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COMPUTER SIMULATION: TRAFFIC-RELATED AIR POLLUTION AND THE TRAFFIC SIGNAL CYCLE TIME OPTIMIZATION

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ABSTRACT

Emissions of motor vehicles, one of the most important air pollution sources in the city, are emerging as a growing problem in large-scale cities. The amounts of emissions are affected by the number of vehicles in traffic, vehicle technology, geometric and traffic conditions of highways and intersections, environmental factors. Traffic flow is mostly interrupted at Intersections in local traffic especially at city centers. Emissions of these points, where traffic behavior is changed and vehicles stop and go, are higher as compared to uninterrupted flows. In this study, current state emissions at 120 Intersection were determined by SIDRA INTERSECTION software. Then, new emissions are determined by the same software after improvement in signalization. As a result of the study, fuel consumption and pollutant emissions were calculated before and after improvement. As a result of observations at the intersection, current state fuel consumption was calculated as 1718.2, l/hour and CO_2, CO, HC and NO_X emissions were 40464.7, 3.821, 0.482, and 5.060 kg/hour respectively for morning. After that current state fuel consumption was calculated as 1492.1, l/hour and CO_2, CO, HC and NO_X emissions were 3522, 3.116, 0.406, and 3.246 kg/hour respectively for the evening. It has been determined that there were significant differences between current state and after improvement. Improvements on geometric conditions or signalization at intersections may result in decrease in vehicle emissions and improving air quality of cities.

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Introduction. The transport sector is one of the most important contributors with an impact of about 16% on greenhouse gas emissions [1]. Emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X) and carbon dioxide (CO_2) have significant contributions to air pollution in city centers.

The major source of greenhouse gas emissions related to transportation is automobiles and trucks because of the large number of vehicles. These sources constitute more than half of the emissions in the sector [2].

Road and street intersections force vehicular traffic to slow down and stop. The longer the stops, more fuel are consumed and the vehicular emissions increase. Along with the ever-increasing vehicle emissions, it has become important to identify effective traffic control methods to improve traffic flow and reduce emissions per vehicle kilometer [3].

A study by Hydén and Várhelyi (2000) at small roundabouts-as speed reducing measures-was carried out in a Swedish. The time consumption at a time operated signal was reduced heavily by the instalment of a roundabout at a signalized intersection [4].

Conducted a study at three locations in Kansas, where a modern roundabout has replaced a stop controlled intersection. HC, CO, NO_X, and CO_2 in (kg/hr.) were chosen as air pollution indicators. They stated that carbon monoxide (CO) was reduced by 45%, carbon dioxide by 61%, nitrogen oxides (NO_X) by 51%, and hydrocarbons (HC) by 68% [3].

1. Details experimental

1.1 Study Area

The study was conducted in Ulaanbaatar/Mongolia which is a city that has high traffic intensity. It is known that the number of vehicles in Ulaanbaatar has increased by 18.3% in the last 10 years [5]. As a result, it was concluded that one of the main sources of air pollution in city center includes traffic related emissions. In this context, determination of traffic emissions' contribution to air quality, especially at intersections, is importance in terms of taking proper precautions.

The study was conducted at the 120 Intersection which is working days and busiest hours. The intersection is one of the busiest intersections in Ulaanbaatar [6]. At the intersection with high traffic load, especially at peak times, travel times increase and vehicles queue. As a result, vehicle emissions are increasing considerably. A view from the air of the intersection is given in Figure 1.

Fig. 1. 120 Intersection view from the air

1.2 Traffic Volumes

Firstly, video camera was recorded at the intersection to determine the traffic volume. And then traffic counts were obtained visually from records. Video recording was performed between 08:00-09:00 in the morning and 18:00-19:00 in the evening and vehicle volumes were determined for each lane. The volumes were entered at SIDRA for modelling. A view modeling of intersection 120 is given in Figure 2. Traffic volumes in the morning and at the evening for all approaches 1, 2, 3 ... and 12 are given in Table 1.

