THE URBAN STREET AS A POLLUTION HOT-SPOT: SIMULATIONS AND MEASUREMENTS FOR MODEL EVALUATION

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ABSTRACT

Epidemiological studies carried out in different parts of the world have indicated a correlation between morbidity and daily mortality, and concentration of fine particulate matter. A major urban source of the latter is motor vehicles. This is particularly true at air pollution hot-spots within the city road network, which include signalised street intersections and street canyons. In this paper, the latter are emphasised, and the experimental outcome of a brief air pollution monitoring campaign undertaken in a street canyon as well as the associated modelling/simulation are briefly discussed. Modelled data and measurements are compared as a means of evaluating a model developed (and further refined) by the author, and hence test its applicability in air quality review and management, in connection with the siting of urban air quality monitoring stations and the adherence to air quality standards.
Keywords: urban air pollution, street canyon, air quality monitoring, air quality modelling.

1 INTRODUCTION

The air pollution issue remains a very important problem to this day, given its health and associated economic implications. Urban air pollution is of particular importance given the relatively high population density in cities. Airborne particulate matter, which is a common urban air pollutant, has been given a lot of attention in the past three decades, as is evident in the multitude of published studies. For example, Beelen et al. [1] investigated long-term exposure to air pollution and its association with cardiovascular mortality. Their study spanned 22 European cities and concluded that there is suggestive evidence for an association between airborne particulate matter and cerebrovascular disease mortality. Pope et al. [2] concluded that acute exposure to $PM_{2.5}$ is associated with endothelial injury and systemic inflammation. It transpires that air pollution (airborne particulate matter, in particular) are implicated in a range of health effects, including mortality. For example, in the Global Burden of Disease Study 2019 [3], air pollution, including $PM_{2.5}$, was estimated to have contributed to approximately 6.7 million deaths globally. Consequently, urban air quality monitoring campaigns remain essential for the protection of human health.

The application of roadway emission-dispersion models contributes to the optimisation of monitoring campaigns. In particular, modelling assists in the identification of so-called air pollution hot-spots, which are essentially locations associated with a build-up of pollutant concentrations, leading to non-compliance as regards air quality standards. Furthermore, models enable further investigation of unexpected experimental outcomes and provide a desktop check of hunches and hypotheses.

Given that society is still heavily dependent on fossil fuels, air pollution in (confined) roadways remains a very important issue. Different methods have been used in street canyon air quality modelling. One of the most popular approaches is semi-empirical in character, whereby the relevant employed equations are by and large based on experimental data, even though some theoretical equations are also used. The Canyon Plume Box (CPB) model [4] and the Operational Street Pollution (OSP) model [5] are two such models. These and similar

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models have a non-numerical basis and hence are not computationally expensive in that they can run on a desktop computer in a relatively short time. This is why they are considered practical and can also be used as screening models. Evaluation of such models yielded good outcomes. For instance, Buckland [6] applied and evaluated the OSP model, in the UK, and the results turned out to be promising. More recently, sophisticated models such as that by Hood et al. [7] are emerging and proving to be useful too.

The current study constitutes an evaluation of a street canyon emission-dispersion model for mass concentration of various particle size cut-offs released by motor vehicles running on fossil fuel. The model is valid for confined roadways, i.e., streets. It is comprised of both emission and dispersion modules. The model is an improved version of an existing model developed by the author, which is described in full elsewhere (refer to Micallef and Colls [8] for a complete description).

2 MATERIALS AND METHODS

The general idea of the current study was to refine and test the street canyon emission-dispersion model described hereunder. Following improvements of several aspects of the said model, notably in the way that solar irradiance is computed, a monitoring campaign was undertaken to collect relevant data that would enable testing of the refined version of the air quality model. Subsequent to the evaluation exercise, the model was readjusted accordingly. Fig. 1, through a schematic description of the methodology adopted, summarises the main steps in the current study.

