

Development of Mathematical Models for Traffic Emissions Based on Vehicle Delay at Signalized Intersections

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Abstract:

This study aims to develop accurate mathematical models to estimate hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions based on traffic delay parameters at signalized intersections. Using data from six congested intersections in Amman, Jordan, microscopic simulation models were developed and validated. Statistical analysis was then conducted to establish relationships between emissions and two measures of effectiveness: delay per vehicle and intersection control delay. The results revealed a strong inverse linear relationship between delay per vehicle and emissions, with the developed logarithmic models achieving high coefficients of determination of 89.26%, 87.49%, and 98.04% for HC, CO, and NO_x, respectively.

Key words: Traffic Emissions, Signalized Intersections, Mathematical Models, Delay, Hydrocarbon, Nitrogen Oxid.

Introduction:

The rapid growth in vehicle ownership in developing countries has led to severe traffic congestion, particularly at urban signalized intersections. This congestion not only results in significant travel delays but also has adverse environmental consequences due to increased vehicle emissions. Accurate prediction of these emissions is crucial for environmental impact assessments and for evaluating the sustainability of traffic improvement projects. The core problem this research addresses is the need for practical models that can predict emissions based on readily available traffic performance metrics, rather than complex vehicle-specific data. This article hypothesizes that a direct, quantifiable relationship exists between traffic delay and the rate of vehicle emissions. The methodology involves using microscopic simulation to generate performance data, which is then analyzed using statistical regression to develop and validate the proposed mathematical models.

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THE FIRST TOPIC : THEORETICAL FRAMEWORK AND METHODOLOGY

This topic outlines the foundational concepts of traffic-related emissions and details the systematic approach used to collect data and develop the predictive models.

FIRST REQUIREMENT: STUDY METHODOLOGY

The methodology was implemented in a sequential manner to ensure the reliability of the results.

This chapter represents the systematic, theoretical analysis of the methods to be applied in this study.

The tasks were needed are completed during this entire study, Figure 3.1 summarised the ongoing planned to be performed into several steps:

1. Site selection; identify the most congested signalized intersections with appropriate surrounding intersections where AID's could be implimented in Amman.
2. Data collection; collect real traffic data (traffic volume and signal timing and phasing).
3. Develop base simulation models of the current situation for the selected intersections using the microscopic simulation platform Synchro 8.
4. Validate base models using Vissim microscopic simulation software.
5. Evaluation of base simulation models.
6. Develop mathmatical models to evaluate gas emissions using SPSS software platform and Microsoft Exel.
7. Develop a proposed model using alternative intersections.
8. Evaluate the proposed model.
9. Analyze and compare both models using appropriate measures of effectiveness (MOE's).

