Mitigation of traffic pollution emissions in the built environment: a real-time flow actuated tool for on ramp management

Danae - Zoe Mitkas and Ioannis Politis
Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, 54124 Greece

danae.mitka@gmail.com
pol@civil.auth.gr

Abstract. Highways are increasingly common in today’s built environment and contribute majorly in environmental pollution. Mitigation strategies have been developed to decrease the traffic volume but have not been as effective, since the need for car use in transportation keeps growing. The key is to create an efficient road network which will allow the same traffic volume to flow through, with a reduced environmental impact. The main goals of this paper include the investigation and evaluation of alternative ramp metering scenarios on a freeway on-ramp and the development of a “smart” signal controller, with the use of PTV Vissim microsimulation software. A specific area was selected for the implementation of this study. More precisely, interchange K8 on the Ring road of Thessaloniki was chosen, in which, measurements of traffic volume were taken using a drone to record the traffic. Using the Vissim platform, a software model was created and evaluated to determine its accuracy compared to the existing situation. Different scenarios were developed, and the function of the interchange was observed, as well as the percentage of emissions. In the first set of scenarios, the traffic volume was increased by a certain percentage and the results were collected and examined. Next, two new scenarios with the use of ramp metering were developed and a traffic signal was placed on the on-ramp. In the first of these two scenarios, a traffic signal light with a fixed-time traffic program was placed, whereas in the second one, a vehicle-actuated signal light was created, with the use of the VisVAP add-on. A flow chart was generated and used to program the signal light, so that each time high traffic volume was detected by the detectors that were placed in the expressway, the red light was activated. After all the scenarios were created and examined, certain KPI’s regarding CO, NOx and VOC emissions and fuel consumption, as well as other traffic related data, were collected and used for the overall evaluation. The results from the use of the ramp meter, either the fixed-time or the vehicle-actuated, showed that a ramp meter can be very useful in the improvement of the traffic conditions and may have a positive environmental impact, by reducing emissions even up to 70%.

Keywords: Traffic simulation, Vissim, VisVAP, dynamic scenarios, smart scenarios, smart infrastructure, vehicle actuated signal controlling, Intelligent Transportation Systems, interchange, traffic improvement, level of service improvement, environmental impact, environment, emissions.

1. Introduction
Built environment, such as buildings and infrastructure, is an integral part of human development. It provides all necessary structures to assist basic human needs, including food, shelter and transport. Built environment stocks may remain in societies from years to over a century, therefore have long-term impact on human development, as well as the environment and emission growth. As urban centers expand, and different means of transportation are used by constantly growing populations, the need for a sustainable built environment increases and transportation planning becomes a significant challenge...
for engineers. Sustainability is based on three pillars: environment, economy and society. Transportation can be unsustainable in all three ways, which makes traffic engineering even more complex.

Daily commuters and occasional travellers perform a variety of trips, which must be delivered with efficiency. Changes in the built environment could be a potential solution to problems that occur, such as traffic congestion and delays, and have been investigated through the past years. These changes can be beneficial for the environmental impact too. Creating efficient road networks can have positive effects both on traffic conditions and the environment.

While the increasing desire of people to travel makes transportation management ever more complex, technology continues to yield efficient solutions. Technological advances offer to any engineer the tools to process large volumes of data, to create models using microscopic simulation software, and to produce results with high levels of accuracy. The tool used in this paper to analyse the situation was the microsimulation software PTV Vissim 10, which allows the user to create traffic models very close to reality.

The main objective of this work is to evaluate the application of Ramp Metering on an on-ramp and to investigate the application of alternative scenarios and their effects on the environment, by using microsimulation software. Ramp metering was developed in an effort to improve traffic conditions and reduce congestion of interchanges. Controlling freeway entrances is designed to prevent the increase of traffic volume within the freeway (FHWA, 2014). For this purpose, traffic lights are placed on the on-ramps, to control the rate at which vehicles enter the freeway. These traffic lights can be either fixed timed or vehicle actuated, which can be full traffic actuated or semi traffic actuated. In the first type, traffic is recorded on all accesses of an interchange or junction, whereas in the second type traffic is recorded to one or more entrances, but not in all of them (Frantzeskakis, Goliad & Pitsiava-Latinoopoulou, 2009). With a vehicle actuated ramp meter, the entering vehicles are stopped as soon as it is detected that the Level of Service has dropped in the freeway. Vehicles are released again when lower traffic volume and higher speed is detected in the mainline.