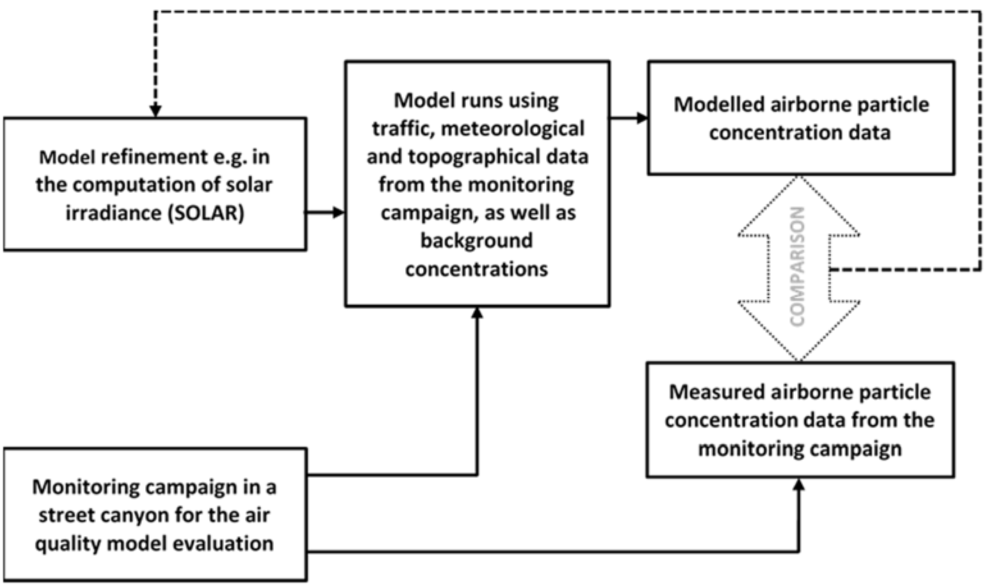

Figure 1: General schematic representation of the adopted methodology.

The general structure of the model is modular, and is schematically shown in Fig. 2. The salient features of the various modules employed are described in the following thematic subsections.

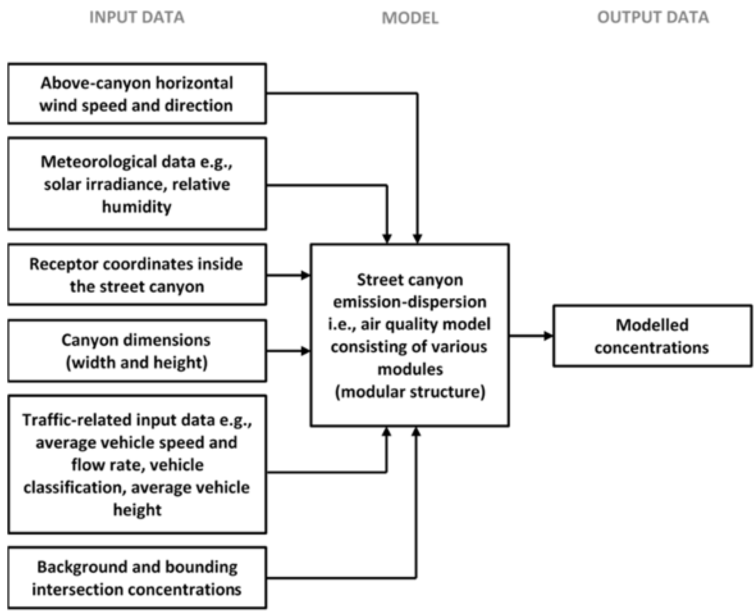

Figure 2: General schematic representation of the street canyon emission-dispersion, i.e., air quality model. The model input and output data are clearly shown.

2.1 Direct and indirect vehicular emissions

The estimation of motor vehicle emissions is an essential and fundamental part of the street canyon air quality model being considered in the current study. Both direct (emitted from the exhaust tailpipe) and indirect emissions, e.g., resuspended road dust and dust from brake-wear and tyres, are taken into account in the calculations. Emission factors for vehicle-derived particulate matter are computed using the methodology of PMFAC [9]. In fact, the emission model PMFAC is incorporated as a module within the street canyon air quality model. It is one of the many modules constituting the street canyon model. It is worth noting that precise calculation of emission factors is essential since the outcome of the dispersion model is very much dependent on the emission calculations.

The calculated emission factors take into account parameters such as ambient temperature, average vehicle speed, vehicle flow rate, road gradient and vehicle type, e.g., different types of heavy-duty vehicles in accordance with the number of wheels, vans, passenger cars, motor cycles. Vehicles running on a cold engine, which lead to substantially more emissions, are taken into account as well. This is particularly important when trips tend to be of short distance, as is the case in Malta, given its size.

