).

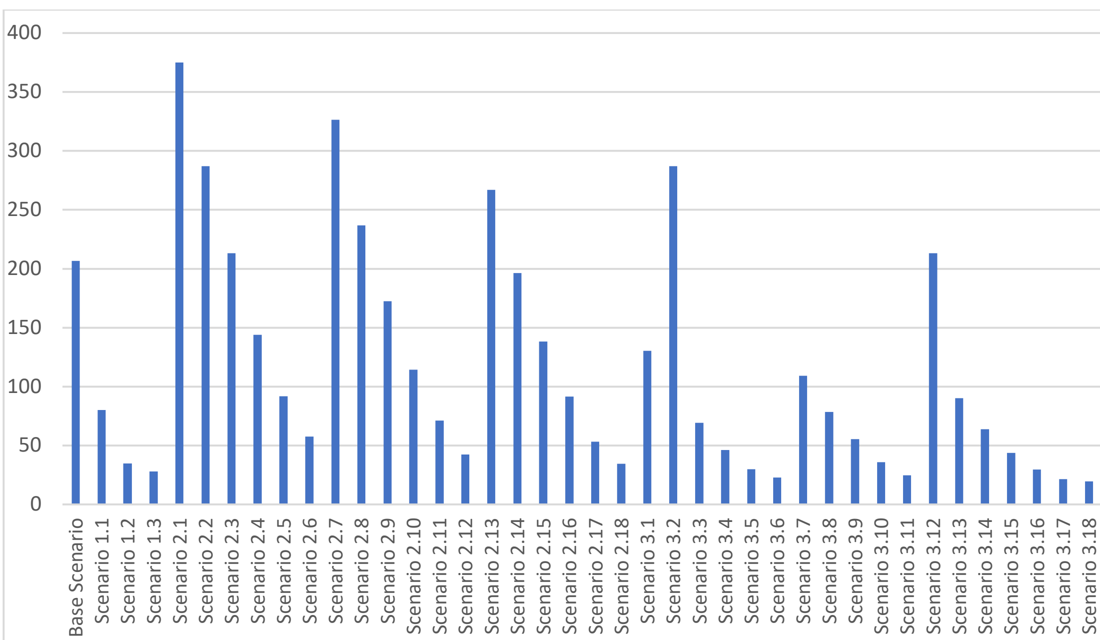

Figure 15. Average delays (s).

Under Scenarios 1.x it is obvious that there is a reduction of both the queue lengths and the delay times. More specifically, one additional toll lane (Scenario 1.1) leads to a 56.2% reduction of the average queue length and a 61.3% reduction of the average delay time, while with the ninth toll booth

(Scenario 1.2) the average queue length is decreased by 80.1% and the delay time by 83.1%. However, the activation of the 10th toll booth (Scenario 1.3) does not lead to a greater improvement of the traffic conditions compared to Scenario 1.2.

Scenarios 2.x are divided in three subcategories based on the penetration rates of the ETC lane by vehicles of classes 3 and 4. It is obvious that traffic conditions do not improve with low penetration rates of the ETC lane. This is due to the removal of one payment booth and therefore a queuing lane, while at the same time a limited percentage of traffic volume use this lane. The benefits of the ETC lane gradually increase while the penetration rates grow and there is a different threshold for each subcategory above which the average queue lengths and delay times are lower than the base scenario.

More specifically, for the first subcategory (10% penetration rate of vehicle classes 3 and 4), the scenarios with a percentage of use of the ETC lane, equal to 5% and 10%, there is an increase in both the average queue length and delay time. The first case in which a decrease occurs is scenario 2.4 with a decrease of 14.3% for the queue length and 30.4% for the delay time. The decline continues and the decrease reaches its maximum value, as expected in scenarios 2.6 with percentages of 58.6% for the average queue length and 72.2% for the delay time.

In the second subcategory (20% penetration rate of vehicle classes 3 and 4), there are reductions from scenario 2.9 (2.0% for the average queue length and 16.2% for the delay time), with its maximum value, as expected, being at scenario 2.12 and is equal to 68.6% in the average and 79.5% for the average delay.

Regarding the third subcategory (30% penetration rate of vehicle classes 3 and 4), there is a 20.5% and 5% decrease for the average queue length and the average delay time in scenarios 2.15 and 2.14, respectively. This downward trend continues as the penetration rates increase and the maximum reduction on scenarios 2.12 and 2.18 for subcategories 2.12 and 2.18, respectively.

4.2. Environmental Results

Using the EnViVer option, based on the VERSIT + exhaust emission model from TNO, it is possible to determine vehicle emissions based on vehicle paths and other information derived from Vissim. Initially, the validity of vehicle speeds and accelerations is vital for the quality modeling of emissions. With PTV Vissim, these can be exported to vehicle logs that can be imported into EnViVer for further analysis. Vehicle types are used to specify additional attributes, such as fuel type or pollutant category, in each EnViVer vehicle. In EnViVer, detailed estimates of CO, NOx, and VOC emissions in the area are prepared in the form of graphs or tables for ease of interpretation.

Figures 16–18 show the percentage differences of air pollutants (CO, NOx, and VOCs) emissions, between all simulation scenarios and the current situation. All figures follow almost the same trend as the calculation of air pollutants in Vissim is based on average fuel consumption.

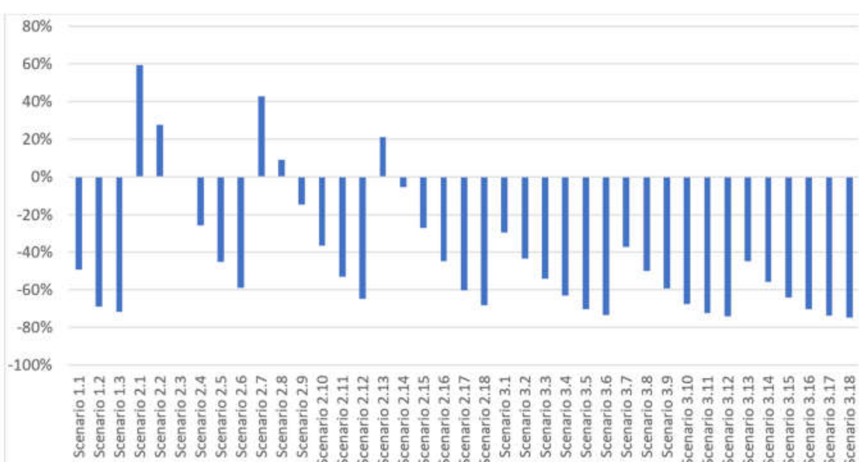

Figure 16. CO emissions results comparison with existing situation (%).