10. GIS analysis; both models are incorporated Arc GIS platform.

11. Identification of new routes.

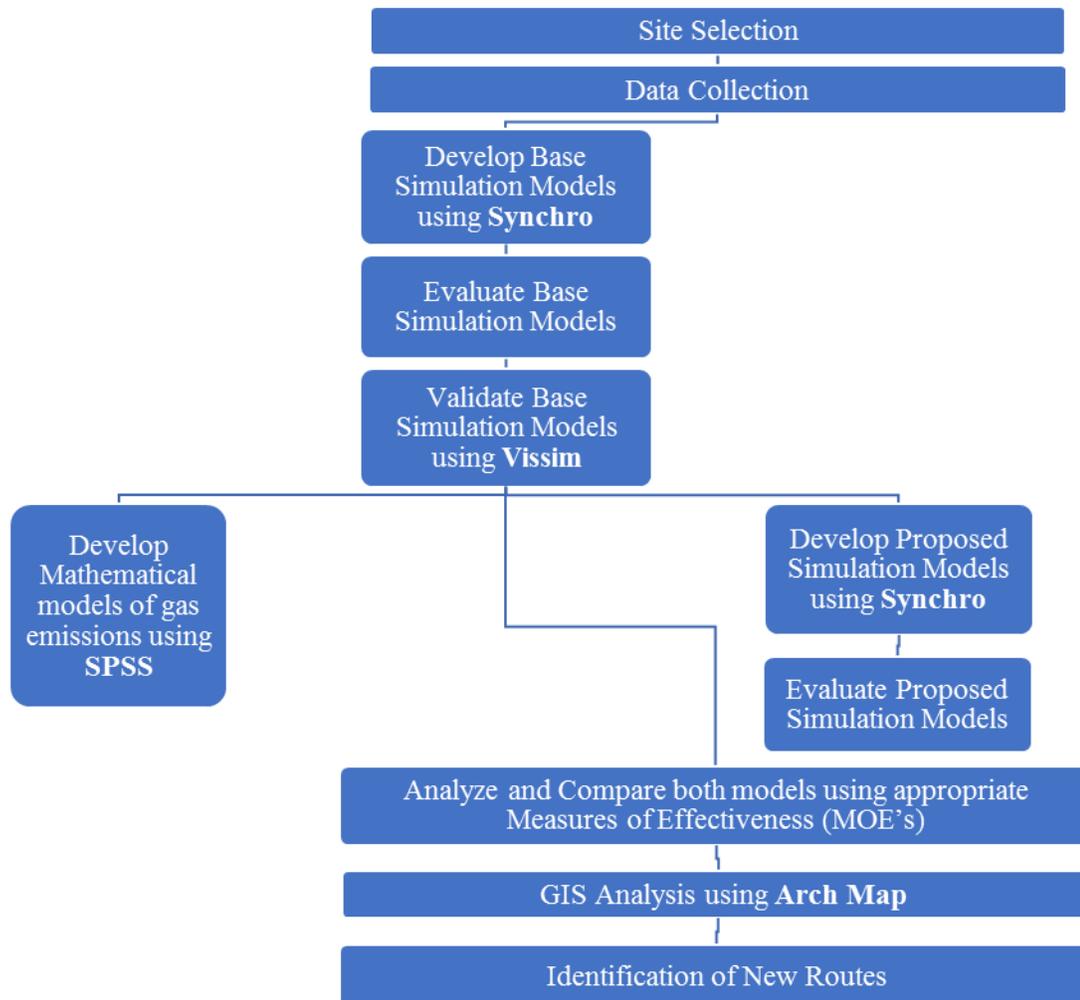


Figure 3.1: Proposed Work Flow Chart

Firstly: Data Collection and Base Model Development

The traffic data on the selected signalized intersections was available from the department of traffic operations at GAM only for through and left turn movements. right turn movement and volume at alternative intersections were counted manually for one hour in February, Appendix A shows the traffic volume calculations of right turn movement. In the same manner data was collected on the prior and after signalized intersections, while on roundabouts data was available from transportation planning department at GAM, all movements traffic volume are represented as a through movement get in or out from arterial roads toward the main selected intersections, including the percentage of heavy vehicles (H.V).

Three weekdays of February, 2019, 11th, 12th, and 13th, were selected to decide which day is to be used for analysis and to estimate when the peak hour occurred. Figure 3.8 through 3.13 show the highest daily volume of the six main intersections occurs on Tuesday, Feb. 12th, 2019, which considered the day of analysis, figures also give an indication that the morning peak occurs from 7:30 to 8:30 am.

This chapter discusses the base model development and validation. Also, it describes the proposed AID models development.

1. Develop a base simulation model for the current situation using the microscopic simulation platform Synchro 8.
2. Validate the model; develop the proposed AID simulation model
3. Evaluation of base simulation model.

4. Develop and evaluate gas emissions mathematical models.
5. Evaluate the proposed models.

4.1 Base Model Development

The base model development for the current intersections starts after the data has been collected and prepared. It was constructed using the existing geometric and traffic data for the six selected intersections. The geometric design for the current situation was imported into SYNCHRO 8 as DXF file from AUTOCAD draft brought from GAM, defining the links length, number of lanes, lane width, approach volumes and cycle length. Figure 4.1 through Figure4.6. shows the base model for the six selected arterial road. Also, it shows traffic volume for each movement. The need to create the base model is important for several reasons; first for the model validation to ensure that the SYNCHRO 8 generated traffic volumes similar to those observed in the field. Also, it is needed for comparison and evaluation purposes.



Figure 4.1: SYNCHRO Model for Current Situation of Al-Assaf Intersection



Figure 4.2: SYNCHRO Model for Current Situation of Elba House Intersection



Figure 4.3: SYNCHRO Model for Current Situation of Firas Square

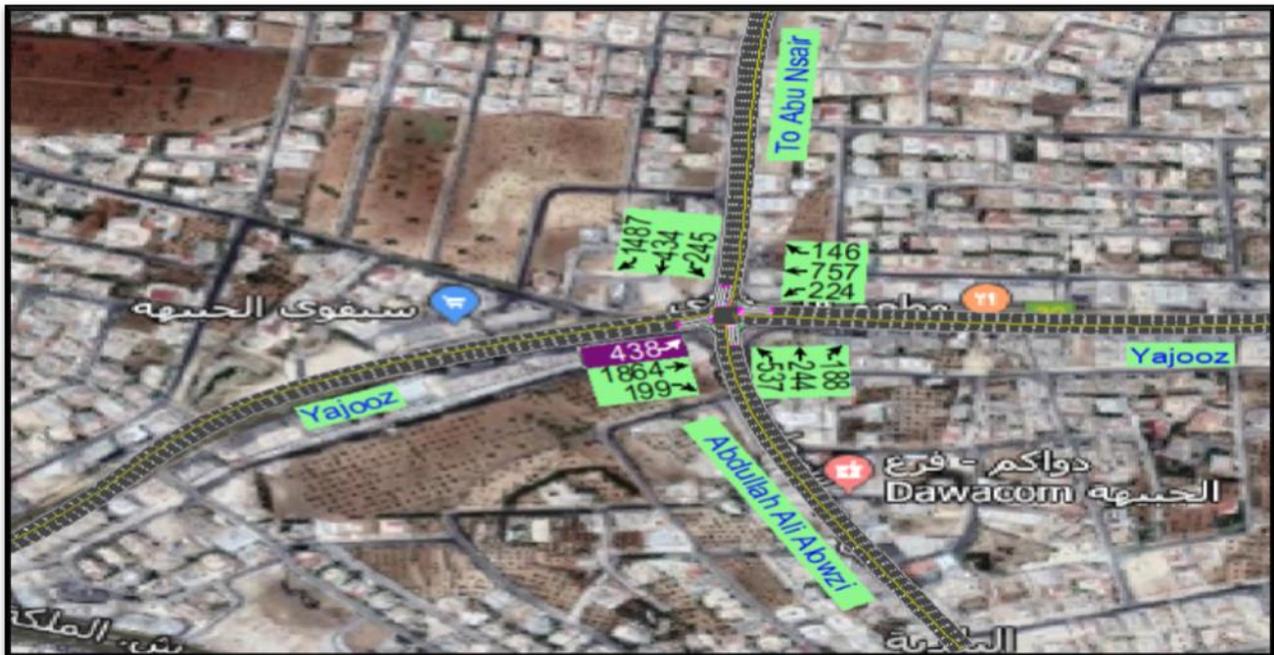


Figure 4.4: SYNCHRO Model for Current Situation of Jbaiha Intersection



Figure 4.5: SYNCHRO Model for Current Situation of Princess Alia Intersection



Figure 4.6: SYNCHRO Model for Current Situation of Wadi Saqra Intersection

It worth mentioning that, the traditional measures that were tested to improve the performance of the six selected intersections included signal timing optimization.

The SYNCHRO software was used to optimize signals phasing and cycle lengths. It was found that the current signalized intersections were running on the optimal signal timing and phasing.

