traffic congestion, fuel consumption, energy consumption

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EMISSION AND ENERGY CONSUMPTION CHARACTERISTICS OF INTERRUPTED OVER-SATURATED FLOW FOR URBAN ROADS WITH HETEROGENEOUS TRAFFIC

Summary. Road transport is a major source of air pollution particularly in towns and cities. In urban areas road traffic accounts for more than half of the emissions of nitrogen oxides, carbon mono-oxide and volatile organic compounds. This paper presents emission and energy consumption characteristics of urban roads with interrupted oversaturated flow comprising of heterogeneous traffic. Model has been developed for heterogeneous traffic under constraints of roadway geometry, vehicle characteristics, driving behaviour and traffic controls and has been calibrated and validated for interrupted oversaturated traffic conditions. Interrupted oversaturated flow conditions prevail in urban areas of most of the developing countries. The model developed shall predict carbon mono- oxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon dioxide (CO_2) and fuel and energy consumption estimates for urban roads operating under oversaturated conditions of flow. Since model provides improved estimates of speed, delay and congestion it provides better estimates of emissions and energy consumption.

CHARAKTERYSTYKA EMISJI ORAZ ZUŻYCIA ENERGII DLA PRZERYWANEGO PRZESYCONEGO PRZEPŁYWU RUCHU NA DROGACH MIEJSKICH Z RUCHEM ZRÓŻNICOWANYM

Streszczenie. Transport drogowy to główne źródło zanieczyszczenia powietrza szczególnie w dużych i małych miastach. Na terenach miejskich ruch uliczny stanowi ponad połowę emisji tlenków azotu, tlenku węgla oraz lotnych związków organicznych. Niniejsza praca prezentuje charakterystykę emisji oraz zużycia energii na drogach miejskich z przerywanym przesyconym przepływu ruchu drogowego. Opracowano model zróżnicowanego ruchu ulicznego biorąc pod uwagę geometrię dróg, charakterystyki pojazdów, zachowanie kierowców oraz kontrole drogowe. Wszystkie te czynniki zostały skalibrowane oraz potwierdzone dla przerywanego przesyconego przepływu ruchu drogowego. Przerywany przesycony przepływ ruchu drogowego to warunki dominujące na terenach miejskich większości krajów rozwijających się. Opracowany model powinien pomóc przewidywać szacunkowe emisje tlenku węgla (CO), tlenków azotu (NOx), lotnych związków organicznych (VOC) dwutlenku węgla (CO2) oraz zużycie paliwa i energii dla dróg miejskich w warunkach przesyconego ruchu drogowego. Ponieważ model umożliwia ulepszone szacunkowe wyliczenia dla prędkości, opóźnień oraz zagęszczenia ruchu prezentuje on lepsze szacunkowe dane o emisji i zużyciu energii.

1. INTRODUCTION

Road transport is a major source of air pollution particularly in towns and cities. In urban areas road traffic accounts for more than half of the emissions of nitrogen oxides (NOx), carbon mono-oxide (CO) and volatile organic compounds (VOC). Nitrogen oxides such as mono-nitrogen oxides (NO) and nitrogen di-oxide (NO_2) react with ammonia, moisture, and other compounds to form nitric acid vapour and related particles. These small particles penetrate deeply into sensitive lung tissue damaging it; causing premature death in extreme cases. Inhalation of such particles may cause or worsen respiratory diseases such as emphysema and bronchitis. It may also aggravate existing heart disease. When oxides of nitrogen and volatile organic compounds react in the presence of sunlight, ground level ozone is formed, a primary ingredient in smog. Carbon monoxide poisoning is the most common type of fatal air poisoning in many countries. Carbon monoxide is highly toxic. It combines with hemoglobin to produce carboxyhemoglobin, which is ineffective in delivering oxygen to bodily tissues. The environmental impact of transport is significant because it is a major user of energy, and burns most of the world's petroleum. By sub sector, road transport sub-sector is the largest contributor to global warming. Other environmental impacts of transport systems include traffic congestion and automobile-oriented urban sprawl, which can consume natural habitat and agricultural lands. By reducing transportation emissions globally, it is predicted that there will be significant positive effects on Earth's air quality, acid rain, smog and climate change [1-4].