Different scenarios were created for a selected area of study, with the use of the Vissim simulator. These scenarios examined the function of the network under different traffic volumes and with the use of ramp metering, which aimed to meliorate traffic congestion and emissions. The software was proved to be very useful in this procedure, since it allows the user to make any changes or add new data in the network. At the end of the experimental procedure, certain Key Performance Indicators (KPI’s) were collected to compose the results. These KPI’s included CO Emissions, NOX Emissions, VOC Emissions, Fuel Consumption and Level of Service.

2. Environmental impact and Ramp metering

Following the demands of society, a complete transport study must not only focus on the reduction of travel time, but also requires minimizing the environmental impact. The main objective is to create sustainable transport systems that both improve traffic conditions and also take into account the environmental impact. The situation in freeways often resembles that of urban roads prior to the installation of signal lights, congested axes, confusion prevailing at interchanges and reduced sense of security, while they should offer unlimited mobility to all commuters.

Therefore, in order to achieve full exploitation of the capacity of the freeways, at no extra cost to the environment, traffic control measures must be taken. One of them could be Ramp metering, which can restore normal traffic conditions and improve the Level of Service at the main axis. According to studies, the implementation of Ramp metering to highways leads to the reduction of traffic density and delays, and thus to a significant reduction of emissions.

3. Description of Area of Study

A certain interchange on the inner Ring Road of Thessaloniki (highway 111) was selected. Ring Road 111 is an urban highway which connects the western part of the city with the Airport in the south east. It is a dual expressway with three lanes per direction. The studied interchange K8 carries the traffic from the city center, through the on-ramp, to the Ring Road. The interchange has three entrance axes (A, B, C) and two exits (1, 2). Axes B and C merge into axis A.
3.1. Problems observed at the area of study

The studied interchange is required to serve high traffic volumes daily and congestion problems occur frequently, especially during morning peak hours. The mainline often fails to serve the large number of entering vehicles, which leads to congestion. The situation is worsened by the fact that the mainline is uphill before and after the interchange, forcing the vehicles to lower their speed.

4. On field Traffic Observations

In order to create the most accurate representation of the current situation in the Vissim simulation software, it was necessary to measure the traffic load on field. Visiting and observing the field was necessary to recognize all the peculiarities of the study area and to have them imprinted on the model. To measure the traffic volume in the study area, a high-resolution camera drone was used to record the traffic. Specifically, the dji Phantom 4 drone was selected, for its flight stability and high definition image.

![Figure 1. Screenshot of the traffic recording.](image)

After the recording was completed, the data was processed to determine the composition of the traffic and to form the Origin-Destination Matrix. The insertion of data in the Vissim simulation program and according to the international bibliography, the results must be in a one-hour (60 minutes) interval, and therefore were adapted to this interval. The final Origin-Destination Matrix for a one-hour interval is shown below.

| Destination | 1 | 2 |
|-------------|---|---|
|             | Cars | Trucks | Buses | Cars | Trucks | Buses | Total |
| A           | 3396 | 117    | 11    | 33   | 0      | 0      | 3557  |
| B           | 668  | 6      | 2     | 232  | 2      | 0      | 910   |
| C           | 838  | 22     | 3     | 82   | 0      | 1      | 946   |
| Total       | 4902 | 145    | 16    | 347  | 2      | 1      | 5413  |

PTV Vissim 10.0 was used to process the data. Vissim microsimulation software was chosen for its capability to simulate as close as possible to real-life conditions and for its user-friendly environment.
“Microscopic Simulation” or Microsimulation means that each entity (car, train, pedestrian) of reality is simulated individually, and represented by a corresponding entity in the simulation, considering all relevant properties. Vissim also makes it possible to analyze the interaction between vehicles and infrastructure, as in the case of "intelligent" signals, alternating signposts and vehicle communication (C2X). Vissim software provides its users with a set of additional tools. One of these tools is VisVAP (Vehicle Actuated Programming) which enables the user to design a flow chart that controls some part of the infrastructure (eg, traffic lights). This add-on was chosen because it enables the user to create scenarios of dynamic response to events. The fixed-time signal can be replaced with a vehicle actuated signal which is adapted to the traffic conditions.