4.2 Model Validation

The base model is only potentially as accurate as the validation processes undertaken during development. Validation should be done using the most appropriate and efficient techniques. (Toledo and Kotsiopoulos, 2004) proposed two ways of model validation, visual methods and mathematical methods. The visual method of validation, which is a graphical representation of data from the real and simulated models are put both side by side to see how different the real and simulated models are. On the other hand, the mathematical validation method applies the goodness of fit measures, confidence intervals, and statistical tests to determine how similar the real and simulated models are.

It should be noted here that the Synchro software disable the changing the random seed number which limits the validation this process. For this reason, Vissim microscopic simulation software was used for this purpose, Vissim was not used in the model development process because of the unavailability of the full version of the program and only student version was available which runs the model for only 600 sec.

The maximum throughput volume was used for the validation purposes.

Eighty runs were carried out using different random seed numbers for each base model. Since the simulation models are valid, their result could be used to develop mathematical models of gas emissions with respect to the other MOE's, intersection delay and the delay per vehicle.

The IBM SPSS software platform which offers advanced statistical analysis, was used to develop the mathematical models of HC, CO, and NO_x emissions. correlation between variables was examined, different relationships was also tested among the three gas emission types and the other two MOE's, in addition to a summary of each of these models.

Stepwise regression method was used for both independent variables, which are intersection delay and delay per vehicle. Table 4.2 shows the variables introduced in the regression model for estimating gas emissions.

Table 4.2: Variables Entered for Gas Emissions

Variables Entered	Method
Intersection Delay	Stepwise (Criteria: Probability-of-F-to-enter <=0 .05.
Delay per Vehicle	Stepwise (Criteria: Probability-of-F-to-enter <= 0.50.

Hydrocarbon (HC)

The HC emission models were evaluated through integrated models, as a function of intersection delay and delay per vehicle, then a simple model was evaluated with respect to a single dependent variable separately.

Table 4.3 shows the correlation matrix between the six variables and the significance of the correlation.

Table 4.3: Correlations between Variables

		Emission/Lane (g/l)	Delay/Veh. (sec/veh)	Int. Delay (sec)
Pearson Correlation	Emission/Lane (g/l)	1.000	.183	.552
	Delay/Veh. (sec/veh)	.183	1.000	.653
	Int. Delay (sec)	.552	.653	1.000
Sig. (1-tailed)	Emission/Lane (g/l)	.	.364	.128
	Delay/Veh. (sec/veh)	.364	.	.080
	Int. Delay (sec)	.128	.080	.
N	Emission/Lane (g/l)	6	6	6
	Delay/Veh. (sec/veh)	6	6	6
	Int. Delay (sec)	6	6	6

It can be seen that the correlation between intersection delay and HC emission has a large positive strength of association with Pearson coefficient (r) of 0.552, while the correlation between delay per vehicle and HC emission a small positive strength of association with Pearson coefficient (r) 0.183.

The integrated model can be presented using coefficients in Table 4.4 As follow

$$HC \text{ gas emissions} = 0.007 (\text{intersection delay}) - 0.02 (\text{delay per vehicle}) + 10.656 \dots \dots \text{Equation 1}$$

Table 4.4: Coefficients^a of the HC Integrated Emission Model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error				Beta	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance
1 (Constant)	10.656	1.446		7.368	.005	6.054	15.259					
Delay/Veh. (sec/veh)	-.002	.004	-.309	-.506	.648	-.013	.010	.183	-.281	-.234	.573	1.745
Int. Delay (sec)	.007	.006	.754	1.235	.305	-.012	.026	.552	.581	.571	.573	1.745

a. Dependent Variable: Emission/Lane (g/l_n).

Therefore, the model is insignificant of fitting the two variables, but is it significant of representing the coefficient, which is considerable for predicted models.

Table 4.5 Of ANOVA output corroborates the insignificance of fitting the two variables with significance level of 0.0513. but, as illustrated in Table 4.6, correlation between the two independent variables, intersection delay and delay per vehicle, is strongly associated with r of 0.653.

Table 4.5: The Results of the ANOVA^a Regression Analysis of HC Emission

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.555	2	1.778	.841	.513 ^b
	Residual	6.339	3	2.113		
	Total	9.894	5			

a. Dependent Variable: Emission/Lane (g/l_n)

b. Predictors: (Constant), Int. Delay (sec), Delay/Veh. (sec/veh)

Table 4.6 shows the integrated model of dependent variables, intersection delay and delay per vehicle.

Table 4.6: Correlations^a of HC Emission Model's Independent Variables

Model		Int. Delay (sec)	Delay/Veh. (sec/veh)
1	Correlations	Int. Delay (sec)	1.000
		Delay/Veh. (sec/veh)	-.653
	Covariances	Int. Delay (sec)	3.526E-5
			-1.413E-5

Delay/Veh. (sec/veh)	-1.413E-5	1.328E-5
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a. Dependent Variable: Emission/Lane (g/ln)

seven models are tested to fit each of the two variables, Table 4.7 represents these models and their significance which are not significant.

Table 4.7: Simple HC emission models' coefficient of dependent variables.