Traffic flows may be classified as uninterrupted flows and interrupted flows. In uninterrupted flow, traffic flow condition results from interactions among vehicles in traffic stream between vehicles and the geometrical and environmental characteristics of the roadway. These flows do not have external elements such as traffic signals which might interrupt the traffic flow. However, interrupted-flows have controlled and uncontrolled access points that can interrupt the traffic flow. These access points include traffic signals, stop signs, yield signs and other types of control that stops traffic periodically or slows it significantly, irrespective of amount of traffic. The traffic flows may be further described as unsaturated, saturated and oversaturated [2]. In unsaturated conditions arrival flows (q_a) are below capacity ($q_a \leq Q$). The travel speed at a given flow rate (v_u) is between v_f and v_n ($v_f \geq v_u \geq v_n$) where v_f is the free-flow speed and v_n is the speed at capacity. With increasing flow rate in unsaturated flow conditions, speeds are reduced below the free-flow speed due to traffic delays resulting from interactions between vehicles. After reaching maximum flow at capacity, traffic follows either saturated flow or oversaturated flow. In saturated flow the forced (congested) flow conditions exist with flow rates reduced below capacity ($q < Q$) which are associated with reduced speeds ($v < v_n$) as observed at a reference point along the road. In this region, flow rates (q) are reduced flow rates due to forced flow conditions, not demand flow rates (q_a). However, oversaturated conditions, i.e. arrival (demand) flow rates above capacity ($q_a > Q$) are associated with reduced travel speeds ($v < v_n$) observed by travel through the total section, e.g. by an instrumented car. In this case, the flow represents the demand flow rate which exceeds the capacity value as measured at a point upstream of the queuing section [5-8].

Congested traffic conditions increase emissions and reduce speed compared to free flow conditions [9]. A study by Hallmark *et al*. [10] found that driving patterns (i.e., speeds) at different intersections are significantly influenced by queue position, downstream and upstream lane volume, incidents, percent of heavy vehicles, and posted link speed. Rakha *et al*. [11] concluded that proper signal coordination could significantly reduce emissions.

Emissions also vary with respect to drivers' attitude, experience, gender, physical condition, and age. Aggressive driving increases emissions compared to normal driving [12]. Sierra Research found that most drivers spend about 2% of total driving time in aggressive mode, which contributes to about 40% of total emissions [13].

So far, emissions on urban roads with interrupted traffic flows having oversaturated flow conditions have not been the priority of researchers. There is a need to investigate the shape of emission curves with reference to speed-flow curves for this type of urban road scenario. An investigation of oversaturated flow is very much relevant for developing countries [9-13].

This paper presents emission and energy consumption characteristics of urban roads with interrupted oversaturated flow comprising of heterogeneous traffic. Model has been developed for heterogeneous traffic under constraints of roadway geometry, vehicle characteristics, driving behavior and traffic controls and has been calibrated and validated for interrupted oversaturated traffic conditions. Interrupted oversaturated flow conditions prevail in urban areas of most of the developing countries. The model developed shall predict carbon mono- oxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon dioxide (CO_2) and fuel and energy consumption estimates for urban roads operating under oversaturated conditions of flow. Since model provides improved estimates of speed, delay and congestion it provides better estimates of emissions and energy consumption.

2. SIMULATION MODEL

The simulation tool used in this paper is VISSIM 5.3 (official license available). VISSIM uses the psycho-physical driver behavior model developed by WIEDEMANN [14]. The basic concept of this model is that the driver of a faster moving vehicle starts to decelerate as he reaches his individual perception threshold to a slower moving vehicle. Since he cannot exactly determine the speed of that vehicle, his speed will fall below that vehicle's speed until he starts to slightly accelerate again after reaching another perception threshold. This results in an iterative process of acceleration and deceleration. Stochastic distributions of speed and spacing thresholds replicate individual driver behavior characteristics. VISSIM's traffic simulator allows drivers on multiple lane roadways to react to preceding vehicles as well as to neighboring vehicles on the adjacent travel lanes. Moreover, approaching a traffic signal results in a higher alertness for drivers at a distance of 100 meters in front of the stop line. VISSIM simulates the traffic flow by moving “driver-vehicle-units” through a network. Every driver with his specific behavior characteristics is assigned to a specific vehicle. As a consequence, the driving behavior corresponds to the technical capabilities of his vehicle. Attributes characterizing each driver-vehicle-unit are (1) Technical specifications of the vehicle, e.g. length, maximum speed, potential acceleration, actual position in the network, actual speed and acceleration (2) behavior of driver-vehicle-unit, e.g., psycho-physical sensitivity thresholds of the driver (ability to estimate, aggressiveness), memory of driver, acceleration based on current speed and driver's desired speed (3) interdependence of driver-vehicle-units, e.g. reference to leading and following vehicles on own and adjacent travel lanes, reference to current link and next intersection, reference to next traffic signal. VISSIM incorporates Dutch national research institution TNO's microscopic exhaust gas emission model VERSIT+. VISSIM links the emission data of the TNO model with the simulated traffic behavior and determine or predict the level of harmful emission [14].