5. Development and Evaluation of the model

5.1. Development of the model

The study area was designed in the Vissim software. The road network resulted from a sequence of links and connectors. In this study area one of the most important elements was the inclination of the different parts of the network. The driving behavior of the vehicles was chosen, such as that found on freeways (Free Lane selection), except for the part of the entering axis where it was chosen to be an urban motorized network. Accordingly, the speed limits of the vehicles were set at 90 km/h and 60 km/h, and then adjusted to the other vehicle categories. Traffic data is imported for every possible route, creating the most accurate representation of the current situation. All possible routes (Static Vehicle Routes) (A-1, B-1, C-1, A-2, B-2, C-2) are given in the simulation, with the corresponding loads percentage of total for each direction (RelFlow).

Table 2. Vehicle distribution rates on the respective routes.

| Route | Percentage | Number of Vehicles |
|-------|------------|--------------------|
| A-1   | 99.1 %     | 3557               |
| A-2   | 0.9 %      |                    |
| B-1   | 74.3 %     | 946                |
| B-2   | 25.7 %     |                    |
| C-1   | 91.2 %     | 910                |
| C-2   | 8.8 %      |                    |

The Vehicle Composition is also introduced for each axis.

Table 3. Vehicle Composition for each axis.

| Vehicles | Entrance Lanes |
|----------|----------------|
|          | A              | B              | C              |
| Cars     | 96.7 %         | 99.1 %         | 97.4 %         |
| Trucks   | 3 %            | 0.7 %          | 2.3 %          |
| Buses    | 0.3 %          | 0.2 %          | 0.3 %          |

Data Collection Points are used to collect data from the Vissim model and Data Collection Measurements are then extracted and processed in Excel sheets. In order to obtain reliable results from the simulation model, it needs to be performed more than once. Vissim software is a stochastic model, and consequently different outcomes result from different simulation runs. Thus, a suitable Number of Runs is selected and then the results are taken from the average of the repetitions. For this paper, the number of 10 repetitions was selected.
5.2. Evaluation of the model
To create an accurate model, the resulting values should be compared to the actual measured values. Using the above-mentioned methods, the results were gathered to create the Origin-Destination Matrix for one simulation hour. The following table shows the results.

Table 4. Origin – Destination Matrix for one hour of simulation.

| Destination | 1 | 2 |
|-------------|---|---|
|              | Cars | Trucks | Buses | Cars | Trucks | Buses | Total |
| A           | 3395 | 116    | 11    | 32   | 0      | 0      | 3554  |
| B           | 665  | 6      | 2     | 230  | 2      | 0      | 905   |
| C           | 861  | 3      | 22    | 86   | 0      | 1      | 973   |
| Total       | 4921 | 125    | 35    | 348  | 2      | 1      | 5432  |

These results were compared with the results of the measurements reported in Table 1 and for their evaluation the GEH Statistical Index was used. The GEH index is used in traffic engineering, traffic forecasting and modelling to compare two sets of traffic load.

The GEH Index is calculated as follows:

\[ GEH = \sqrt{\frac{2(M - C)^2}{M + C}} \]

Where:
- \( M \) = Hourly traffic volume as derived from the model
- \( C \) = Hourly traffic volume as derived from the measurements

If \( GEH < 5 \), it is assumed that the simulation is probably executed correctly. The following table presents the results as they were obtained by comparing the hourly volumes of the simulation and those measured for the study area.

Table 5. Results for the Statistical Index GEH.

| Axis | Hourly traffic Volume from model (M) | Hourly traffic Volume from measurements (C) | GEH  |
|------|-------------------------------------|---------------------------------------------|------|
| A    | 3554                               | 3557                                       | 0.050|
| B    | 905                                | 910                                        | 0.166|
| C    | 973                                | 946                                        | 0.872|

The indicator was particularly small and therefore acceptable.

Then, a comparison of the Travel Time measured with the Travel Time resulting from 10 simulation runs was performed for a predetermined distance. After the data was processed, the following chart was generated.
The error is again acceptable as all values have a deviation of less than 5%.