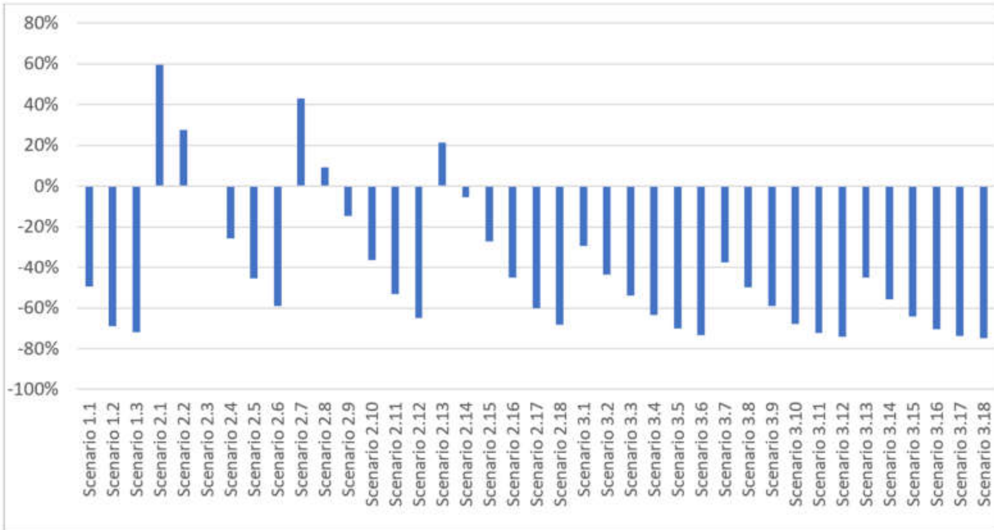

Figure 17. NOx emissions results comparison with existing situation (%).

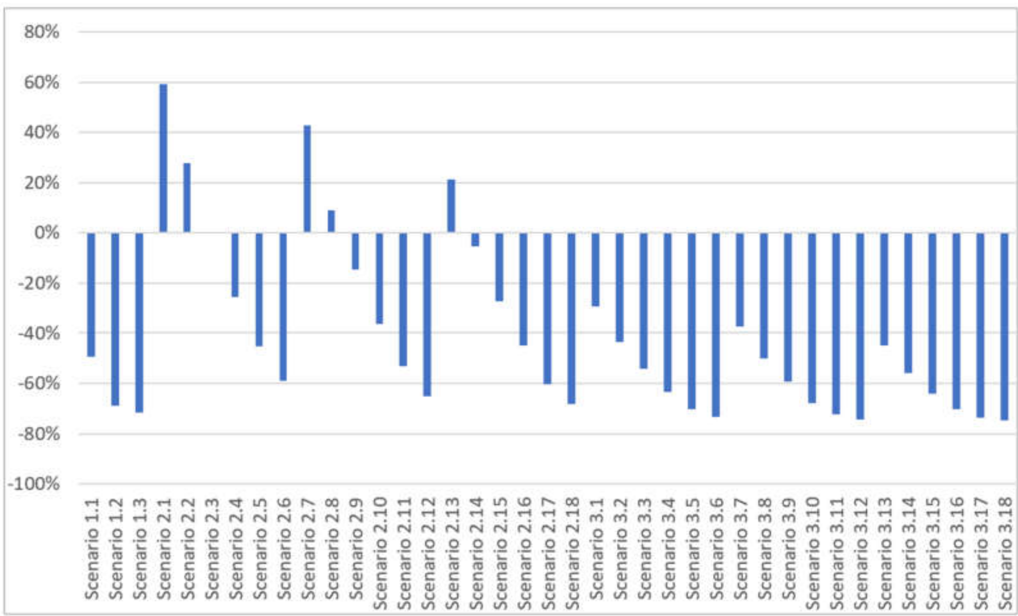

Figure 18. VOC emissions results comparison with existing situation (%).

As the figures above show, Scenarios 1.x are associated with a great reduction of all types of emissions, which reach up to 72% on scenario 1.3. In Scenarios 2.x, the environmental impact seems to be worse among the scenarios with low penetration rates of ETC lanes (e.g., 2.1, 2.2, 2.8, 2.9, 2.13, and 2.14). The increase of ETC lane usage by private vehicles though produces great reduction of air pollution caused by traffic, which reaches 59%, 65%, and 68% in scenarios 2.6, 2.12, and 2.18, respectively. In scenarios 3.x, a decline in environmental impact can be spotted even for low penetration rates, as was also the case in traffic results. The greater reduction, as was expected, appears in scenarios 3.6, 3.12, and 3.18 for each subcategory and is equal to 73%, 74%, and 75%, respectively.

4.3. Financial Evaluation

The traffic and environmental results showed that both set of scenarios (without the implementation of ETC lane and those with ETC lane) seem to improve under specific conditions (e.g., high penetration rates); the existing situation with lower queue lengths and air pollution emissions. To identify the most profitable scenario, we performed a preliminary financial assessment for all scenarios. Each scenario is associated with a travel time and air pollutant emissions difference (increase or decrease). The benefits from each scenario can be divided into three categories:

- Benefits for the road users
- Benefits for the toll operator
- Environmental benefits

The financial input values for the three categories has been estimated and is presented in Tables 3–6.

Table 3. Alternative scenarios for toll plaza operation.