3. DATA COLLECTION, MODEL CALIBRATION AND VALIDATION

Jaipur city in India is chosen to investigate emission characteristics of interrupted oversaturated flow as the city size, its roads, type of vehicles, mixed traffic and driver's aptitude represent most of the countries. A representative network of urban road network, comprising of two signalized intersections and one un-signalized intersection in between, is decided to investigate emission of CO, NO_x, VOC and fuel consumption at urban roads. The investigation is conducted for this network as a whole so that results will provide a realistic estimate of traffic emissions in urban road scenario. Fig. 1 shows VISSIM simulation snap shot.

The model construction procedure consists of (i) identification of important geometric features (ii) collection and processing of traffic data (iii) analysis of mainline data to identify recurring bottlenecks (iv) VISSIM coding (v) calibration based on observations from (iii). Calibration is the process by which individual components of simulation model are refined and adjusted so that simulation model accurately represents field measured or observed traffic conditions. With regard to calibration, traffic simulation model contain numerous variables to define and replicate traffic control operations, traffic flow characteristics and driver behavior. VISSIM simulation model contains default values for each variable, but also allows a range of user applied values for each variable. These variables are changed as per field measurements and observed conditions [14].

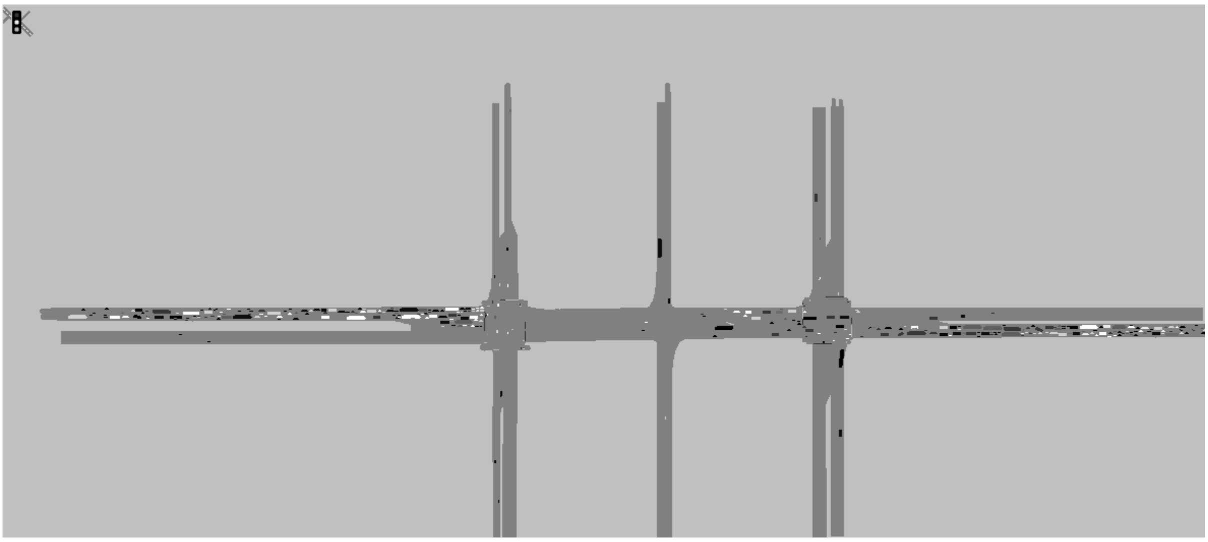

Fig. 1. VISSIM simulation snap shot
Rys. 1. Zdjęcie symulacji VISSIM

Table 1

Traffic composition

Percentage of traffic composition (time: 08:00-20:00)					
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility	Two wheeler	Three wheeler	Bus	HGV	Slow moving vehicle
37	41	11	5	1	5

Here, LCV means Light Commercial Vehicle; SUV means Sports Utility Vehicle; HGV means Heavy Goods Vehicle.