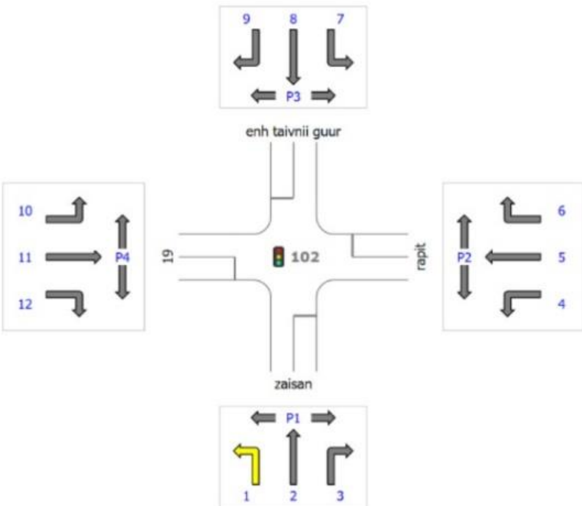

Fig.2. Modeling of intersection 120

Table 1. Traffic volumes intersection in the morning and evening hours

№	Morning 08:00-09:00		Evening 18:00-19:00	
Lane	**L.V**	**H.V**	**L.V**	**H.V**
1	406	7	283	6
2	822	18	806	10
3	573	6	409	10
Total	1801	31	1498	26
4	258	5	232	4
5	741	10	864	24
6	967	12	502	25
Total	1966	27	1598	53
7	548	12	561	18
8	502	12	515	7
9	192	15	49	6
Total	1242	39	1125	31
10	416	7	285	8
11	714	17	748	19
12	477	7	372	17
Total	1607	31	1405	44
	6616	128	5626	154

*L.V: Light vehicle, H.V: Heavy vehicle.

As can be seen from the table, more than 90% of all vehicles are light vehicles or passenger cars. The results of the morning and evening observations show that, 2nd row has the highest and 4nd row has with the least load.

1.3 The cycle of intersection traffic lights

There are a number of parameters that must be entered in the program for the modeling. These are; intersection geometry, traffic data and signaling data. These data were obtained from studies conducted at the field and they were entered to the program for the morning and the evening along with volumes. The phase diagram of the current situation and the cycle time (120 sec) were also entered. Thus, the current situation analysis of the intersection was completed. Then a new cycle period was determined. A new analysis was carried out with the new cycle time for the morning and the evening hours, as all other data remaining the same. By changing the cycle time it was aimed to improve intersection. The emission values obtained for six different analyzes were compared.

2. Traffic emission calculation

Within the framework of national greenhouse gas emissions inventory studies, the use of energy, industrial processes, solvents and other products, agricultural activities and waste emissions can be calculated using the approaches recommended in the International Climate Change Panel (IPCC) Guidelines [7].

The transport sector is one of the key sources mentioned in these guidelines. The application guide offers three different formulas for calculating emissions namely Tier 1, Tier 2 and Tier 3. Emission factors to be used in calculations can be obtained directly from the EMEP/EEA Emission Inventory Guide published by the European Environment Agency [8]. The conventional method of preparing emission inventory is to multiply the emission factors by the activity statistics and the number of vehicles. In this study, emissions were calculated by using SIDRA software instead of the conventional method.

SIDRA is a microsimulation model for realistic assessment of road traffic conditions using in-traffic vehicle data or user defined drive cycles. It uses a power based vehicle model to estimate fuel consumptions and emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). It is ideal to compare traffic and travel conditions before and after intersection and road improvements [6].

SIDRA Intersection software classifies vehicles as "light duty" and "heavy duty" when performing fuel consumption and emission calculations. Fuel consumptions and emissions at the intersections are calculated for standard driving cycle which consists of cruise, deceleration, idling and acceleration [9]. Instantaneous fuel consumption rates (mL/s) can be calculated by the following model.

$$f_t = \alpha + \beta_1 R_T v + [\beta_2 M_v a P_I] > 0 \qquad P_T > 0 \qquad (1)$$
$$f_t = \alpha \qquad P_T < 0$$
$$P_T = \min(P_{max}, P_c + P_I + P_G) \qquad (2)$$
$$P_c = b_1 v + b_2 v^3 \qquad (3)$$
$$P_I = M_v a v / 1000 \qquad (4)$$
$$P_G = 9.81 M_v (G/100) v / 1000 \qquad (5)$$
$$\alpha = f_i / 3600 \qquad (6)$$

Where:

f_t - Instantaneous fuel consumption rate (mL/s),
P_T - Total tractive power (kilowatt, kW),
$P_{max,}$ - Maximum engine power (kW),
P_c - Cruise component of total power (kW),
P_I - Inertia component of total power (kW),
P_G - Grade component of total power (kW),
G - Road grade (per cent), negative if downhill,
M_v - Vehicle mass (kg), including occupants and any other load,
v - Instantaneous speed (m/s) = v(km/h)/3.6
a – Instantaneous acceleration rate (m/s^2), negative for deceleration,
α - Constant idle fuel consumption rate (mL/s),
f_i = 3600(α),: constant idle fuel consumption rate (mL/h),
b_1 - Vehicle parameter related mainly to the rolling resistance (kN),
b_2 – Vehicle parameter related mainly to the aerodynamic drag ($kN/(m/s)^2$),
β_1 - The efficiency parameter which relates fuel consumed to the total power provided by the engine (mL/kJ or g/kJ),
β_2 - The efficiency parameter which relates fuel consumed during positive acceleration to the product of acceleration rate and inertia power ($mL/(kJ.m/s^2)$ or $g/(kJ.m/s^2)$),