Scenarios		Total Volume (Veh. Per Hour)	Total Booths	MTC Booths	ETC Booths	Pen. Rates (Vehicle Classes 3&4)	Pen. Rates (Vehicle Classes 1&2)
Base Scenario		2511	7	7	-	-	-
	1.1	2511	8	8	-	-	-
1.x	**1.2**	2511	9	9	-	-	-
	1.3	2511	10	10	-	-	-
	2.1	2511	7	6	1	10	5
	2.2	2511	7	6	1	10	10
	2.3	2511	7	6	1	10	15
	2.4	2511	7	6	1	10	20
	2.5	2511	7	6	1	10	25
	2.6	2511	7	6	1	10	30
	2.7	2511	7	6	1	20	5
2.x	**2.8**	2511	7	6	1	20	10
	2.9	2511	7	6	1	20	15
	2.10	2511	7	6	1	20	20
	2.11	2511	7	6	1	20	25
	2.12	2511	7	6	1	20	30
	2.13	2511	7	6	1	30	5
	2.14	2511	7	6	1	30	10
	2.15	2511	7	6	1	30	15
	2.16	2511	7	6	1	30	20
	2.17	2511	7	6	1	30	25
	2.18	2511	7	6	1	30	30
	3.1	2511	8	7	1	10	5
	3.2	2511	8	7	1	10	10
	3.3	2511	8	7	1	10	15
	3.4	2511	8	7	1	10	20
	3.5	2511	8	7	1	10	25
	3.6	2511	8	7	1	10	30
	3.7	2511	8	7	1	20	5
3.x	**3.8**	2511	8	7	1	20	10
	3.9	2511	8	7	1	20	15
	3.10	2511	8	7	1	20	20
	3.11	2511	8	7	1	20	25
	3.12	2511	8	7	1	20	30
	3.13	2511	8	7	1	30	5
	3.14	2511	8	7	1	30	10
	3.15	2511	8	7	1	30	15
	3.16	2511	8	7	1	30	20
	3.17	2511	8	7	1	30	25
	3.18	2511	8	7	1	30	30

Table 4. Fuel prices, fuel technology distribution for private vehicles, and average CO_2 emissions based on fuel consumption.

Fuel Prices		Fuel Technology for Private Usage Vehicles		Average CO_2 Emissions/Liter of Fuel	
Fuel Category	**Fuel Price**	**Fuel Category**	**Share (%)**	**Fuel Category**	**CO_2 (g/l fuel)**
Unleaded	1.622	**Unleaded**	51.3	**Unleaded**	2.392
Diesel	1.401	**Diesel**	45.8	**Diesel**	2.640
LPG	0.813	**LPG**	2.9	**LPG**	1.665

Table 5. Occupancy rates for the four vehicle classes.

Vehicle Classes	Occupancy Rate	Source
Vehicle Class 1	1	On-site observations
Vehicle Class 2	1.7	[54]
Vehicle Class 3	30	[55]
Vehicle Class 4	1	On-site observations

Table 6. Input parameters to evaluate traffic related results.

Quantity	Value	Comments
Value of Time Private Vehicles (€/h)	10.8	Adjusted based on consumer price index. Value of time: 9 €/h (2005)
Value of Time HGV (€/h)	27.5	
Peak hour to daily volume percentage (%)	7	Estimated

In order to evaluate delay times and fuel consumption in a momentary manner, we considered past research findings to estimate the value of time for the passengers and occupancy rates for each vehicle class as well as the average fuel prices for each fuel category and the average percentage of vehicles of each fuel technology for the countries of EU [54,56,57]. Tables 4–6 summarize the necessary values to calculate benefits from the traffic impact analysis, while Table 7 provides the input data required to evaluate the environmental results. Finally, Tables 8 and 9 Table 8; Table 9 present the implementation cost elements and project evaluation data, respectively. The traffic volume during the peak-hour corresponds to 7% of the total traffic volume of the day, as was identified by the retrieval of historic data. Thus, to calculate the yearly profits, we multiply the hourly benefits with the value 14.28 (100/7 = 14.28) and then we multiply by 300 to make projections annually based [58]. Table 10 shows the financial profit or losses caused by the different (greater or lower) delays and fuel consumption for each scenario.

Table 7. External cost of air pollutants.

Air Pollutant	External Cost (€/tn)	Source
NO_x	6000	[59]
VOC	930	[59]
CO_2	42	[59]

Table 8. Implementation cost elements.

Cost Elements	Value	Source
Roadside Infrastructure (€/lane)	40,000	[60]
Central System Installation (€)	1,000,000	[60]
Operational Cost per MTC Booth (€/year)	250,000	Estimated
Operational Cost per ETC Booth (€/year)	156,000 + 4% of profits per year	[60]
OBU (€/Unit)	15	[60]

Table 9. Profits or losses of toll road users (all scenarios).

Scenarios		Profits/Losses Caused by Travel Time Reduction or Increase (€/Year)	Profits/Losses Caused by Fuel Consumption Reduction or Increase (€/Year)	Total Profits/Losses (€/Year)
Base Scenario		N/A	N/A	N/A
1.x	1.1	11,497,841	578,752	12,076,593
	1.2	16,120,414	805,449	16,925,863
	1.3	16,694,307	840,019	17,534,326
2.x	2.1	−16,277,895	−694,150	−16,972,045
	2.2	−8,162,226	−324,439	−8,486,665
	2.3	−1,341,451	3,557	−1,337,894
	2.4	4,788,524	300,249	5,088,773
	2.5	9,689,757	530,321	10,220,078
	2.6	12,877,693	689,998	13,567,691
	2.7	−9,371,351	−501,116	−9,872,467
	2.8	−1,779,232	−105,471	−1,884,703
	2.9	3,689,112	172,627	3,861,739
	2.10	8,570,233	427,145	8,997,378
	2.11	12,384,444	623,837	13,008,281
	2.12	14,910,305	760,371	15,670,676
	2.13	−2,451,646	−248,214	−2,699,860
	2.14	3,255,963	64,268	3,320,231
	2.15	7,693,049	317,558	8,010,607
	2.16	11,355,616	526,767	11,882,383
	2.17	14,524,673	705,707	15,230,380
	2.18	16,045,428	797,779	16,843,207
3.x	3.1	7,595,043	343,294	7,938,337
	3.2	10,627,700	510,121	11,137,821
	3.3	12,663,131	632,251	13,295,382
	3.4	14,639,314	740,714	15,380,028
	3.5	16,101,677	822,244	16,923,921
	3.6	16,747,989	857,794	17,605,783
	3.7	10,340,535	437,784	10,778,319
	3.8	12,703,507	585,935	13,289,442
	3.9	14,443,066	693,389	15,136,455
	3.10	16,060,996	792,344	16,853,340
	3.11	17,029,275	847,617	17,876,892
	3.12	17,309,836	868,887	18,178,723
	3.13	12,594,229	527,217	13,121,446
	3.14	14,486,232	653,632	15,139,864
	3.15	15,921,390	751,538	16,672,928
	3.16	17,019,563	823,795	17,843,358
	3.17	17,633,317	862,828	18,496,145
	3.18	17,686,383	873,940	18,560,323