The geometry of existing network from Danik Bhaskar intersection to JDA intersection on Jawahar Lal Nehru road (4lane divided; with lane width 3.5 m) was created using links and connectors which are the building blocks of VISSIM network. The number of lanes per road and width of each lane, left turning lanes on each approach road, central median, traffic islands and other road features were specified as per existing. After creation of network, the vehicle input for various links was given. The traffic composition is given in Table1.This is followed by specifying the various routes in which vehicles travelled and the volume of these vehicles in each route is specified. The other features viz. positioning of speed limits, conflict zones, stop signs, signal heads are specified as per existing. The data collection points, travel time sections, queue counters and nodes are placed. The driving behavior is calibrated for the following parameters: standstill longitudinal distance between the stopped vehicles, headway time in seconds, following variation which restricts the longitudinal oscillation and indicates how much more distance than desired distance a driver allows before he intentionally moves closer to vehicle in front, threshold for entering ‘following’ controlling the start of deceleration process, following threshold which controls the speed differences during the ‘following’ state, speed dependency of oscillation, oscillation acceleration, standstill acceleration, minimum headway, maximum deceleration of vehicle and trailing vehicle for lane change, overtaking characteristics, minimum lateral distance at different speeds, waiting time for diffusion. The vehicles are calibrated for desired speed distribution, weight distribution, power distribution and model distribution. The links are assigned behavior according to driving behavior. On Indian roads, because of heterogeneity of traffic, it is difficult to enforce lane discipline. Hence, vehicle occupies lateral positions on any part of road based on space availability; overtake within lane from both sides. The validation of the model was carried out by comparing maximum queue length simulated by model for existing intersection on each approach road with field observed values. The simulation model was given multirun with 20 random seed numbers and average of 20 simulation runs was taken as final output of the model. The value of t-statistic, calculated based on observed data (t_o) for all the four approach road on both the signalized intersections is below 2.00. The critical value of t-statics for level of significance of 0.05, at 19 degrees of freedom is 2.093. Thus, value of t-statistic, calculated on the basis of observed data, is less than the corresponding table value. This shows that there is no significant difference between the simulated and observed queue lengths.

4. EMISSIONS FOR INTERRUPTED FLOW

The simulation model validated as above is used to investigate the speed, delay and congestion characteristics of oversaturated flows. The models are developed for these characteristics. Since these models provides better estimates of speed and delay capturing driving behavior in developing countries, heterogeneity of vehicles and no lane discipline, the work is extended to develop model for the emissions characteristics viz CO, NO_x ,VOC and CO_2 emissions and fuel and energy consumption. The values shown are the average of 20 simulation runs with different random numbers so as to have reasonable results to conclude.

4.1. Model for speed and emissions for oversaturated flow

4.1.1. Speed

The variation of speed with v/c ratio for oversaturated flow is shown in Fig. 2.
The Speed – (v/c) curve follows the equation (1):

$$\text{Speed} = 0.8986(v/c)^3 + 1.5463(v/c)^2 - 20.73(v/c) + 38.033 \quad (1)$$

$R^2 = 0.9931$

When compared with BPR curve, MTS curve, HCM curve, Updated BPR curve and Akçelik curve, the shape of Speed- (v/c) ratio curve obtained in Fig 2 resemble with updated BPR curve and hence in agreement with established theories[5-8].