The sub-module MODAL, within PMFAC, caters for modal behaviour of drivers leading to the various driving modes, e.g., cruising, deceleration, acceleration, creep and idle. Modal behaviour is, to a large extent, dictated by traffic lights (mainly located at street intersections) and other control mechanisms, e.g., zebra crossings. The methodology employed in MODAL is that developed by Griffin [10] and subsequently modified by Benson [11]. Essentially, using the Griffin–Benson methodology, emissions are computed element by element for each lane, along the street, taking into account traffic lights at street intersections and zebra-crossings. MODAL is capable of handling multiple control mechanisms within a given street. Nevertheless, it must be emphasised that intersection concentrations at the bounding junctions of the street must be provided by the model user as input data. It should be emphasised that the emission rates employed in MODAL are the work of Singh [9].

Concerning indirect emissions, two types are taken into account namely, particles generated by virtue of tyre, brake and road wear, and resuspension of road dust. The employed methodology is that of U.S. E.P.A., which is used in the so-called PART5 model [12]. The latter was developed for very dry conditions and relatively dusty roadways, so that the actual equations had to be adjusted so as to cater for higher relative humidity as is the case in Malta. For instance, one such adjustment involved the scaling of the road dust emissions by an expression which is a function of relative humidity [13].

2.2 Fuel consumption and vehicle-derived thermal turbulence

Fuel consumption by motor vehicles is linked to the heat generated by their engines. The latter is responsible for thermal turbulence, which becomes appreciable in narrow confined roadways with aspect ratio greater than unity, that are carrying heavy traffic.

FUELFAC is the module used for calculating fuel consumption of motor vehicles in the street. Fuel consumption associated with cruise mode is estimated using CORINAIR data [14], which is speed-dependent for passenger vehicles only. Hence, it was necessary to develop speed-dependent fuel consumption factors for vehicle classes other than passenger cars, e.g., vans, buses, heavy-duty vehicles. Fuel consumption is a function of power demand [15]. Hence, fuel consumption factors for driving modes other than cruise, i.e., creep, idle, deceleration and acceleration, were developed to ensure a more realistic value for the overall fuel consumption, and subsequently, of thermal turbulence generated by motor vehicles. FUELFAC utilises MODAL in the same way that PMFAC does. Indeed, the overall computation accomplished by FUELFAC resembles that of PMFAC. In fact, as is the case in PMFAC, fuel consumption rate is calculated lane-wise, taking into account the fleet characteristics. It is worth noting that petrol and diesel vehicles are treated separately in the calculation of fuel consumption.

2.3 Pre-processing of meteorological input data

The individual modules require certain input data. To facilitate data input by the model user, the required input data is kept to a minimum and requested in a format that is normally readily available and simple. This is particularly the case for meteorological data. Pre-processors are employed within the street canyon air quality model in order to estimate urban-scale parameters from the basic meteorological data inputted by the model user. Here, pre-processing refers to the data processing necessary prior to the actual core calculations performed by the main modules of the model. The meteorological pre-processors used are one of two types. The first type relates to radiation, while the second type concerns atmospheric flow (advection and convective flow). Nevertheless, there is a lot of intersection between the two types of modules, as evident from the ensuing description of the relevant modules.

One of the meteorological pre-processing modules employed in the model enables the estimation of the horizontal component of the wind speed at the roof top of the street canyon from wind speed data collected at a monitoring site, which is distant from the street canyon of interest. An exponent law for the vertical profile of the horizontal component of the wind speed, is assumed. The said exponential law is dependent on the atmospheric stability class and the type of surface [16]. In turn, the former is a function of the wind speed and solar irradiance [17]. Solar irradiance is one of the inputs to the model. Nevertheless, there is provision for its estimation within the model itself through use of the module SOLAR, which was developed and evaluated by Micallef [18]. SOLAR, in its calculation of the hourly-average solar irradiance, takes into consideration cloud cover and albedo (of the urban shed, in this case).

Apart SOLAR, the other radiation-related module for the pre-processing of input data is SSHF. The latter estimates the sensible heat flux associated with the urban surface (excluding motor vehicles) and makes use of the methodology by Smith [19], which is only approximately applicable for the urban case.

In the absence of wind direction standard deviation, Hanna's method [20] is used for its computation. The method by Hanna is computationally simple. As regards ambient temperature, an empirical expression [21] is used to relate that for the urban atmosphere to the temperature measured at a rural or suburban site. In other words, the urban heat island effect is taken into account as and when necessary.