Table 10. Benefits for the toll operator.

Scenarios	Operational Cost of MTC Booth (€/Year)	Operational Cost of ETC Booth (€/Year)	Total Cost (€/Year)	Total Profits/Losses (€/Year)
Base Scenario	1,750,000	N/A	1,750,000	0
Scenario 1.1	2,000,000	N/A	2,000,000	−250,000
Scenario 1.2	2,250,000	N/A	2,250,000	−500,000
Scenario 1.3	2,500,000	N/A	2,500,000	−750,000
Scenarios 2.x	1,500,000	636,411	2,136,411	−386,411
Scenarios 3.x	1,750,000	636,411	2,386,411	−36,411

The benefits for the toll operator result from the operational cost reduction and are presented in Table 10. The operational cost of each MTC booth is estimated and equal to 250,000 €/year.

In order to evaluate an investment, various methods have been developed, that set criteria for the feasibility of a new project [61]. The indexes used are payback period (Pp), internal rate of return (IRR), net present value (NPV), and benefit–cost ratio (BCR). The calculation of the indicators mentioned above requires the lifetime of the project, the construction duration, and the interest rate of the project. Based on past research findings, we used ten years as project's lifetime, one year for the duration of the construction proceedings, and 5% as interest rate [60]. Table 11 summarizes the financial indicators for all simulated scenarios.

Table 11. Financial indicators of project's viability.

Scenarios	Payback Period (Years)	Internal Rate of Return (IRR)	Net Present Value (€)	Benefit-Cost Ratio (BCR)
Scenario 1.1	N/A	N/A	91,930,640	N/A
Scenario 1.2	N/A	N/A	127,683,464	N/A
Scenario 1.3	N/A	N/A	130,487,787	N/A
Scenarios 2.1	N/A	N/A	−124,681,703	−18.08
Scenarios 2.2	N/A	N/A	−70,808,066	−5.78
Scenarios 2.3	N/A	N/A	−26,020,884	−0.81
Scenarios 2.4	1.88	53.27%	13,849,267	1.76
Scenarios 2.5	1.08	92.73%	44,889,206	3.03
Scenarios 2.6	0.94	106.52%	63,789,782	3.45
Scenarios 2.7	N/A	N/A	−78,081,816	−8.55
Scenarios 2.8	N/A	N/A	−27,552,803	−1.28
Scenarios 2.9	2.25	44.46%	7,695,504	1.48
Scenarios 2.10	1.11	89.84%	38,787,342	2.95
Scenarios 2.11	0.90	111.19%	62,212,095	3.61
Scenarios 2.12	0.86	116.50%	76,452,848	3.76
Scenarios 2.13	N/A	N/A	−30,932,351	−2.15
Scenarios 2.14	2.32	43.05%	6,200,096	1.45
Scenarios 2.15	1.12	89.00%	34,276,642	2.94
Scenarios 2.16	0.90	111.28%	56,771,143	3.64
Scenarios 2.17	0.81	122.72%	75,692,085	3.97
Scenarios 2.18	0.84	118.72%	82,786,940	3.82
Scenarios 3.1	0.49	206.13%	43,209,897	7.61
Scenarios 3.2	0.51	197.79%	61,114,331	6.85
Scenarios 3.3	0.56	178.90%	71,924,398	6.01
Scenarios 3.4	0.60	166.73%	82,228,277	5.50
Scenarios 3.5	0.65	153.51%	88,846,770	5.01
Scenarios 3.6	0.73	137.10%	89,587,469	4.44
Scenarios 3.7	0.42	236.65%	60,884,191	8.45
Scenarios 3.8	0.48	209.07%	74,111,647	7.13
Scenarios 3.9	0.54	185.45%	82,805,978	6.18
Scenarios 3.10	0.59	169.18%	90,611,580	5.55
Scenarios 3.11	0.66	151.86%	93,683,484	4.94
Scenarios 3.12	0.75	133.71%	91,838,438	4.31
Scenarios 3.13	0.40	248.33%	75,190,442	8.66
Scenarios 3.14	0.47	213.47%	85,062,556	7.20
Scenarios 3.15	0.53	187.33%	91,622,837	6.20
Scenarios 3.16	0.60	166.61%	95,704,679	5.44
Scenarios 3.17	0.68	147.67%	96,251,762	4.78
Scenarios 3.18	0.77	129.31%	92,788,599	4.16

The results presented in Table 11 show that the financial indicators follow a similar course to that of environmental and traffic results. More specifically, in Scenarios 1.x the addition of each MTC lane returns a positive net present value, as the only additional cost element calculated is the operational cost of the extra booth.

As already mentioned, Scenarios 2.x and 3.x are divided in three subcategories, so the results for these scenarios are presented in subcategories. For the first subcategory (scenarios 2.1–2.6), the interventions are considered viable, when the penetration rate of the ETC lane by passenger vehicles exceed 20%. The threshold above which the proposed intervention is profitable is 15% and 10% for the second (scenarios 2.7–2.12) and third (scenarios 2.13–2.18) subcategories, respectively. When the penetration rates of the ETC lane are lower than the above mentioned, it was observed that the benefit–cost ratio is negative, as the intervention does not improve the traffic and environmental conditions, and therefore there are no benefits. For the same reason, the payback period and the internal rate of return (IRR) are not defined for these scenarios.