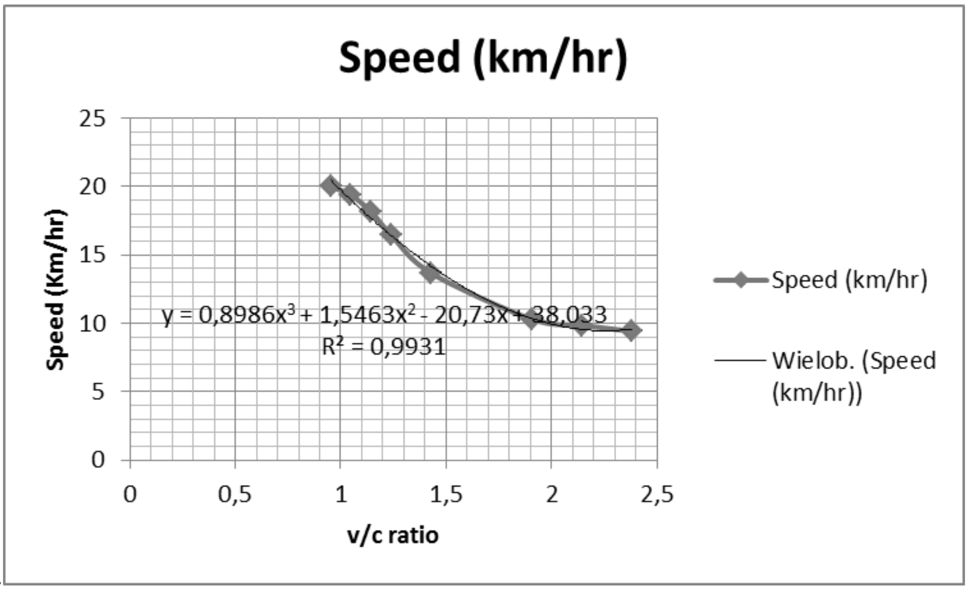

Fig. 2. Speed v/s Volume to Capacity ratio Curve
Rys. 2. Wahania prędkości z współczynnikiem rozmiar/pojemność dla przesyconego ruchu drogowego

4.1.2. Delay

Average delay time per vehicle is a measure of effectiveness (MOE) relevant for investigating and analysing emissions. Fig. 3 shows variation of delay time per vehicle with (v/c) ratio.

4.1.3. Congestion

The area under the Speed-Flow envelope between any two operating points on it represents loss in freedom of movement between these two traffic conditions, hence congestion [15-16]. Congestion, in general, is the loss in freedom of movement with respect to free flow conditions. Since, the traffic conditions at capacity are acceptable for most of the urban road scenario, the congestion in case of oversaturated flow may be viewed as loss in freedom of movement with respect to traffic condition prevailing at capacity. Thus, Congestion ratio may be defined as a ratio of total congestion at an operating point and total congestion at capacity. Congestion is the biggest contributor to the emissions and energy consumption. Hence, it is worth while to explore congestion before investigating models for emissions.

The average delay time per vehicle can be calculated by equation (2) for oversaturated flows.

$$\text{Average delay time per vehicle} = -9.5647(v/c)^3 + 29.118(v/c)^2 + 18.762(v/c) - 7.8076 \quad (2)$$

$R^2 = 0.9945$

The congestion curve is shown in Fig 4. The curve follows the equation (3)

$$\text{Ratio (congestion at an operating point/ congestion at capacity)} = 247.75(v/c)^2 - 461.11(v/c) + 212.91 \quad (3)$$

$R^2 = 0.9999$

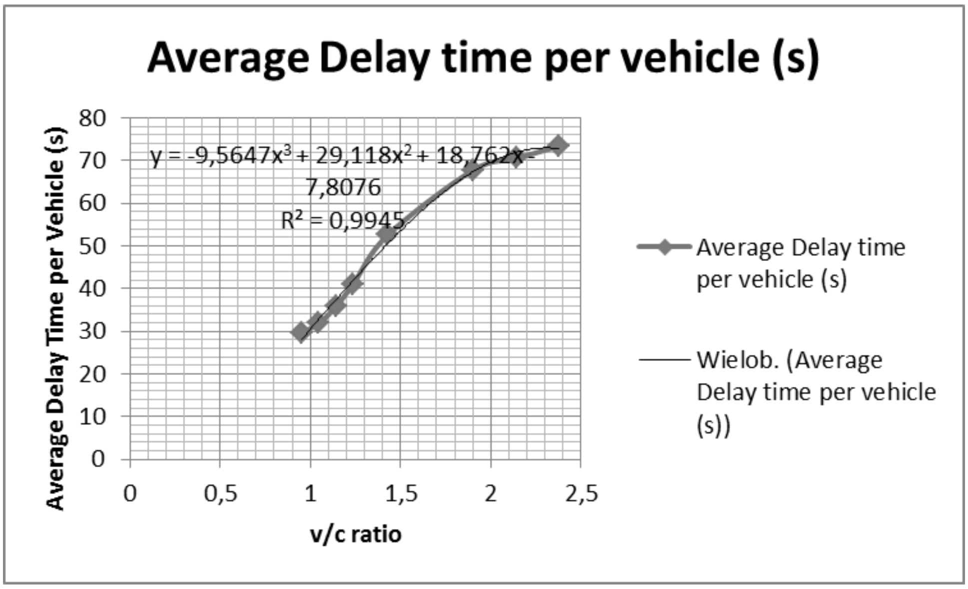

Fig. 3. Average delay time per vehicle v/s (v/c) ratio curve
Rys. 3. Przeciętny czas opóźnień w ruchu w przeliczeniu na jeden pojazd