Relationship	The independent variable is Emission/Lane (g/ln).	The dependent variable is ln(Int. Delay (sec)).					The dependent variable is ln(Delay/Veh. (sec/veh)).				
		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta			B	Std. Error	Beta		
Linear	Emission/Lane (g/ln)	30.732	82.339	0.183	0.373	0.728	56.731	42.859	0.552	1.324	0.256
	(Constant)	-30.181	1007.193		-0.030	0.978	-397.9425	524.265		-0.759	0.490
Logarithmic	log(Emission/Lane (g/ln))	442.920	978.176	0.221	0.453	0.674	697.071	507.188	0.566	1.374	0.241
	(Constant)	-760.465	2440.700		-0.312	0.771	-1445.526	1265.513		-1.142	0.317
Inverse	1 / Emission/Lane (g/ln)	-6085.169	11476.101	-0.256	-0.530	0.624	-8418.439	5945.927	-0.578	-1.416	0.230
	(Constant)	849.682	959.948		0.885	0.426	992.206	497.362		1.995	0.117
Quadratic	Emission/Lane (g/ln)	2105.619	1223.086	12.569	1.722	0.184	599.579	834.745	5.833	0.718	0.524
	Emission/Lane (g/ln) ** 2	-85.810	50.505	-12.405	-1.699	0.188	-22.450	34.469	-5.289	-0.651	0.561
	(Constant)	-12430.840	7345.634		-1.692	0.189	-3642.299	5013.329		-0.727	0.520
Cubic	Emission/Lane (g/ln)	1097.329	613.249	6.550	1.789	0.171	341.91245	422.421	3.326	0.809	0.478
	Emission/Lane (g/ln) ** 3	-2.413	1.379	-6.405	-1.750	0.178	-0.645	0.950	-2.791	-0.679	0.546
	(Constant)	-8516.072	4918.456		-1.731	0.182	-2666.861	3387.954		-0.787	0.489
Power	ln(Emission/Lane (g/ln))	1.950	3.142	0.296	0.621	0.569	2.8969794	1.691	0.651	1.713	0.162
	(Constant)	2.108	16.526		0.128	0.905	0.191	0.807		0.237	0.824
Exponential	Emission/Lane (g/ln)	0.145	0.265	0.263	0.546	0.614	0.238	0.143	0.639	1.664	0.172
	(Constant)	46.806	151.767		0.308	0.773	14.506	25.367		0.572	0.598

Table 4.8 shows models summery, it can be seen that the adjusted R square has negative values, because a small sample size was used to build the model, overfitting of model, so the R square was used to evaluate the models.

R square has a higher value of quadrant and cubic relation of the dependent variable intersection delay, 0.508 and 0.522, respectively, which considered moderated.

Table 4.8: Model Summary of HC Emissions.

Relationship	The dependent variable is ln(Int. Delay (sec)).			The dependent variable is ln(Delay/Veh. (sec/veh)).		
	R	R Square	Adjusted R Square	R	R Square	Adjusted R Square
Linear	0.183	0.034	-0.208	0.552	0.305	0.131
Logarithmic	0.221	0.049	-0.189	0.566	0.321	0.151
Inverse	0.256	0.066	-0.168	0.578	0.334	0.167
Quadratic	0.712	0.508	0.179	0.625	0.391	-0.015
Cubic	0.722	0.522	0.203	0.630	0.397	-0.005
Power	0.296	0.088	-0.140	0.651	0.423	0.279
Exponential	0.263	0.069	-0.163	0.639	0.409	0.261
The independent variable is Emission/Lane (g/ln).						

Figure 4.7 represents the HC Emissions versus Intersection delay for the seven proposed mathematical models, it can be seen none of them fits the points, as well as the models that represented in Figure 4.8, HC Emissions versus delay per vehicle.