On a level road (G=0, PG=0), the instantaneous cruise fuel consumption rate (a=0, PI=0) is calculated by using following equations (7a, 7b, 7c, 8a and 8b):

$$f_{ct} = \alpha + \beta_1 P_c f_t = \alpha \qquad (7a)$$
$$f_{ct} = \alpha + \beta_1 (b_1 v + b_2 v^3) \qquad (7b)$$
$$f_{ct} = \alpha + c_1 v + c_2 v^3 \qquad (7c)$$

Where:

$$c_1 = b_1 \beta_1 \qquad (8a)$$
$$c_2 = b_2 \beta_1 \qquad (8b)$$

The unit of c_1 parameter is mL/m and the unit of c_2 parameter is $(mL/m)/(m/s)^2$.

Equation 7c is used in model calibration for fuel consumption. After calibration, the values of c_1, c_2 and β_1 are determined. Then, the inputs of the model (A and B parameters) are calculated by using following equations (Eq. 9a, 9b).

$$A = 1000\, c_1 \qquad (9a)$$
$$B = c_2 / 0.01296 \qquad (9b)$$

Where, the unit of A parameter is mL/km and the unit of B parameter is $(mL/km)/(km/h)^2$.

b_1 and b_2 parameters are calculated indirectly by Equations 10a and 10b.

$$b_1 = c_1/\beta_1 \quad \text{if} \quad \beta_1 > 0 \tag{10a}$$
$$b_1 = 0 \quad \text{if} \quad \beta_1 = 0$$
$$b_2 = c_2/\beta_1 \quad \text{if} \quad \beta_1 > 0 \tag{10b}$$
$$b_2 = 0 \quad \text{if} \quad \beta_1 = 0$$

The purpose of using c_1 and c_2 in Eq. 10a and 10b is to obtain a reasonable representation of drag power provided by engine in fuel consumption. The instantaneous carbon dioxide (CO_2) emission (g/s) is directly estimated by using the instantaneous fuel consumption rate (Eq. 11).

$$f_i(CO_2) = f_{CO2} f_t(\text{fuel}) \tag{11}$$

Where:

$f_t(\text{fuel})$ - fuel consumption rate (mL/s),
f_{CO2} - CO_2 to fuel consumption rate (g/mL) or (kg/L).

Model estimates carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) emission rates (mg/s) by using the same procedure with different parameters (Akçelik et al., 2012). These parameters are given in Table 2 for light duty vehicles and Table 3 for heavy duty vehicles respectively.

Table 2. SIDRA INTERSECTION fuel consumption and emission model parameters (light duty vehicle).

*	Fuel	CO	HC	NOx
Idling rate, f_i	1200.0	1620.0	340.0	300.0
Drag parameter, A	16.0	138.0	9.0	14.0
Drag parameter, B	0.004	0.0743	0.0031	0.0068
Efficiency parameter, β	0.1	0.294	0.029	0.166

*Mass: 1600 kg, Max power: 120kW, CO_2 to fuel consumption rate: 2.35

Table 3. SIDRA INTERSECTION fuel consumption and emission model parameters (heavy duty vehicle).

*	Fuel	CO	HC	NOx
Idling rate, f_i	1200.0	1620.0	340.0	300.0
Drag parameter, A	16.0	138.0	9.0	14.0
Drag parameter, B	0.004	0.0743	0.0031	0.0068
Efficiency parameter, β	0.1	0.294	0.029	0.166

*Mass: 15000 kg, Max power: 170kW, CO_2 to fuel consumption rate: 2.63

Results. As a result of the observations, firstly the current situation of intersection was modeled with SIDRA then total fuel consumptions and carbon dioxide, carbon monoxide, hydrocarbons, and nitrogen oxide emissions were calculated. After that, the same parameters were calculated with the new cycle time. Total fuel consumptions and air pollutant emissions for the morning and evening hours are given in Table 4 and Table 5.