Based on the above comparisons, the model's adequacy for reliable results has emerged. All procedures were performed on the basic model (Scenario 0), without any interference to the current situation.

6. Development and Evaluation of Alternative Scenarios
Specific Key Performance Indicators (KPI's) were chosen and used for the evaluation and the comparison of the scenarios.

The chosen KPI's are the following:
- CO Emissions
- NO\textsubscript{X} Emissions
- VOC Emissions
- Fuel Consumption
- Level of Service

6.1. Development of Scenarios
The results for the emissions refer to the total number of vehicles in the network for one hour of simulation and result from the average of the measurements after 10 simulation runs.

6.1.1. Scenario 0 – Base Case. The base case scenario shows the current situation without any interference with infrastructure or traffic data. The results from this scenario are shown in the table below.

| KPI's               | Scenario 0 |
|---------------------|------------|
| CO Emissions (gr)   | 5751.33    |
| NO\textsubscript{X} Emissions (gr) | 1119.00   |
| VOC Emissions (gr)  | 1132.93    |
| Fuel Consumption (gal) | 82.28     |
| Level of Service    | A          |

![Figure 2. Comparison of model Travel Time with measured Travel Time.](image-url)
6.1.2. Scenario 1.1 – Alteration of Traffic Volume. In this scenario the traffic volume was altered. The initial volume of main axis (A) was increased by 20% (New Volume: 4268) and the network’s operation was observed. The new results are shown in the table.

Table 7. Results for Scenario 1.1.

| KPI's                | Scenario 1.1   |
|----------------------|----------------|
| CO Emissions (gr)    | 11579.67       |
| NO\textsubscript{x} Emissions (gr) | 2249.09       |
| VOC Emissions (gr)   | 2679.06        |
| Fuel Consumption (gal) | 165.37        |
| Level of Service     | B              |

6.1.3. Scenario 1.2 – Alteration of Traffic Volume. In this scenario, the traffic volume was altered. The initial volume of main axis (A) was increased by 30% (New Volume: 4624) and the network’s operation was observed. It must be mentioned that with the new volume the network was unable to meet such a high demand and as a result, many vehicles (about 210), entering from the on-ramp did not complete their trip. Such a phenomenon was not observed in the previous cases.

Table 8. Results for Scenario 1.2.

| KPI's                | Scenario 1.2   |
|----------------------|----------------|
| CO Emissions (gr)    | 38524.02       |
| NO\textsubscript{x} Emissions (gr) | 7495.37       |
| VOC Emissions (gr)   | 8928.13        |
| Fuel Consumption (gal) | 551.13        |
| Level of Service     | E              |

6.1.4. Scenario 1.3 – Alteration of Traffic Volume. In this scenario the traffic volume was altered. The initial volume of main axis (A) was increased by 30% (New Volume: 4624) and the initial volume of entering axis (C) was increased by 20% and the network’s operation was observed. It must be mentioned that with the new volume the network was unable to meet such a high demand and as a result, many vehicles (about 390), entering from the on-ramp failed to complete their trip and the network eventually collapsed. Such a phenomenon was not observed in the scenarios 0 and 1.1.

Table 9. Results for Scenario 1.3.

| KPI's                | Scenario 1.3   |
|----------------------|----------------|
| CO Emissions (gr)    | 42358.86       |
| NO\textsubscript{x} Emissions (gr) | 8241.49       |
| VOC Emissions (gr)   | 9817.07        |
| Fuel Consumption (gal) | 605.99        |
| Level of Service     | E              |

6.1.5. Scenario 2.1 – Alteration of Infrastructure. Scenarios 1.2 and 1.3 with the particularly high volume, which is likely to be observed especially in days with bad weather conditions, indicate the need for some intervention. In the following scenarios the application of ramp metering will be presented and evaluated. The following scenarios will be created based on scenario 1.2 where there is a high volume, but the network remains operational. In scenario 1.3, the fact that a large number of vehicles failed to complete their trip affects the final results, producing values that do not correspond to a real situation. In Scenario 2.1 the installation of a fixed time traffic light will be implemented. The traffic light will be placed on the on-ramp, shortly before entering the B axis. Besides the traffic light, a flashing amber light will be placed earlier on the entering axis (C) to alert the drivers of the presence of a red traffic light.
ahead and therefore to reduce their speed. The aim of this installation is to achieve an improvement both on traffic conditions and on the environmental impact. One would think how such an intervention will improve the emission levels, since vehicles on the entering axis are forced to make an additional stop, which automatically causes extra emissions. However, stopping the vehicles on the entering axis facilitates the movement of the vehicles on the rest axes which serve larger traffic loads. Therefore, while emissions from vehicles on the entering axis (Volume C: 946) are likely to increase, the emissions produced by the vehicles on the other two axes (Volume A&B: 5534) are reduced since the vehicles are able to achieve an optimal speed. Overall, the result is beneficial.