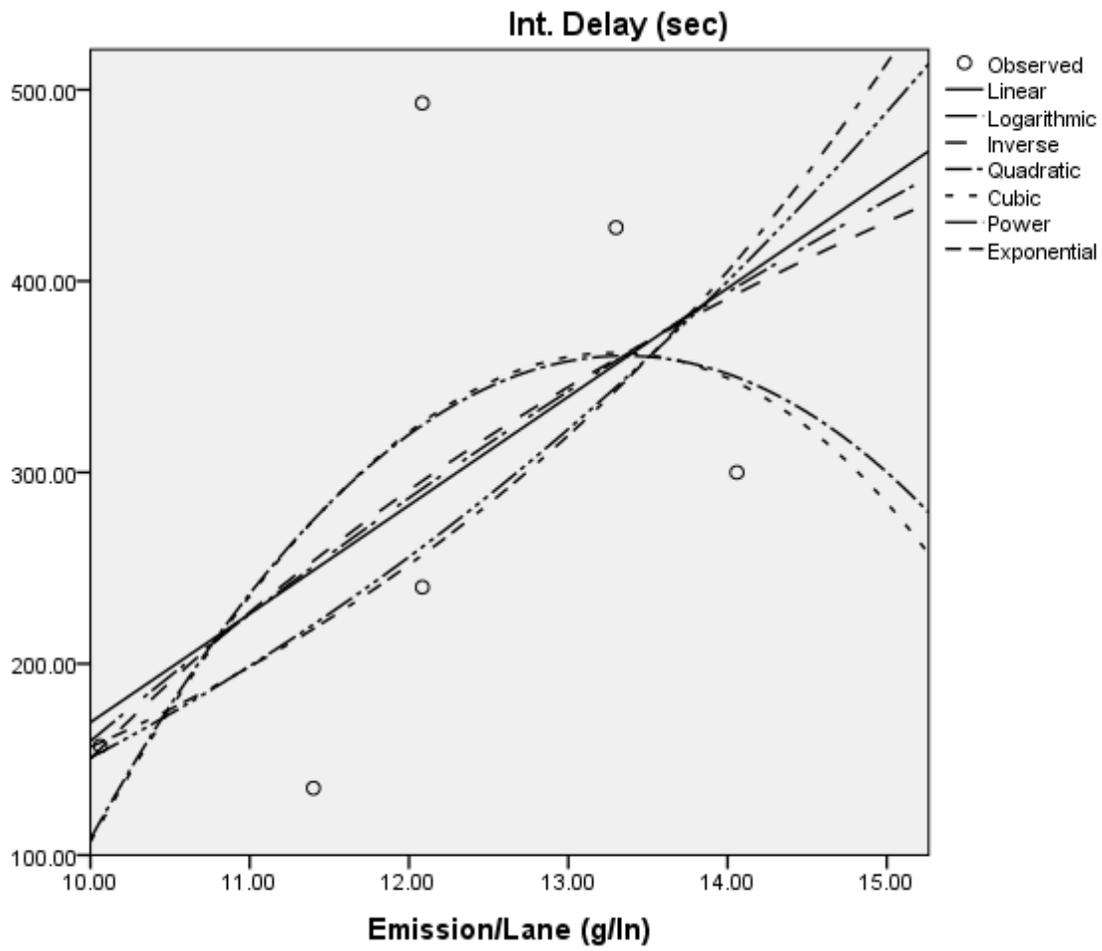


Figure 4.7: HC Emissions versus Intersection Delay

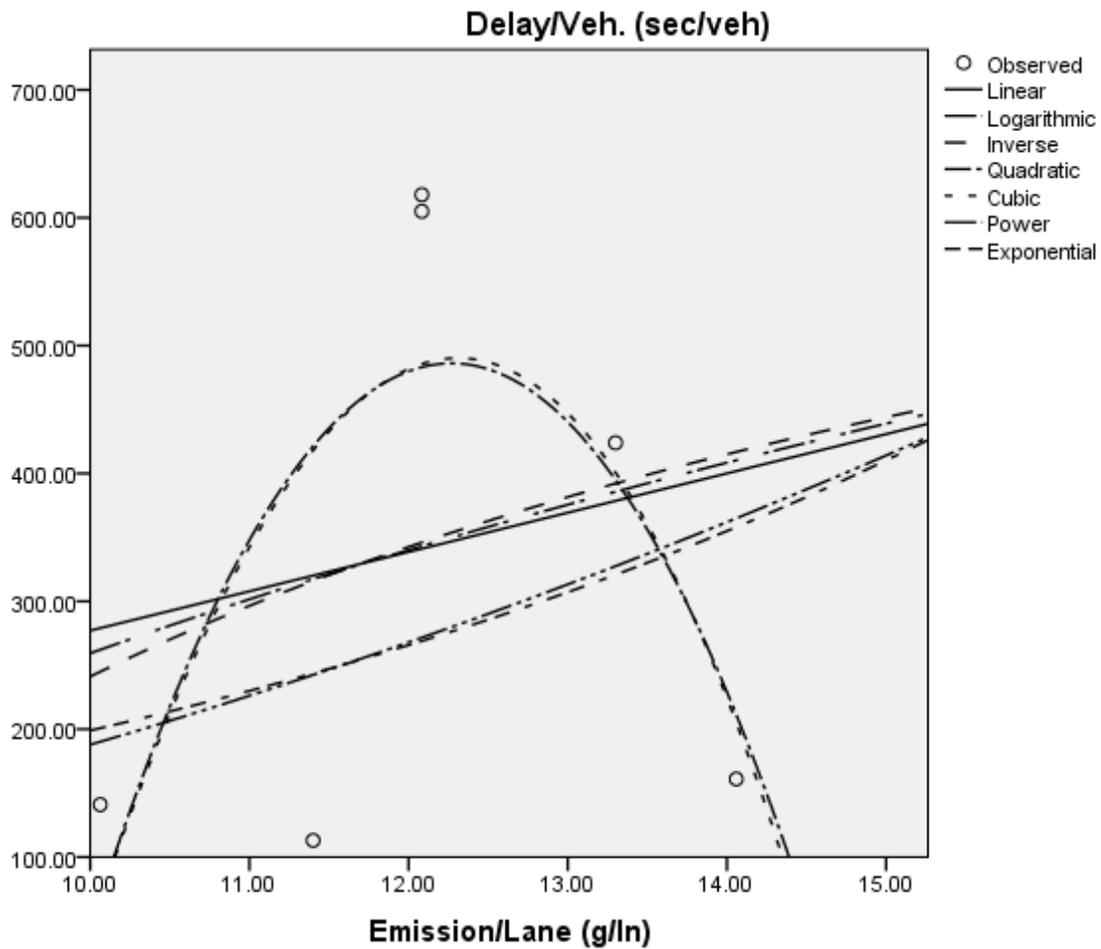


Figure 4.8: HC Emissions versus Delay per Vehicle

Carbon monoxide (CO)

The CO emission models were evaluated through integrated models, as a function of intersection delay and delay per vehicle, then a simple model was evaluated with respect to a single dependent variable separately.

Table 4.9 shows the correlation matrix between the six variables and the significance of the correlation.

Table 4.9: Correlations between Variables and CO Emissions

		Emission/Lane (g/ln)	Delay/Veh. (sec/veh)	Int. Delay (sec)
Pearson Correlation	Emission/Lane (g/ln)	1.000	-.649	.107
	Delay/Veh. (sec/veh)	-.649	1.000	.653
	Int. Delay (sec)	.107	.653	1.000
Sig. (1-tailed)	Emission/Lane (g/ln)	.	.082	.420
	Delay/Veh. (sec/veh)	.082	.	.080
	Int. Delay (sec)	.420	.080	.
N	Emission/Lane (g/ln)	6	6	6
	Delay/Veh. (sec/veh)	6	6	6
	Int. Delay (sec)	6	6	6

It can be seen that the correlation between delay per vehicle and CO emission has a large negative strength of association with Pearson coefficient of -0.649, while the correlation between delay per vehicle and CO emission has a small positive strength of association between intersection delay with Pearson coefficient (r) 0.107.