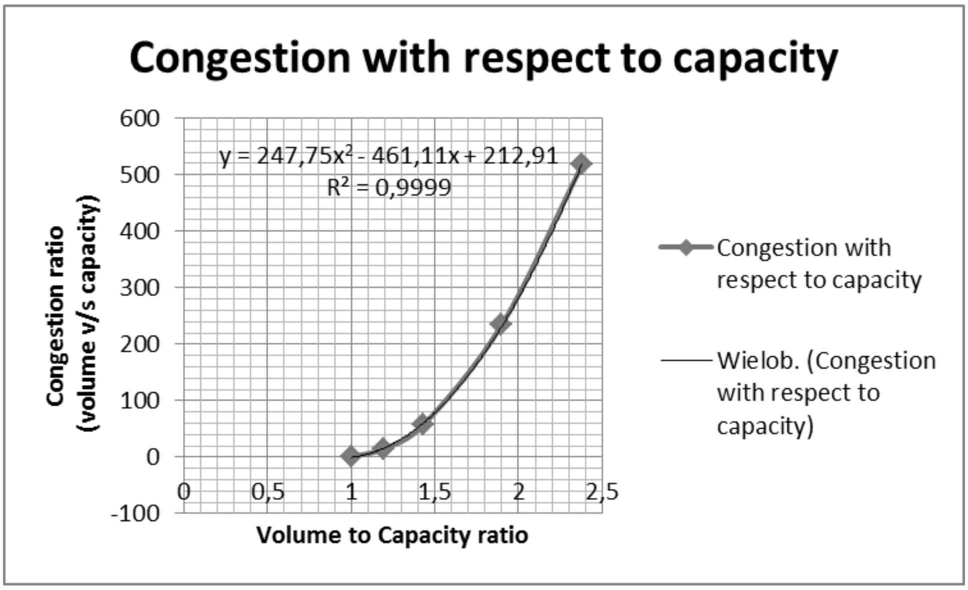

Fig. 4. Congestion curve
Rys. 4. Krzywa zagęszczenia ruchu

Since the model developed captures factors that are responsible for congestion including geometry, sight distance, vehicular characteristics, vehicular interactions, heterogeneous composition, vehicle types, operating conditions, aggressive behaviour of driver, no lane discipline etc.,it is able to provide improved estimates of speed delay and congestion. Consequently, the models developed for emission are able to provide better estimates of emission. The carbon monoxide emissions are found to follow curve shown in Fig. 5 for oversaturated flow condition.

4.1.4. Emission carbon-monoxide

The curve follows the equation given in (4):

$$\text{Emission CO} = -22.464(v/c)3 - 515.4(v/c)2 + 2656.1(v/c) - 869.44 \quad (4)$$

$R^2 = 0.9987$

The model calculates the CO emissions for oversaturated condition. There is a steep increase in CO emissions up to v/c ratio 1.5. The rate of increase decreases beyond that. The emissions correspond to speed to (v/c) ratio curve in Fig. 2,3 and 4.

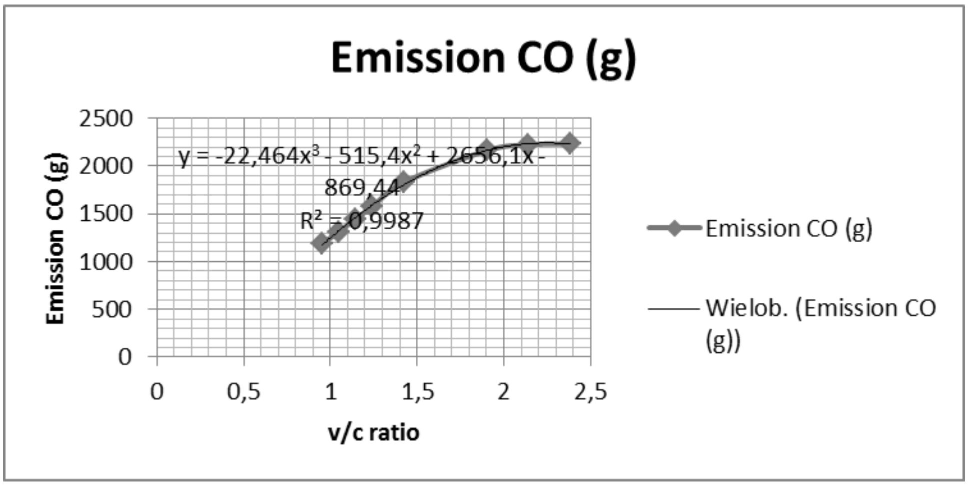

Fig. 5. CO emission Curve
Rys. 5. Krzywa emisji CO

4.1.5. Emission NO_x

The shape of NOx emission-flow curve resembles with CO emission curve, hence not shown again. The curve follows the equation given in (5):

$$\text{Emission } NO_x = -0.7401(v/c)^3 - 120.46(v/c)^2 + 550.36(v/c) - 186.36 \quad (5)$$

$R^2 = 0.9984$

The NOx emissions also correspond to Fig. 2, 3 and 4. The nitrogen oxides emitted during oversaturated traffic flows can be calculated from model given by (5).