Table 4. Calculated fuel consumptions and emissions for the morning

Emissions	Fuel (lt/h),	CO_2 (kg/h)	CO (kg/h)	CH (kg/h)	NO_2 (kg/h)
100c (Change)	1775.6	4186.9	3.643	0.483	3.165
110c (Change)	1610.0	3796.5	3.349	0.430	2.916
120c (Current situation)	1718.2	4064.7	3.821	0.482	5.060
130c (Change)	1660.3	3927.5	3.686	0.461	4.828
140c (Change)	1715.4	4058.0	3.814	0.481	5.044
150c (Change)	1701.4	4024.9	3.783	0.476	5.004

Table 5. Calculated fuel consumptions and emissions for the evening

Emissions	Fuel (lt/h),	CO_2 (kg/h)	CO (kg/h)	CH (kg/h)	NO_2 (kg/h)
100c (Change)	1853.7	4374.3	3.744	0.524	3.744
110c (Change)	1565.2	3694.2	3.241	0.430	3.335
120c, (Current situation)	1492.1	3522	3.116	0.406	3.246
130c (Change)	1434.9	3387.3	3.014	0.388	3.163
140c (Change)	1390	3280.6	2.933	0.373	3.089
150c (Change)	1349	3202.3	2.855	0.361	3.017

Vehicle emissions are mostly related to fuel consumptions. For that reason, when we have a look at the fuel consumption rates, one can see that, fuel consumptions are reduced significantly after changing cycle time both for the morning and evening hours.

As can be seen from Table 4, in the morning hours, the fuel consumption rate was 1718,2 l/h for the current situation and decreases to 1434,9 l/h after changing cycle time.

As can be seen from Table 5, in the evening hours, the fuel consumption rate was 1542.1 l/h for the current situation and decreases to 1349 l/h after changing cycle time. A comparison of the cycles is given in Figure 3.

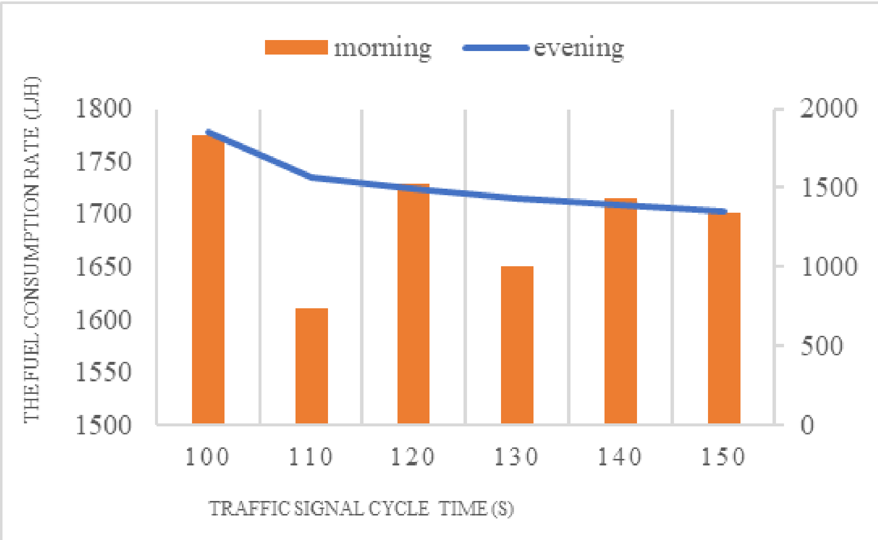

Fig. 3. Fuel consumption in the morning and evening at the intersection

When the morning and evening fuel consumptions rates and emissions were compared, it could be seen that, morning results are higher than evening results for all parameters.

This is due to higher volumes in the morning hours. Moreover, vehicles start and stop, results in higher fuel consumption rates and higher emissions. Future research on emission calculations based on signalization improvement, are very important in terms of environmental and economic considerations.

Conclusions. The most outstanding result in our study was that, the signalization improvements at the intersections have reduced the amount of emissions significantly. SIDRA is one of the most important software in the world used to obtain reliable data in such studies. Furthermore, it can be said that this software is more advantageous than the conventional calculation methods to prepare emission inventory. In the conventional method, the road type is selected as urban, rural or highway and it is assumed that vehicles travel at a constant speed.

In SIDRA, vehicles are not assumed to be at a constant speed, otherwise slowdown and stop-and-start movements are also taken into consideration. Hence, the emissions calculated by this software are thought to be more sensitive. The values obtained by the software can be compared with field studies to make a better evaluation. Therefore, further studies will be conducted on field sampling at the intersection. With the increase of these kind of studies, the default parameters used in the program (f_i, A, B, β) can be changed by new parameters determined nationally.

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