The integrated model can be presented using coefficients in Table 4.10 As follow

$$\text{CO gas emissions} = 1.184 (\text{intersection delay}) - 0.984 (\text{delay per vehicle}) + 381.550 \dots \text{Equation 2}$$

Table 4.10: Coefficients^a of the CO Integrated Emission Model

Model	Unstandardized Coefficients		Standardized Coefficients Beta	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error				Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1 (Constant)	381.550	70.091		5.444	.012	158.490	604.609					
Delay/Veh. (sec/veh)	-.984	.177	-1.254	-5.571	.011	-1.546	-.422	-.649	-.955	-.949	.573	1.745
Int. Delay (sec)	1.184	.288	.926	4.116	.026	.269	2.100	.107	.922	.701	.573	1.745

a. Dependent Variable: Emission/Lane (g/l_n)

Therefore, the model is insignificant of fitting the two variables and the coefficient. Table 4.11 Of ANOVA output shows the significance of fitting the two variables with significance level of 0.026. Table 4.12 illustrated correlation between the two independent variables, intersection delay and delay per vehicle, is also strongly associated with r of -0.653.

Table 4.11 The Results of the ANOVA^a Regression Analysis.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	155971.658	2	77985.829	15.714	.026 ^b
	Residual	14888.505	3	4962.835		
	Total	170860.163	5			

a. Dependent Variable: Emission/Lane (g/l_n)

b. Predictors: (Constant), Int. Delay (sec), Delay/Veh. (sec/veh)

Table 4.12: The Correlations ^a of CO Emission Model's Independent Variables

Model		Int. Delay (sec)	Delay/Veh. (sec/veh)
1	Correlations	Int. Delay (sec)	1.000
		Delay/Veh. (sec/veh)	-.653
	Covariances	Int. Delay (sec)	.083
		Delay/Veh. (sec/veh)	-.033

a. Dependent Variable: Emission/Lane (g/l_n)

seven models are tested to fit each of the two variables, Table 4.13 Represents these models and their significance which are not significant.

Table 4.13: Simple CO Emission Models' Coefficient of Dependent Variables

Relationship	The independent variable is Emission/Lane (g/ln).	The dependent variable is ln(Int. Delay (sec)).					The dependent variable is ln(Delay/Veh. (sec/veh)).				
		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta			B	Std. Error	Beta		
Linear	Emission/Lane (g/ln)	0.084	0.389	0.107	0.216	0.840	-0.827	0.485	-0.649	-1.705	0.163
	(Constant)	259.484	165.075		1.572	0.191	665.809	205.924		3.233	0.032
Logarithmic	ln(Emission/Lane (g/ln))	20.904	76.334	0.136	0.274	0.798	-158.208	97.514	-0.630	-1.622	0.180
	(Constant)	172.273	442.659		0.389	0.717	1251.044	565.480		2.212	0.091
Inverse	1 / Emission/Lane (g/ln)	-3026.308	9228.018	-0.162	-0.328	0.759	18058.188	12277.299	0.592	1.471	0.215
	(Constant)	308.528	82.042		3.761	0.020	246.035	109.152		2.254	0.087
Quadratic	Emission/Lane (g/ln)	0.083	1.909	0.106	0.043	0.968	-1.365	2.360	-1.071	-0.578	0.604
	Emission/Lane (g/ln) ** 2	0.000	0.003	0.001	0.001	1.000	0.001	0.004	0.434	0.234	0.830
	(Constant)	259.567	242.903		1.069	0.364	709.447	300.274		2.363	0.099
Cubic	Emission/Lane (g/ln)	17.300	3.789	22.117	4.566	0.045	20.271	3.759	15.901	5.393	0.033
	Emission/Lane (g/ln) ** 2	-0.067	0.015	-51.670	-4.606	0.044	-0.084	0.014	-39.408	-5.771	0.029
	Emission/Lane (g/ln) ** 3	0.000	0.000	30.731	4.620	0.044	8.830E-05	0.000	23.696	5.852	0.028
	(Constant)	-433.825	173.499		-2.500	0.130	-161.886	172.142		-0.940	0.446
Power	ln(Emission/Lane (g/ln))	0.035	0.278	0.062	0.125	0.907	-0.461	0.341	-0.559	-1.350	0.248
	(Constant)	214.509	346.080		0.620	0.569	3827.388	7577.611		0.505	0.640
Exponential	Emission/Lane (g/ln)	0.000	0.001	0.065	0.131	0.902	-0.002	0.002	-0.555	-1.334	0.253
	(Constant)	243.584	146.010		1.668	0.171	672.017	496.293		1.354	0.247

Table 4.13 shows models summary, it can be seen that the adjusted R square has negative values, because a small sample size was used to build the model, overfitting of model, so the R square was used to evaluate the models.

R square has a higher value of cubic relation of the independent variable, intersection delay, 0.915 and 0.969 for the independent variable, delay per vehicle, which sound great.

Table 4.14: Model Summary of CO Emissions.

Relationship	The dependent variable is ln(Int. Delay (sec)).			The dependent variable is ln(Delay/Veh. (sec/veh)).		
	R	R Square	Adjusted R Square	R	R Square	Adjusted R Square
Linear	0.107	0.012	-0.236	0.649	0.421	0.276
Logarithmic	0.136	0.018	-0.227	0.630	0.397	0.246
Inverse	0.162	0.026	-0.217	0.592	0.351	0.189
Quadratic	0.107	0.012	-0.647	0.657	0.431	0.052
Cubic	0.957	0.915	0.788	0.984	0.969	0.922
Power	0.062	0.004	-0.245	0.559	0.313	0.141
Exponential	0.065	0.004	-0.245	0.555	0.308	0.135
The independent variable is Emission/Lane (g/ln).						

Figure 4.9 represents the CO Emissions versus Intersection delay for the seven proposed mathematical models, it can be seen the cubic model almost fits the points, as well as the cubic model that represented in Figure 4.10, CO Emissions versus delay per vehicle.