2.4 Physical processes within the street canyon

Advection and turbulence are two main factors that determine the dispersion of pollutants within the street canyon. Hence, the modelling of the two physical processes is important, and forms an integral part of the dispersion calculations discussed in the subsequent subsection.

The horizontal component of the wind speed parallel to the orientation of the street is assumed to vary logarithmically in the vertical direction. The logarithmic law for the wind speed vertical profile assumes open terrain. This is reasonably valid parallel to the street (but not orthogonal to its orientation). For the cross-canyon case, i.e., when the wind is blowing at right angles to the street orientation at the street canyon roof top, calculations are accomplished using the wind field model by Hotchkiss and Harlow [22]. The latter consists of two mathematical equations: one for the horizontal component of the wind vector and another for the vertical component, i.e., the wind vector is resolved into two components within the cross-sectional plane with respect to the street canyon. Strictly speaking, the equations are valid for a street canyon with an aspect ratio of unity. Nevertheless, Hayden et al. [23] derived a correction factor through scale model experiments, that enables the use of the two equations for aspect ratios that differ from one.

In relation to the street canyon, there are two main sources of turbulence namely, motor vehicles and the environment. Each of these two sources contributes to both thermal and mechanical turbulence. Mechanical and thermal turbulence are modelled using the same methodology employed in the CPB model, cited earlier. The methodology is based on empirical data from wind tunnel experiments. The main mathematical equation used in the calculation has two parts. One part estimates mechanical turbulence and the second part concerns thermal turbulence. Both parts are in essence empirical parametrisations. It is worth noting that the second part requires knowledge of the sensible heat flux emitted by the urban surface, which is calculated through the use of SSHF, and the vehicle-generated heat flux, which is estimated using FUELFAC.

Calculation of the turbulence field is necessary because it has direct bearing on the dispersion parameters of the Gaussian plumes which are discussed in the following subsection. The most important dispersion parameter is the one associated with the vertical direction, which takes a non-zero value at source since mixing of the effluent happens soon after emission. This initial mixing is caused by the moving train of vehicles. Consequently, it is worth noting that in the bottom half of the street canyon, the vertical dispersion parameter is assumed to be proportional to the average aerodynamic height of the vehicles (which exceeds their actual physical height). The average aerodynamic height of the vehicles is estimated using a model by Yamartino and Wiegand [4]. The said model has been numerically generated from multiple runs of the ROADWAY dispersion model [24].

2.5 Dispersion and dilution of emissions

The two main scenarios of street canyon dispersion are associated with (a) advection parallel to the street orientation, and (b) cross-canyon flow at the roof top of the street. The two scenarios lead to different types of dispersion. In particular, in the second case, vortex formation can occur depending on the magnitude of the wind speed.

In case (a), a simple Gaussian model valid for line sources is employed since the vehicles, although seemingly point sources, in succession they resemble a line source. Along the direction of orientation of the street canyon, advection dominates. Dispersion occurs transverse to the orientation of the street. Hence two dispersion parameters are invoked: one in the vertical direction and another, horizontal and perpendicular to the street orientation. The Gaussian dispersion parameters are a function of turbulence. The Gaussian model takes into account plume depletion by deposition and settling of airborne particulate matter, which is detailed in the following subsection.

Under certain conditions, namely, when the roof top wind is predominantly orthogonal to the street canyon orientation, a vortex is assumed to form within the canyon, such that its axis is parallel to the orientation of the street canyon. Essentially, in three-dimensions, the flow is helical in character. Vortex formation allows for recirculation of pollutants emitted within the canyon. There is downward flow along the façade of the downwind building, cross-canyon flow along the bottom of the canyon but opposite in direction to that at the roof top, and upward flow along the façade of the upwind building. This recirculation process is modelled via a convergent infinite series. The current model uses the same technique employed by the CPB model. Modulating convergence is the pollutant lifetime within the street canyon, which is essentially the time that the pollutant takes to escape from the roof top of the street canyon. This parameter is estimated from model equations due to Lee and Park [25]. Apart from the recirculated pollutant, there is also the direct contribution, which is added to the former during the calculations.

It is worth noting that the height of the vortex centre is expressed as a function of the street canyon aspect ratio and the location corresponding to minimum wind speed within the street canyon. The latter is computed through incremental multiple runs of Hotchkiss and Harlow's model, based on a wind field minimisation algorithm made available by Robert J. Yamartino (personal communication).