### Table 10. Results for Scenario 2.1.

| KPI's                | Scenario 2.1 |
|----------------------|--------------|
| CO Emissions (gr)    | 20309.92     |
| NO\textsubscript{x} Emissions (gr) | 3951.48     |
| VOC Emissions (gr)   | 4706.92     |
| Fuel Consumption (gal) | 290.55    |
| Level of Service     | C            |

#### 6.1.6. Scenario 2.2 – Alteration of Infrastructure with a “smart” scenario. This scenario involves infrastructure intervention using a light signal, but this is a scenario of dynamic response to an event. The traffic light will remain in the same position and the signal program will be altered. This model is based on a traffic actuated signalling system. This type of signalling is useful for cases where large traffic loads appear at a node for specific time intervals, but without a certain pattern. The vehicle passes are recorded by special detectors placed on the main axis and transmitted to the signalling device. The VisVAP add-on was used to create this scenario. A flow chart was created, in which, when the Level of Service on the main axis is detected greater than C, then the red-light signal is actuated. This ensures a desirable Level of Service even at high volume conditions. The signal program was implemented and produced the results shown in Table 11.

### Table 11. Results for Scenario 2.2.

| KPI's                | Scenario 2.2 |
|----------------------|--------------|
| CO Emissions (gr)    | 10576.84     |
| NO\textsubscript{x} Emissions (gr) | 2057.87     |
| VOC Emissions (gr)   | 2451.28     |
| Fuel Consumption (gal) | 151.31    |
| Level of Service     | B            |

#### 6.2. Evaluation of Results

The following tables were created to compare the results that occurred from the different scenarios.

### Table 12. Comparison of Emission Results.

| Scenario | CO (kg) | Percentage | NO\textsubscript{x} (kg) | Percentage | VOC (kg) | Percentage |
|----------|---------|------------|--------------------------|------------|----------|------------|
| Scenario 0 | 5.751 | -- | 1.119 | -- | 1.332 | -- |
| Scenario 1.1 | 11.559 | +100% | 2.249 | +100% | 2.679 | +101% |
| Scenario 1.2 | 38.524 | +570% | 7.495 | +570% | 8.928 | +570% |
| Scenario 1.3 | 42.358 | +636% | 8.241 | +636% | 9.817 | +637% |
Table 13. Comparison of Emission Results after the implementation of Ramp Metering.

| Scenario    | CO (kg)  | Percentage | NOx (kg) | Percentage | VOC (kg) | Percentage |
|-------------|----------|------------|----------|------------|----------|------------|
| Scenario 1.2| 38.524   | --         | 7.495    | --         | 8.928    | --         |
| Scenario 2.1| 20.309   | -47.3%     | 3.951    | -47.3%     | 4.706    | -47.3%     |
| Scenario 2.2| 10.577   | -72.5%     | 2.058    | -72.5%     | 2.451    | -72.5%     |

Emissions: As expected, the increase of traffic volume will increase emissions as it causes network congestion and a drop in vehicle speed. The increase is due to both the higher traffic volume and the delays caused by the congestion. The increase in emissions is so immense because simulation models estimate the emissions exponentially. The implementation of Ramp Metering lead to a noticeable improvement of the situation as emissions were greatly reduced. This improvement resulted from the better flow of vehicles in the network, as the traffic volume remained the same.

Fuel Consumption: The reduction in fuel consumption is sizeable after the implementation of Ramp Metering. Scenario 2.2 reached the levels of Scenario 1.1 while the traffic volume was higher.