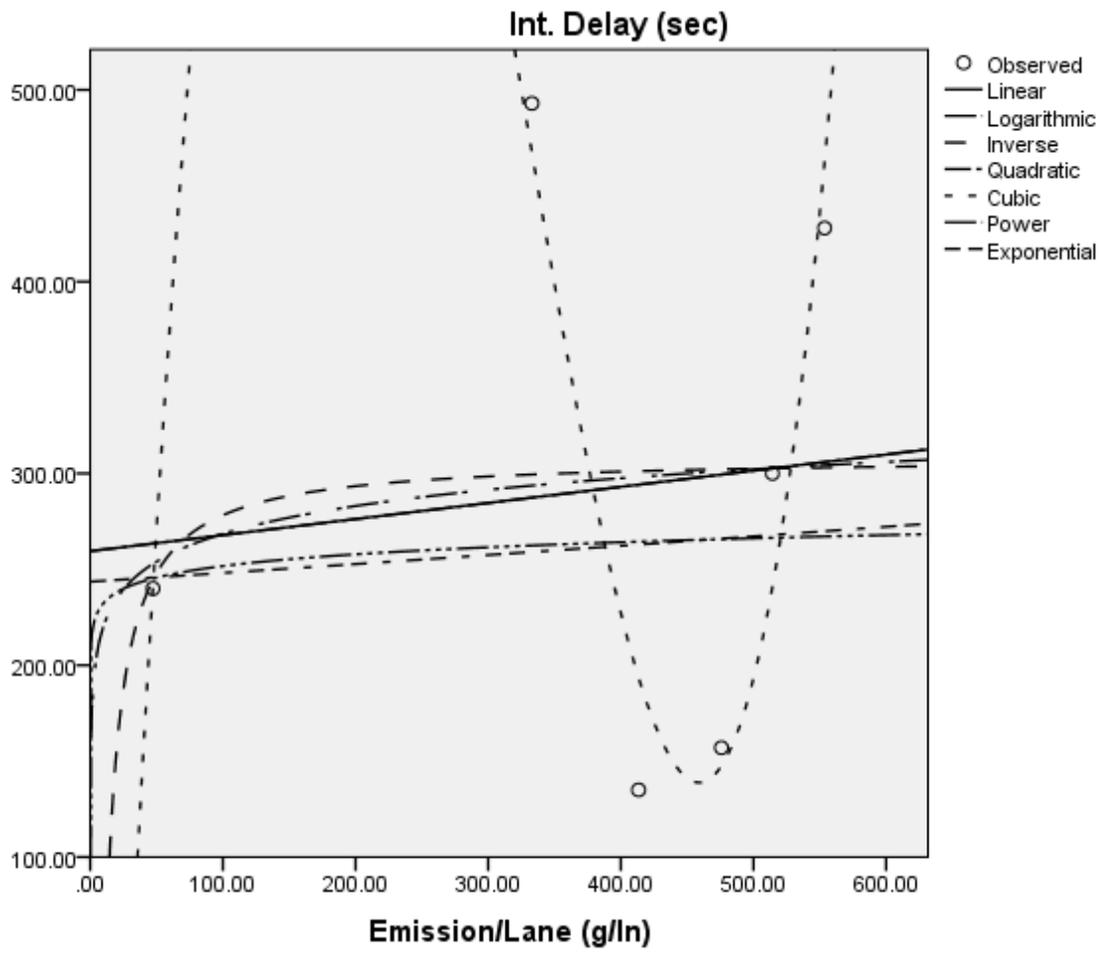


Figure 4.9: CO Emissions versus Intersection Delay

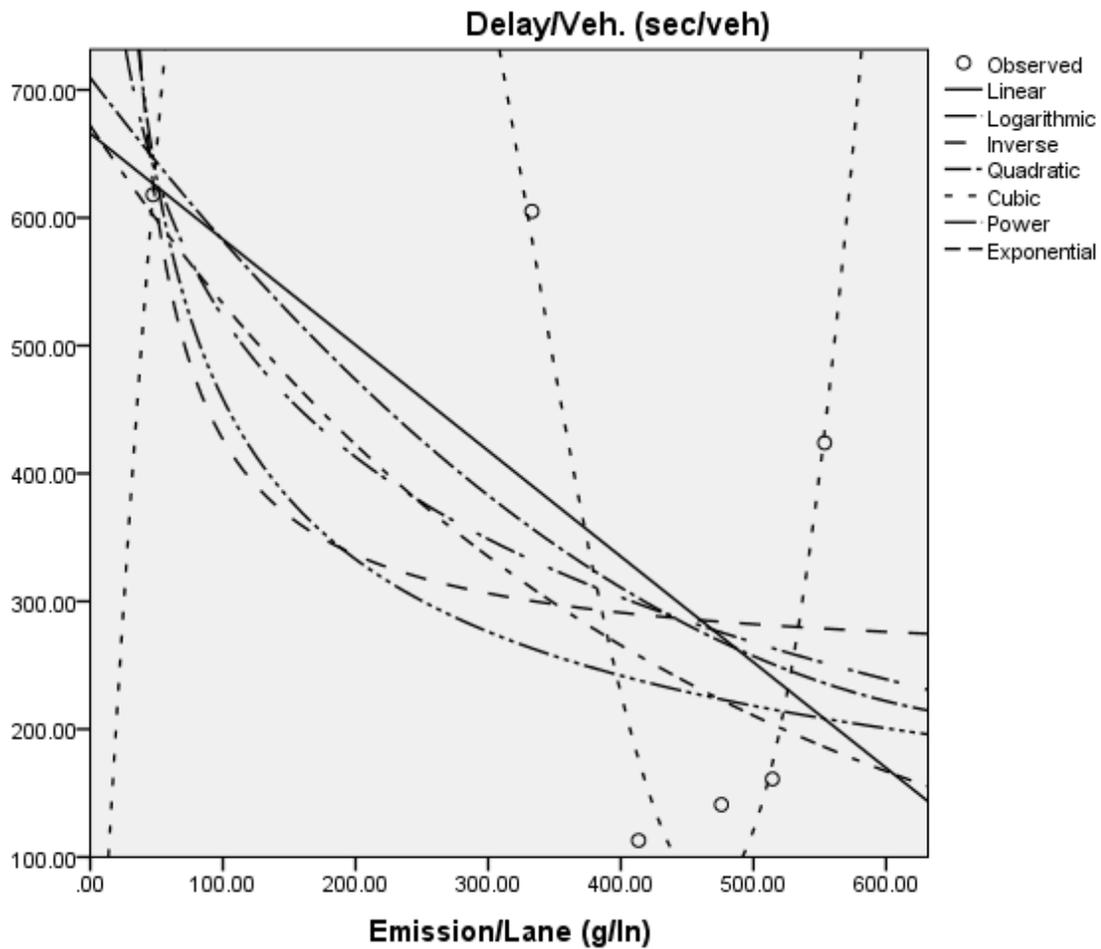


Figure 4.10: CO Emissions versus Delay per Vehicle

Nitrogen Oxid (NO)