For Scenarios 3.x, based on the indicators, it is obvious that even for low penetration rates by passenger vehicles the interventions are viable. It is noteworthy though, that the penetration rate increase does not lead to a greater profit of the investment. On the contrary, the payback period is longer and the internal rate of return decreases, while the investment remains profitable.

These conclusions are also obvious in Figure 19, which presents the benefit–cost ratio value for all scenarios involving the implementation of ETC lane. For penetration rates of HGV equal to 10% (scenarios 2.1–2.6), the ratio exceeds zero, when the penetration rate of passenger cars is greater than 16%. For penetration rates of HGV equal to 20% (scenarios 2.7–2.12) and 30% (scenarios 2.13–2.18), the rates of passenger vehicles for which positive values of the ratio appear, is equal to 11% and 6.5%, respectively.

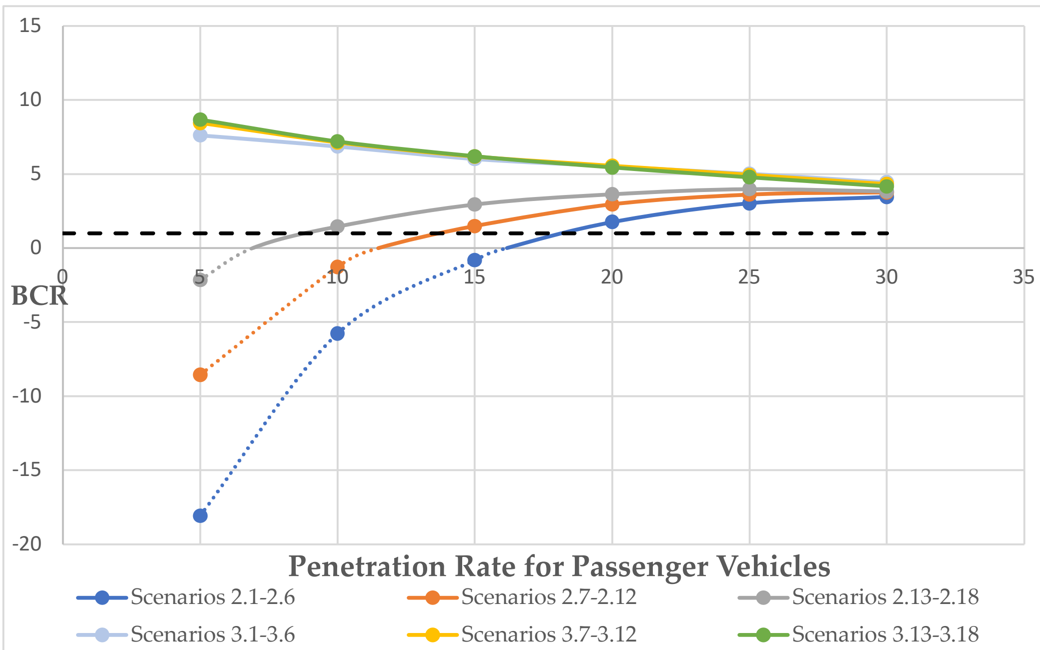

Figure 19. Benefit–cost ratio.

In order for the investment to be considered viable, BCR should be greater than one. As shown in Figure 19, for Scenarios 2.x, the penetration rates of passenger vehicles should exceed 18%, 13.5%, and 8% for each subcategory, respectively, to have a benefit–cost ratio greater than one. Regarding Scenarios 3.x, on all three subcategories the chart line follows a similar course. Initially, the ratio's value is between 7.6 and 8.6 and gradually decreases, as the penetration rates increase, converging to a value just above 4.

It is worth mentioning that the convergence between the values of the benefit–cost index of all scenarios is at a value near 4. This can be attributed to the convergence observed in both traffic and environmental results as the penetration rates of the ETC lane increase. In other words, we can conclude that as the operation of the station normalizes traffic (queue length, travel time) and environmental factors (emissions) tend to stabilize at certain values, thus causing the benefit–cost ratio to converge.

The benefits of the interventions have a great influence on the course of the financial indicators. This is because the costs remain constant between the scenarios of the same category (ETC installation, central system implementation, maintenance and operation of the ETC lane, and operational cost of the MTC lane). The only variable cost is that of the on-board units, which depends directly on the penetration rate of the ETC lane.

5. Discussion

In this paper, we investigated whether the implementation of ETC lanes can improve traffic conditions on an existing toll station and yield environmental and financial benefits. Our study site was an existing toll station near Thessaloniki Metropolitan Area, Greece, where only MTC booths are currently available. Three scenario subcategories were tested using VISSIM to simulate the network of the study site and model the proposed interventions.

The successive addition of MTC lanes leads to an improvement of the current situation by reducing queues, delays, and emissions. In scenarios where the station operated with ten MTC lanes, the traffic conditions were very good with the average queue length remaining low and approximately equal to three passenger cars. These results were expected as the additional lanes decongest the toll plaza, but the necessary MTC lanes are more than the ETC lanes, which would lead to the same level of service [31].

In Scenarios 2.x, it seems that the reduction of the lanes available for manual toll collection causes greater traffic and environmental problems when the penetration rates of the electronic payment lane are small. This finding confirms the suggestion of Levinson et al. (2002), that an increase in ETC lanes causes delays and long queues for nonequipped users [49]. The increase of the penetration rates of the electronic payment lane, leads to benefits of the intervention, culminating in scenarios 2.12 and 2.18, where very short queue lengths were observed, as was also the case on the study conducted by Chen et al. (2014) who concluded that the implementation of a single ETC lane would decongest the toll station [34]. The financial results of scenarios 2.x were similar to the traffic and environmental, as the interventions lead to losses for low penetration rates, with the greater profits calculated for the larger penetration rates (30% for both passenger vehicles and HGV).