Level of Service: The Level of Service in Scenario 1.3 was calculated to be E by the Vissim software, but the fact that a large number of entering vehicles were unable to complete their trip indicates that the network suffered a complete saturation and therefore the actual Level of Service was F. Overall, the implementation of Ramp Metering had positive effects on the network, even if it was not possible to reach free flow conditions. It is important to observe that an improvement in the environmental impact can be achieved and at the same time keep the Level of Service of the network high, just by altering the infrastructure.

7. Effects of different Scenarios on the traffic conditions

KPI’s regarding the traffic conditions were also examined throughout the aforementioned procedure, to ensure that the use of ramp metering is beneficial both for the environment and traffic. The cumulative results of these KPI’s are shown and compared in the following tables.

Table 14. Comparison of Traffic Results.

| Scenario    | Total Travel Time (sec) | Percentage | Average Vehicle speed - start (km/h) | Percentage | Average Vehicle speed - end (km/h) | Percentage |
|-------------|-------------------------|------------|-------------------------------------|------------|----------------------------------|------------|
| Scenario 0  | 49.98                   | --         | 93.85                               | --         | 79.36                            | --         |
| Scenario 1.1| 63.03                   | +26.1%     | 92.81                               | -1.1%      | 60.16                            | -24.3%     |
| Scenario 1.2| 84.35                   | +68.7%     | 86.34                               | -8.0%      | 52.69                            | -33.7%     |
| Scenario 1.3| 81.07                   | +62.2%     | 87.45                               | -6.8%      | 56.74                            | -28.7%     |

Table 15. Comparison of Traffic Results after the implementation of Ramp Metering.

| Scenario    | Total Travel Time (sec) | Percentage | Average Vehicle speed - start (km/h) | Percentage | Average Vehicle speed - end (km/h) | Percentage |
|-------------|-------------------------|------------|-------------------------------------|------------|----------------------------------|------------|
| Scenario 1.2| 84.35                   | --         | 86.34                               | --         | 52.69                            | --         |
| Scenario 2.1| 68.13                   | -23.8%     | 91.35                               | +5.8%      | 60.54                            | +14.8%     |
| Scenario 2.2| 66.45                   | -21.22%    | 91.99                               | +6.5%      | 58.41                            | +10.8%     |

It needs to be mentioned that all the measurements regarding the traffic conditions were taken on the left lane of the main axis and for a predefined distance.

As expected, the increase of the traffic volume caused an increase in the travel time and a drop in vehicle speed as it causes network congestion. The fact that scenario 1.3 has a smaller percentage increase than scenario 1.2, while the network is loaded with more vehicles, is due to the collapse of the
network and many vehicles have failed to complete their journey. The application of Ramp Metering on the network was particularly positive. Traffic conditions were improved both by the use of a simple static signal and by the vehicle actuated signal. Undoubtedly, one would expect the case of the “smart” signal to show even better results, and so it did. The implementation of a signaling system adapted to the traffic conditions could only produce positive results.

8. Qualitative Results

The Vissim software model was implemented as close as possible to the actual conditions as all geometric and geomorphological characteristics of the area were considered when creating the model. Different scenarios were implemented on the model and analyzed, for different traffic loads and for the application of Ramp Metering.

The application of Ramp Metering on the network was particularly positive. Traffic conditions were improved both by the use of a simple static signal and by the vehicle actuated signal. Undoubtedly, one would expect the second case to show even better results, and so it did. The implementation of a signaling system adapted to the traffic conditions could only produce positive results.

Overall, placing the traffic light on the on-ramp improved the situation at many levels. Ramp Metering ensures uninterrupted flow in the main axis, and safe entry of vehicles from urban roads to freeways. As shown in scenario 2.2, vehicles are only allowed to enter when there is sufficient space in the main axis. It was also observed that even a simple intervention in the network, such as the installation of a traffic light, can have positive effects not only on the traffic but also on the protection of the environment.

Concerning the emissions, the results were very encouraging as they were apparently reduced after the application of Ramp Metering. Although a traffic light has been added, and some vehicles are forced into an additional stop, the level of air pollution is decreased. This is easily explained by the fact that when the entering vehicles are forced into an extra stop and reignition, the flow in the other two axes, whose load is almost five times higher, is greatly facilitated. Thus, the overall results appear to be positive.

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