4.1.6. Emission VOC

The shape of VOC emission-flow curve resembles with CO emission curve, hence not shown again. The VOC emissions follow the model given in equation (6):

$$\text{Emission VOC} = 0.592(v/c)^3 - 149.17(v/c)^2 + 662.07(v/c) - 224.09 \quad (6)$$

Krzywa emisji CO

$R^2 = 0.9983$

Thus, VOC emissions can be calculated from (6) for oversaturated interrupted flows.

4.1.7. Emission carbon-dioxide

The shape of CO_2 emission-flow curve resembles with CO emission curve, hence not shown again. The curve follows equation (7):

$$CO_2 \text{ emission} = -0.6672(v/c)^3 - 77.4(v/c)^2 + 356.68(v/c) - 120.23 \quad (7)$$

$R^2 = 0.9984$

This model calculates the carbon dioxide emission for urban traffic flows. The improvement in traffic flow conditions can bring about significant reduction of carbon dioxide and can make important contribution in addressing problem of global warming.

4.1.8. Fuel consumption

Model is also developed for fuel consumption and energy consumption for oversaturated flow. The fuel consumption and energy consumption for a network can be optimized by selecting appropriate operating condition of traffic for this type of flow.

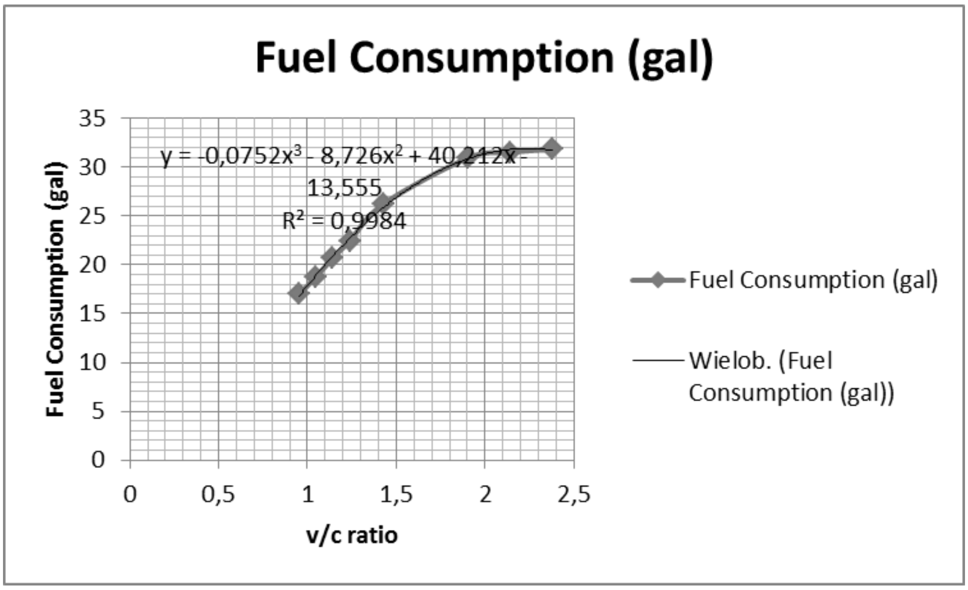

Fig. 6. Fuel consumption curve
Rys. 6. Krzywa zużycia paliwa

Fig. 6 shows the fuel consumption-flow curve. The curve follows the equation (8):

$$\text{Fuel Consumption} = -0.0752(v/c)^3 - 8.726(v/c)^2 + 40.212(v/c) - 13.555 \quad (8)$$

Here, $R^2 = 0.9984$

This model calculates the fuel consumption in oversaturated flow conditions of interrupted flows.

4.1.9. Energy consumption

The energy consumption curve follows the equation given by (9)

$$\text{Energy Consumption} = -9.1112(v/c)^3 - 1056.9(v/c)^2 + 4870.5(v/c) - 1641.7 \quad (9)$$

$R^2 = 0.9984$

This curve can be used to design operating conditions for traffic along with speed- flow, Delay-flow and congestion curves in Fig. 2, 3 and4 respectively so that there may be savings in energy consumption.