On scenarios of the third category, there was an improvement of the operating conditions of the station even from the first scenario, where the penetration rate of the ETC lane is low. The increase of the penetration rate resulted in very good operating conditions of the station on scenarios 3.6, 3.7, 3.11, 3.12, 3.16, 3.17, and 3.18 with an average queue length almost equal to that of the three passenger vehicles. This result was expected, as a lane was added to the existing facility, thus absorbing a percentage of traffic volume, which increased as the penetration rates of the ETC lane increased. The efficiency of the electronic payment lane in improving the operating conditions of the station is a strong correlation of the penetration rates. As long as the lane usage rate remains low, traffic conditions and emissions not only do not improve but are getting worse. Regarding the financial impact of these scenarios, the most profitable scenarios are those with lower penetration rates as the additional ETC lane cannot serve the increased volume of vehicles that use it, thus making the investigation of scenarios with more than one ETC lane necessary.

5.1. Policy Implications and Recommendations

The optimal toll station setup is a crucial factor for the profit maximization and impact reduction. Many factors need to be defined before choosing the location of the toll plaza, the collection method, and the toll rates. The findings of this study could be useful to the toll operator, to define the best combination of ETC and MTC booths for different traffic volumes and mixture. This research could be used for existing toll stations or for designing a new station.

It should be mentioned that the toll station examined in this study is located at a national highway, which is under concession tender by the Greek Government. Among various economic and financial indices that need to be examined by the candidate consortiums, is that of Operating and Capital Expenses (OPEX & CAPEX). This study contributes by identifying the optimal penetration levels for ETC private and HGV users where the financial gains return positive. This information is vital for the relief of the financial risk of the investment.

5.2. Constraints and Limitations

This study was based on certain assumptions and included certain limitations, which are presented below, in order to evaluate their influence on the results and the reliability of the study.

- Queue length at the toll station was measured indirectly through the number of cars stopped at the queue. The usage of a drone may result in more accurate formulation of the queue at the toll station.
- The model was calibrated using the maximum queue length as it was not possible to calculate the average queue length during the on-site observation.
- No scenarios were simulated with penetration rates greater than 30%, or scenarios with more than one ETC lanes.
- The total number of toll booths remains constant and the booths are allocated on both directions depending on the vehicle volume. The increased number of booths in one direction causes a reduced number in the opposite direction, which may influence its operating condition, but this paper evaluated the operation at one direction only.
- The parameters that were used to calculate the annual profits from the hourly profits (peak hour load = 7% of the daily load and 300 days/year) were estimated based on previous studies.
- The value of time for the passengers was determined for the year 2005 and was converted using the consumer price index. To the best of authors knowledge, not updated value of time estimations were available.
- We did not consider the safety improvements from ETC implementation, which would increase the social benefits and increase the profitability of the project, as past research suggested [24,25].
- The percentage of users that choose the ETC lanes was estimated based on a study for Attiki Odos, which is a similar urban highway in Athens Metropolitan Area and the only one with available public data.

5.3. Suggestions for Future Research

The present study can be used in other toll stations and could be the basis for further research regarding the installation of electronic toll collection lanes, as part of the continuous effort to modernize the road infrastructure. More specifically, future planned work is to investigate the implementation of a second electronic toll collection lane (ETC only or simultaneous use for ETC and MTC) for penetration rates greater than 30%. It would be beneficial to consider the possibility of dynamically activating the second lane for ETC in real-time based on the traffic volume and traffic conditions in general. Vissim is an extremely useful tool as it allows the testing of various scenarios with low effort, while it is possible to add scripts written in programming language, which would change certain parameters of the model based on factors that the user has set. These features could be used to test scenarios were the toll station setup (total MTC and ETC lane number) is not static but changes dynamically based on traffic volume or other conditions (e.g., certain queue length).

Another suggestion for future work is to model a network with the addition of autonomous vehicles on the traffic volume, as the percentage of autonomous vehicles is expected to rise in the following years. Autonomous vehicles are expected to have different traffic profiles (e.g., acceleration, deceleration, time/space gaps etc.) and therefore are expected to behave in a different manner compared to the existing conventional conditions. Muhammad et al. (2020) in their research found that the increase of autonomous vehicles would increase the average speeds and the introduction of autonomous buses would increase the total road capacity [62]. This research proposed solutions with the implementation of ETC lanes, using DSRC technology, where the vehicles need to slow down but not perform a full stop to pay the toll fee, as this is the most common system to be used on individual facilities [3]. Currently there are various ETC technologies that may have less restrictions and would increase profits. Traffic modeling offers many benefits, but many proposed interventions may have to be tested in real life, to evaluate its performance. Thus, it would be beneficial to use real vehicles to assess the interventions proposed in real traffic conditions and afterwards quantify their benefits through simulation studies like that in this paper.

Finally, as it was mentioned above, the percentage of drivers that would choose ETC lanes was estimated based on past research, so a questionnaire survey could be conducted, to determine the opinion of the road users regarding their willingness to acquire an on-board-unit and use ETC lanes, as previous studies found that many users are reluctant to consent to their data being processed by the toll operator without any guarantee or a compensation [63].