2.6 Depletion of the emission plume

The emission plume loses pollutant through two main mechanisms, namely, dry and wet deposition. The latter is generally speaking associated with washout for low level sources of pollution, and occurs in the lower strata of the atmosphere. For the washout correction, a simple exponential law is assumed. Dry deposition is the result of diffusion at the air–surface boundary. Closely associated with dry deposition, there is also gravitational settling. The latter is the case for relatively large airborne particles.

In the model, the above-mentioned depletion mechanisms are taken into account. Nevertheless, correction for dry deposition is only applied for the case when flow is predominantly parallel to the street canyon, since the associated mechanisms are only effective after the emission plume would have travelled a substantial distance downwind of source [26]. Cross-canyon flow, which leads to vortex formation, is associated with short-range distances and hence the dry deposition mechanisms are ineffective. In the model, the correction for dry deposition is accomplished using the formulation by Overcamp [27]. In the latter, diffusive dry deposition is catered for by reducing the strength of the image source, which is introduced to take into account reflection of the Gaussian plume at the boundaries (building façades confining the street, and ground). The source height in the Gaussian plume model is reduced in order to account for gravitational settling of the airborne particles. It is worth noting that, the model by Sehmel and Hodgson [28] is used to calculate the dry deposition velocity for airborne particles of various aerodynamic diameters, since this parameter is required as input to Overcamp's model.

2.7 External processes affecting the air quality within the street canyon

Generally speaking, a street canyon will be bounded by intersections. Pollution tends to accumulate at street junctions, so that the upwind intersection serves as a source of pollution to the street section of interest. This source of pollution is modelled using the Gaussian point source model, which is simple enough to facilitate implementation. Furthermore, there is the background concentration (required as input by the model user) which mainly feeds the street from its roof top through entrainment. The two sources are considered external to the street environment but nevertheless, they can have an appreciable effect on the pollutant concentration in the street of interest.

Countering entrainment at the roof top of the canyon, there is fresh air injection along the façade of the downwind building. This is especially the case when conditions allow for vortex formation. Fresh air injection acts as a diluter, and is modelled as a Gaussian plume.

It should be emphasised that the most important external influence remains the background concentration, which is essentially the concentration of the pollutant of interest above the urban shed. This is either measured or estimated using regional air quality models.

3 EVALUATION OF THE MODEL

Model evaluation was accomplished through field experiments as explained here.

3.1 Monitoring site and technique

With any type of modelling, experimental evaluation is necessary, as this makes the model output more credible. On this occasion, the street canyon air quality model discussed in the previous section was evaluated for approximately 26 hours spread over four days, capturing various scenarios. The chosen street for the evaluation exercise is located in a major town in Malta, namely Birkirkara. It is a main, two-way traffic roadway with two lanes in total. The street is approximately oriented along the east–west direction. One lane carries traffic eastward, while the traffic on the other lane flows in the opposite direction, i.e., westward. The roadway is confined on either side by buildings of approximately the same height (roughly equal to 13 m). The aspect ratio of the street canyon is equal to unity. The chosen section of the said street has no curvature, and is bound by two junctions, one at each end. The junctions carry automated traffic lights. It is a typical roadway that cuts through towns in Malta. On average, the street caters for approximately 1,040 vehicles/h^{-1}, which are roughly equally distributed between the two lanes.

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Monitoring was carried out midway along the stretch of roadway. Two optical particle counters were used to measure the mass concentration of airborne particulate matter as detailed hereunder. Each of the two monitors was placed at approximately 1.5 m height, close to the kerbside of a very narrow pavement (which is typical in urban areas, in Malta). The two monitors were located one on each side of the roadway to try to capture the vortex effect described in the previous section. Nevertheless, in this paper, data from only one monitor is reported, namely the one which was closer to the westward lane. A complete analysis will be presented in the near future.

Concurrent with the measurement of airborne particle mass concentration, data required as input by the model were also collected. Model input data pertains to meteorology, e.g., data relating to wind and solar radiation, and traffic. The latter includes average traffic speed and flow rate, as well as types of vehicles, for each of the two lanes separately. Vehicle classification was carried out manually and on site by several individuals that were assigned to each lane; the whole exercise was quite tedious and laborious. Filming was avoided so as to ensure compliance with the relevant laws concerning data protection. It was necessary to collect model input data so that modelled concentrations could be generated and compared to corresponding measured values obtained during monitoring. The said comparison constitutes the core of the evaluation exercise.