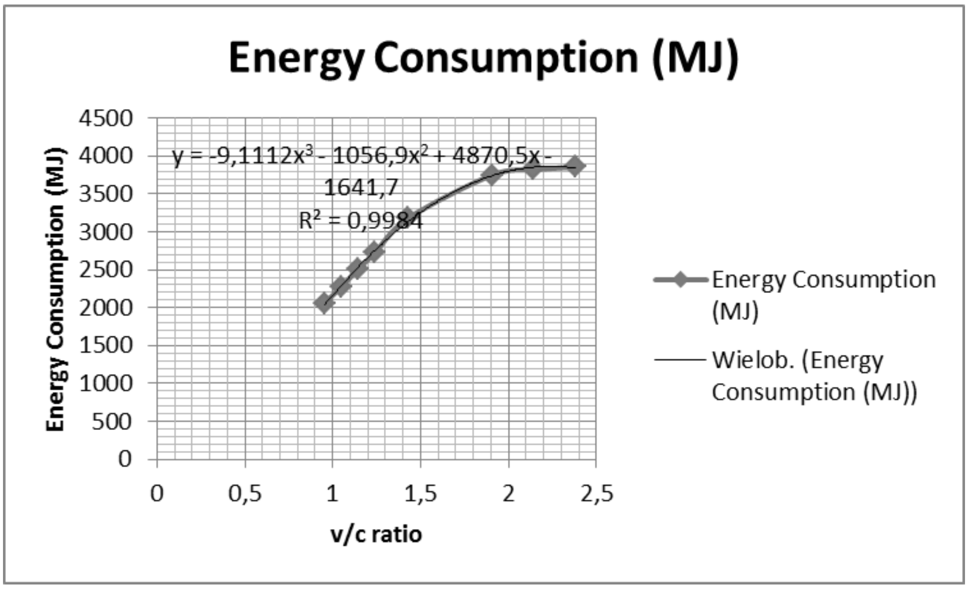

Fig. 7. Energy Consumption curve
Rys. 7. Krzywa zużycia energii

4.2. Effect of traffic composition

In order to study the effect of the traffic composition which ordinary prevails in mid size to big cities in developing countries like India, the following combinations are studied by varying percentage of Car/Jeep/Taxi/SUV/LCV /ambulance/Utility and two wheelers in Table 1 while keeping percentage of other categories of vehicles as same
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 30%; Two wheeler: 48%
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 32%; Two wheeler: 46%
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 34%; Two wheeler: 44%
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 36%; Two wheeler: 42%
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 38%; Two wheeler: 40%
Car/Jeep/Taxi/SUV/LCV /ambulance/Utility: 40%; Two wheeler: 38%

However, within this rage of variation in these type of vehicles, results are not found to vary significantly (within 5%). Hence, results obtained for traffic composition of Table 1 are reasonably justified for this range of traffic composition as well.

5. CONCLUSION

In order to explore the oversaturated flow condition of interrupted flow, investigations are carried out for speed, delay and congestion. The congestion is quantified as loss in freedom of movement. The models are developed for improved estimation of these fundamental variables and MOEs. The investigation is carried out using micro-simulation model which has been developed, calibrated and validated for a representative network and heterogeneous traffic under constraints of roadway geometry, vehicle characteristics, driving behavior and traffic controls. The emission characteristics and emission curves of urban roads with interrupted flow comprising of heterogeneous traffic are explored and models are developed. These models shall provide improved estimates of emissions of carbon mono- oxide, nitrogen oxides, volatile organic compound, carbon dioxide emissions and fuel and energy consumption under oversaturated conditions of flow. The various emission (CO, NO_X, VOC) and fuel and energy consumption curves corresponds to speed to (v/c) ratio curve and follows variation of speed with flow. It is found that with the increase in flow, when the rate of decrease of speed is more the rate of increase of various emissions is also more. As the rate of decrease of speed decreases, the rate of increase of emissions also decreases. The emission conditions deteriorate severely with increase in oversaturation. The change in traffic condition at capacity (v/c ratio 1) to traffic condition at v/c ratio 1.5 witnesses a change of approximately 50% in emissions with respect to capacity. At traffic condition v/c ratio 2 the change with respect to capacity is approximately 75% while at v/c ratio 2.4 the change with respect to capacity is approximately 78%. Fuel consumption and energy consumption curves also follow the same trend.

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