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References

1. Victoria Transportation Policy Institute Transportation Cost and Benefit Analysis II–Travel Time Costs Available online: www.vtpi.org/tca/tca0502.pdf (accessed on 10 September 2020).
2. Schneider, S. *Toll Financing of U.S. Highways*; Dalmont: Washington, DC, USA, 1985; ISBN 3663537137.
3. Iseki, H.; Demisch, A. Examining the linkages between electronic roadway tolling technologies and road pricing policy objectives. *Res. Transp. Econ.* **2012**, *36*, 121–132.
4. US-PIRG. *Do Roads Pay for Themselves? Setting the Record Straight on Transportation Funding*; US-PIRG: Denver, CO, USA, 2010; pp. 1–45.
5. EIU. *Driving Change How Policymakers Are Using Road Charging to Tackle Congestion*; EIU: London, UK, 2006.
6. Ramandanis, I.-D. Feasibility Study of Electronic Tolling Scenarios in Highways, Using a Microscopic Traffic Simulation Model. Diploma Thesis, Aristotle University of Thessaloniki, Thessaloniki, Greece, 2020.
7. Komsta, H.; Brumercikova, E.; Bukova, B. Application of NFC technology in passenger rail transport. *Transp. Probl.* **2016**, *11*, 43–53.
8. Brumercikova, E.; Bukova, B.; Nedeliakova, E. A proposal for the account-based ticketing application in passenger transport in the Slovak Republic: A case study. *Sustainability* **2020**, *12,* 5491.
9. Astarita, V.; Calabria, U.; Calabria, U. A Simple Road Pricing System Based on Mobile Phone and Time of Use Toll Policy. In Proceedings of the XX Convegno Annuale e Seminario Scientifico della Società Italiana dei Docenti di Trasporti, Trieste, Italy, 17–18 October 2013.
10. Dias, J.; Matos, J.N.; Oliveira, A.S.R. A New NFC and Smartphone-based Toll Collection System. *Procedia Technol.* **2014**, *17*, 130–137.
11. Kurth, M.; Kozlowski, W.; Ganin, A.; Mersky, A.; Leung, B.; Dykes, J.; Kitsak, M.; Linkov, I. Lack of resilience in transportation networks: Economic implications. *Transp. Res. Part D Transp. Environ.* **2020**, *86*, 102419.
12. Bär, L.; Ossewaarde, M.; van Gerven, M. The ideological justifications of the Smart City of Hamburg. *Cities* **2020**, *105*, 102811.
13. Wang, J.; Ren, Y.; Shen, L.; Liu, Z.; Wu, Y.; Shi, F. A novel evaluation method for urban infrastructures carrying capacity. *Cities* **2020**, *105*, 102846.
14. McCahill, C.; Jain, S.; Brenneis, M. Comparative assessment of accessibility metrics across the U.S. *Transp. Res. Part D Transp. Environ.* **2020**, *83*, 102328.
15. Vojtek, M.; Kendra, M.; Zitrický, V.; Daniš, J. Principles of logistics applied to railway passenger transport. In Proceedings of the 18th International Scientific Conference—LOGI 2017, Ceske Budejovice, Czech Republic, 19 October 2017; Volume 134.
16. Majercak, P.; Majercak, J. Logistics Indicators for Measuring Performance of Logistic System in the Company. In Proceedings of the 3rd International Conference on Education Reform and Management Innovation, ERMI, Bangkok, Thailand, 5–6 September 2015; pp. 151–155.
17. Schwimmer, E.; Gomez-Ibanez, J.A.; Casady, C. Toll-managed lane pioneers: Lessons from five US states. *Case Stud. Transp. Policy* **2019**, *7*, 655–666.

18. Jou, R.C.; Chiou, Y.C.; Kuo, C.W.; Tan, H.I. Freeway drivers' willingness to pay for an on board unit under an electronic toll collection system. *Transp. Res. Part C Emerg. Technol.* **2013**, *27*, 16–24.
19. Jou, R.C.; Chiou, Y.C.; Chen, K.H.; Tan, H.I. Freeway drivers' willingness-to-pay for a distance-based toll rate. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 549–559.
20. Lin, X.; Susilo, Y.O.; Shao, C.; Liu, C. The implication of road toll discount for mode choice: Intercity travel during the chinese spring festival holiday. *Sustainability* **2018**, *10*, 2700.
21. Holguín-Veras, J.; Encarnación, T.; González-Calderón, C.A. User perception of fairness of time-of-day pricing and other typical toll discounts. *Transp. Res. Part A Policy Pract.* **2020**, *137*, 560–581.
22. Panou, K. An empirical model for setting and adjusting road-toll rates based on optimized equity and affordability strategies. *Case Stud. Transp. Policy* **2020**.
23. Abdel-Aty, M.A.; Radwan, E. Modeling traffic accident occurrence and involvement. *Accid. Anal. Prev.* **2000**, *32*, 633–642.
24. Abuzwidah, M.; Abdel-Aty, M. Safety assessment of the conversion of toll plazas to all-electronic toll collection system. *Accid. Anal. Prev.* **2015**, *80*, 153–161.
25. Saad, M.; Abdel-Aty, M.; Lee, J. Analysis of driving behavior at expressway toll plazas. *Transp. Res. Part F Traffic Psychol. Behav.* **2019**, *61*, 163–177.
26. Zarrillo, M.L.; Radwan, A.E.; Al-Deek, H.M. Modeling traffic operations at electronic toll collection and traffic management systems. *Comput. Ind. Eng.* **1997**, *33*, 857–860.
27. Van Dijk, N.M.; Hermans, M.D.; Teunisse, M.J.G. Designing the Westerscheldetunnel Toll Plaza using a combination of queuing and simulation. In Proceedings of the Winter Simulation Conference, Phoenix, AZ, USA, 5–8 December 1999; pp. 1272–1279.
28. Ozbay, K.; Mudigonda, S.; Bartin, B. Development and calibration of an integrated freeway and toll plaza model for New Jersey Turnpike using Paramics microscopic simulation tool. *IEEE Conf. Intell. Transp. Syst. Proc. ITSC* **2005**, *2005*, 1165–1170.
29. Ito, T. Process Simulation Approach To Design And Evaluation of Toll Plaza With ETC Gates. *Int. J. Simul.* **2002**, *6*, 14–21.
30. Poon, N.; Dia, H. Evaluation of toll collection performance using traffic simulation. In Proceedings of the 27th Conference of Australian Institutes of Transport Research (CAITR 2005), AITR, Brisbane, Australia, 7–9 December 2005; p. 20.
31. Hamid, A.H.A. Simulation of Traffic Operation And Management at Malaysian Toll Plazas Using VISSIM. *Malays. Univ. Transp. Res. Forum Conf.* **2011**, 13–21.
32. Pratelli, A.; Schoen, F. Multi-toll-type motorway stations optimal layout. *WIT Trans. Built Environ.* **2006**, *89*.
33. Abdelwahab, H.T. Traffic micro-simulation model for design and operational analysis of barrier toll stations. *Ain. Shams Eng. J.* **2017**, *8*, 507–513.
34. Ma, J.; Yin, Y.; Huang, H.; Pan, D. Safe, Smart, and Sustainable Multimodal Transportation Systems © ASCE 2014 3743. *CICTP* **2014**, *2014*, 3743–3751.
35. Aksoy, G.; Celikoglu, H.B.; Gedizlioglu, E. Analysis of Toll Queues by Micro-simulation: Results from a Case Study in Istanbul. *Procedia-Soc. Behav. Sci.* **2013**, *111*, 614–623.
36. Obelheiro, M.R.; Cybis, H.B.B.; Ribeiro, J.L.D. Level of service method for Brazilian toll plazas. *Procedia - Soc. Behav. Sci.* **2011**, *16*, 120–130.
37. Transport. Available online: https://www.eea.europa.eu/themes/transport/intro (accessed on 20 October 2020).
38. Gharehbaghi, K.; McManus, K.; Robson, K. Minimizing the environmental impacts of mega infrastructure projects: Australian public transport perspective. *J. Eng. Des. Technol.* **2019**, *17*, 736–746.
39. Weng, J.; Wang, R.; Wang, M.; Rong, J. Fuel consumption and vehicle emission models for evaluating environmental impacts of the ETC system. *Sustainability* **2015**, *7*, 8934–8949.
40. Tseng, P.H.; Lin, D.Y.; Chien, S. Investigating the impact of highway electronic toll collection to the external cost: A case study in Taiwan. *Technol. Forecast. Soc. Chang.* **2014**, *86*, 265–272.
41. Li, X.; Lv, Y.; Sun, W.; Zhou, L. Cordon- or link-based pricing: Environment-oriented toll design models development and application. *Sustainability* **2019**, *11*, 258.
42. Perera, L.; Thompson, R.G.; Wu, W. A multi-class toll-based approach to reduce total emissions on roads for sustainable urban transportation. *Sustain. Cities Soc.* **2020**, *63*, 102435.
43. Milenković, M.; Stepanović, N.; Glavić, D.; Tubić, V.; Ivković, I.; Trifunović, A. Methodology for determining ecological benefits of advanced tolling systems. *J. Environ. Manag.* **2020**, *258*.