Airborne particle mass concentration was measured using optical particle counters by Grimm Labortechnik Ltd. (Model 1.104/5). On this occasion, three particle size cut-offs were considered namely, suspended particulate matter (SPM), PM_{10} and $PM_{2.5}$. It is worth noting that, for the optical particle counters used in this study, SPM is roughly equivalent to PM_{15} given that it includes all airborne particles that make it to the measurement chamber of the instrument and taking into account that the inlet to the chamber is fitted with a 15 µm cut-off cyclone sampling head.

The main issue with optical particle counters is that particles whose aerodynamic diameter is small compared to the wavelength of the light source in use, are missed. Fortunately, these missed particles while contributing substantially to the number concentration, they do so marginally to the mass concentration. In this current study, the latter type of concentration was considered so that the mentioned issue was of marginal importance. Nevertheless, under-measurement by the monitors remains a possibility, especially in light of the argument presented in the following paragraph.

Aerosol particles associated with direct emissions by vehicles tend to have aerodynamic diameters in the range 0.14–0.25 µm [29], which is at the limiting end of detection for most optical particle counters. One cannot dismiss the fact that a substantial number of these particles are missed by optical particle counters. Once again, it is fair and valid to mention that the mass contribution of these aerosol particles is not significant. It is the larger aerosol particles, associated with indirect emissions by vehicles, that make up the mass.

Another issue pertains to the density of the sampled aerosol. Mass concentration is directly dependent on the density of the pollutant, so that gravimetric adjustment was imperative and hence accomplished successfully as per the manufacturers' instructions.

3.2 A comparison between modelled and experimental data

Fig. 3 shows the time series for hourly-averaged PM_{10} concentration that was measured during the monitoring campaign (dashed line). One observes that the associated trace follows the time series for the corresponding hourly-averaged PM_{10} concentration that was obtained from model runs. Nevertheless, there is clearly discrepancy between the two. The model

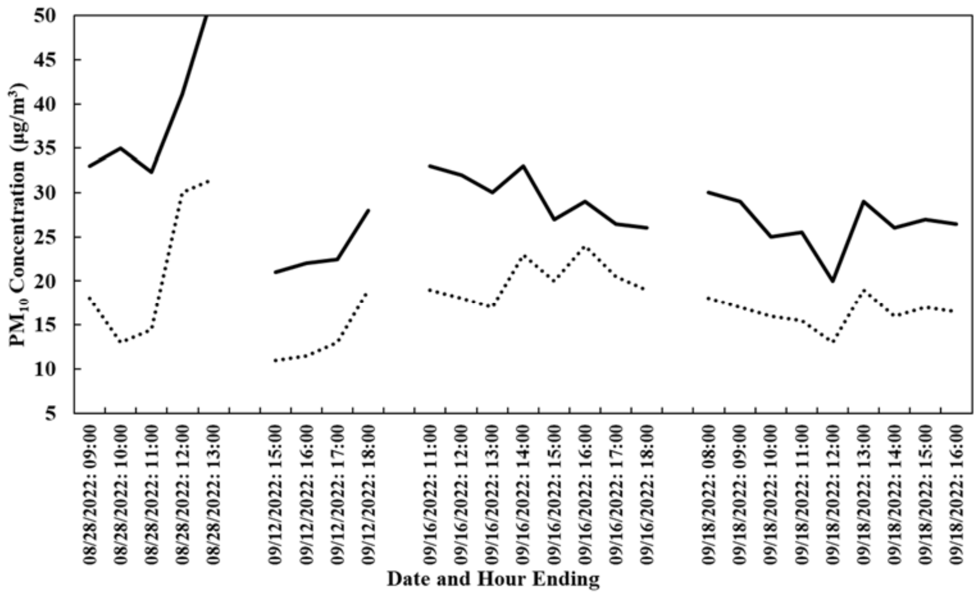

Figure 3: Time series comparison of measured (dashed line) and modelled (solid line) PM_{10} mass concentration.

seems to over-estimate but manages to capture the variations well. This is a very important point since mere calibration of the model would bring the two sets of data into agreement as discussed further on.

While over-estimation of the model is a possibility, it was already highlighted in the previous subsection that optical particle counters under-measure concentrations of vehicle-derived airborne particulate matter. Nevertheless, for reasons which were already mentioned, it is very unlikely that this can explain the discrepancy between the two sets of data.

On average, the ratio of the measured to modelled values for PM_{10} concentration works out to be approximately equal to 0.6. The latter value was used as a calibrating factor for the model. Fig. 4 is a replication of Fig. 3, after adjusting the time series of the modelled concentration, using the calibration factor. Referring to Fig. 4, agreement is very much evident, following calibration.

To further confirm the outcome of the time series analysis, a scatter graph was plotted as shown in Fig. 5, and the associated linear regression analysis accomplished. The correlation coefficient turned out to be equal to 0.5 (regression line forced through the origin) and 0.6 (regression line allowed to assume a non-zero intercept), with a corresponding gradient equal to 1.6 and 1.1, respectively. In the latter case, the intercept turned out to be approximately equal to 10 $\mu g\ m^{-3}$. The associated gradient is close to unity and hence the intercept can be interpreted as being a systematic discrepancy between modelled and measured values.

The model evaluation exercise undertaken as part of the current study indicates that the model performance is satisfactory (at least for PM_{10}) although there exists room for improvement.

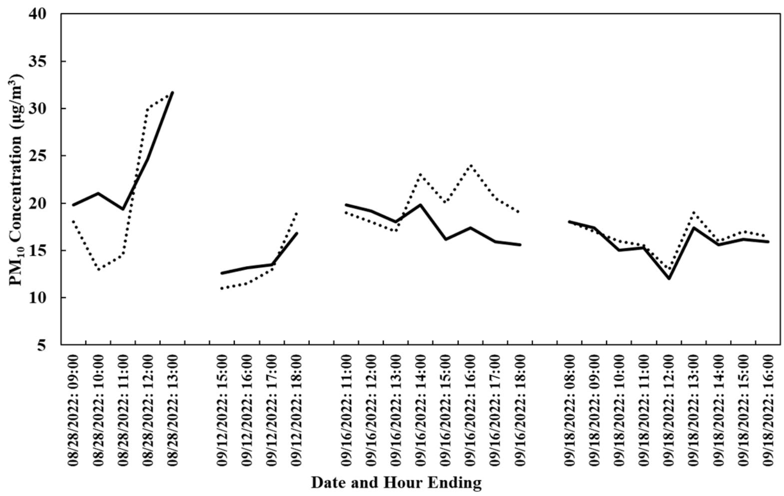

Figure 4: Time series comparison of measured (dashed line) and 'corrected' modelled (solid line) PM_{10} mass concentration. The correction or calibration factor is equal to 0.6.

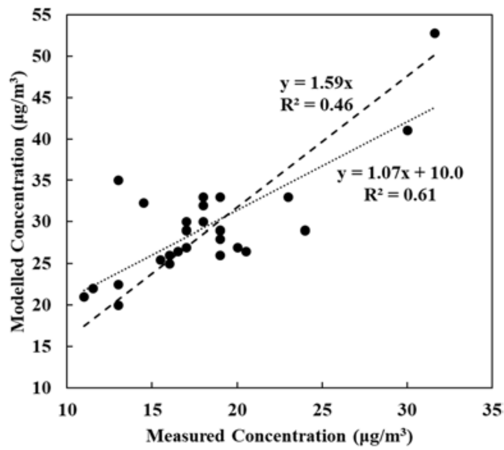

Figure 5: Scatter plot (including linear regression analysis) of modelled versus measured mass concentrations of PM_{10}.

4 CONCLUSION AND FUTURE WORK

In summary, this research paper gives a succinct description of a street canyon air quality model consisting of both emission and dispersion components. The model, which is coded in the Fortran computer language, is built in modular form to facilitate upgrades of the corresponding subroutines. The model is capable of estimating the mass concentration of airborne particulate matter (specifically, SPM, PM_{10} and $PM_{2.5}$) in confined roadways. Indeed, the current version of the said model is an upgrade of an existing model which was developed by the author as part of a previous research project [8].

Evaluation of the model was accomplished using two optical particle counters at fixed locations in a typical Maltese trunk road cutting through a relatively large town in the centre of the Island. Correlation between the calculated concentration and that obtained through monitoring was reasonable (correlation coefficient equal to 0.6), and proves to be suitable for both research purposes as well as a screening model.

For the future, it is the intention of the author to upgrade the model further so as to include modules pertaining to reactive gases such as nitrogen oxides. Additionally, relevant script will be included in the computer program so that the software is equipped with a suitable user-friendly interface. This would facilitate its use by the non-experts.

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