44. Wang, J.; Hu, X.; Li, C. Optimization of the freeway truck toll by weight policy, including external environmental costs. *J. Clean. Prod.* **2018**, *184*, 220–226.
45. Odeck, J.; Welde, M. The accuracy of toll road traffic forecasts: An econometric evaluation. *Transp. Res. Part A Policy Pract.* **2017**, *101*, 73–85.
46. Odeck, J. Estimating and predicting the operational costs of road tolls: An econometric assessment using panel data. *Transp. Res. Part A Policy Pract.* **2019**, *130*, 466–478.
47. Regan, M.; Smith, J.; Love, P.E.D. Financing of public private partnerships: Transactional evidence from Australian toll roads. *Case Stud. Transp. Policy* **2017**, *5*, 267–278.
48. Mao, X.; Gan, J.; Zhao, X. Debt risk evaluation of toll freeways in Mainland China using the grey approach. *Sustain.* **2019**, *11*, 1–17.
49. Levinson, D.; Chang, E. A model for optimizing electronic toll collection systems. *Transp. Res. Part A Policy Pract.* **2003**, *37*, 293–314.
50. Map of E75. Available online: https://www.openstreetmap.org/?query=41.1127%2C22.5558#map=7/39.571/21.237&layers=T (accessed on 10 September 2020).
51. Egnatia-Odos Egnatia Odos-Price List and Vehicle Classification Page. Available online: https://www.egnatia.eu/en/for-the-citizen/stathmoi-diodion-timokatalogoi/ (accessed on 16 July 2020).
52. Toledo, T.; Koutsopoulos, M.; Ben-Akiva, M.; Jha, M. Microscopic traffic simulation: Models and application. *Oper. Res. Comput. Sci. Interfaces Ser.* **2005**, *31*, 99–130.
53. PTV Group. *PTV VISSIM 11 User Manual*; PTV Group: Karlsruhe, Germany2018, p. 1055.
54. Fiorello, D.; Martino, A.; Zani, L.; Christidis, P.; Navajas-Cawood, E. Mobility Data across the EU 28 Member States: Results from an Extensive CAWI Survey. *Transp. Res. Procedia* **2016**, *14*, 1104–1113.
55. European Environment Agency Long distance Bus Occupancy Rates. Available online: https://www.eea.europa.eu/data-and-maps/figures/long-distance-bus-occupancy-rates%0D%0A (accessed on 10 September 2020).
56. Ministry of Development & Investments Fuel Prices. Available online: http://www.fuelprices.gr/ (accessed on 9 January 2020).
57. Eurostat Passenger Cars in the EU. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_cars_in_the_EU (accessed on 10 September 2020).
58. Barbas, G.; Kopsacheilis, A.; Politis, I. Small scale intervention in a major city center interchange. Economic, environmental and sustainability analysis. *Transport. Res. Procedia* **2017**, *24*, 41–49.
59. Victoria Transportation Policy Institute Transportation Cost and Benefit Analysis II–Air Pollution Costs. Available online: www.vtpi.org/tca/tca0510.pdf (accessed on 10 September 2020).
60. 4icom. *Steer Davies & Gleave Study on "State of the Art of Electronic Road Tolling"*; 4icom: Paris, France, 2015; p. 125.
61. Sambrakos, E. *Οικονομική των Μεταφορών*; Εκδόσεις, 1st ed.; ΒΑΡΒΑΡΗΓΟΥ: Peiraias, Greece, 2017; ISBN 978-960-7996-67-1.
62. Muhammad, T.; Kashmiri, F.A.; Naeem, H.; Qi, X.; Chia-Chun, H.; Lu, H. Simulation Study of Autonomous Vehicles' Effect on Traffic Flow Characteristics including Autonomous Buses. *J. Adv. Transp.* **2020**, *2020*.
63. Riley, P.F. The tolls of privacy: An underestimated roadblock for electronic toll collection usage. *Comput. Law Secur. Rep.* **2008**, *24*, 521–528.

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