The NO_x emission models were evaluated through integrated models, as a function of intersection delay and delay per vehicle, then a simple model was evaluated with respect to a single independent variable separately.

Table 4.15 shows the correlation matrix between the six variables and the significance of the correlation.

Table 4.15: Correlations between Variables and NO_x Emissions.

		Emission/Lane (g/lane)	Delay/Veh. (sec/veh)	Int. Delay (sec)
Pearson Correlation	Emission/Lane (g/lane)	1.000	-.647	.015
	Delay/Veh. (sec/veh)	-.647	1.000	.653
	Int. Delay (sec)	.015	.653	1.000
Sig. (1-tailed)	Emission/Lane (g/lane)	.	.083	.489
	Delay/Veh. (sec/veh)	.083	.	.080
	Int. Delay (sec)	.489	.080	.
N	Emission/Lane (g/lane)	6	6	6
	Delay/Veh. (sec/veh)	6	6	6
	Int. Delay (sec)	6	6	6

It can be seen that the correlation between intersection delay and NO_x emission has a small positive strength of association with Pearson coefficient (r) of 0.015, while the correlation between delay per vehicle and NO_x emission has a large negative strength of association with Pearson coefficient (r) of -0.647.

The integrated model can be presented using coefficients in Table 4.16 as follow

$$\text{NO}_x \text{ gas emissions} = 0.31 \text{ (intersection delay)} - 0.028 \text{ (delay per vehicle)} + 38.291 \dots \text{Equation 3}$$

Table 4.16: Coefficients^a of the NO_x Integrated Emission Model

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error				Beta	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance
1 (Constant)	38.291	3.737		10.246	.002	26.397	50.184					
Delay/Veh. (sec/veh)	-.028	.009	-.1145	-3.016	.057	-.058	.002	-.647	-.867	-.867	.573	1.745
Int. Delay (sec)	.031	.015	.763	2.009	.138	-.018	.080	.015	.757	.578	.573	1.745

a. Dependent Variable: Emission/Lane (g/ln)

Therefore, the model is insignificant of fitting the two variables, but is it significant of representing the coefficient. Table 4.17 of ANOVA output corroborates the insignificance of fitting the two variables with significance level of 0.123. but, as illustrated in Table 4.18, correlation between the two independent variables, intersection delay and delay per vehicle, is strongly associated with r of -0.653.

Table 4.17: The results of the ANOVA^a regression analysis.

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	128.382	2	64.191	4.549	.123 ^b
	Residual	42.329	3	14.110		
	Total	170.711	5			

a. Dependent Variable: Emission/Lane (g/l_n)

b. Predictors: (Constant), Int. Delay (sec), Delay/Veh. (sec/veh)

Table 4.18: The Correlations^a of NO_x emission model's independent variables

Model			Int. Delay (sec)	Delay/Veh. (sec/veh)
1	Correlations	Int. Delay (sec)	1.000	-.653
		Delay/Veh. (sec/veh)	-.653	1.000
	Covariances	Int. Delay (sec)	.000	-9.439E-5
		Delay/Veh. (sec/veh)	-9.439E-5	8.865E-5

a. Dependent Variable: Emission/Lane (g/l_n)

Seven models are tested to fit each of the two variables, Table 4.19 represents these models and their significance which are not significant.

Table 4.19: Simple NO_x Emission Models' Coefficient of Dependent Variables

Relationship	The independent variable is Emission/Lane (g/ln).	The dependent variable is ln(Int. Delay (sec)).					The dependent variable is ln(Delay/Veh. (sec/veh)).				
		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta			B	Std. Error	Beta		
Linear	Emission/Lane (g/ln)	-26.087	15.378	-0.647	-1.696	0.165	0.365	12.372	0.015	0.029	0.978
	(Constant)	1322.932	583.082		2.269	0.086	278.469	469.089		0.594	0.585
Logarithmic	ln(Emission/Lane (g/ln))	-1006.987	558.565	-0.670	-1.803	0.146	2.313	461.425	0.003	0.005	0.996
	(Constant)	3984.131	2020.907		1.971	0.120	283.804	1669.450		0.170	0.873
Inverse	1 / Emission/Lane (g/ln)	38129.046	19986.898	0.690	1.908	0.129	292.520	16947.771	0.009	0.017	0.987
	(Constant)	-692.996	548.954		-1.262	0.275	284.214	465.483		0.611	0.574
Quadratic	Emission/Lane (g/ln)	-286.150	257.434	-7.095	-1.112	0.347	-88.834	234.252	-3.590	-0.379	0.730
	Emission/Lane (g/ln) ** 2	3.441	3.400	6.460	1.012	0.386	1.180	3.094	3.611	0.381	0.728
	(Constant)	6139.204	4794.491		1.280	0.290	1930.393	4362.748		0.442	0.688
Cubic	Emission/Lane (g/ln)	-286.150	257.434	-7.095	-1.112	0.347	-1.215	3.150	-3.717	-0.386	0.725
	Emission/Lane (g/ln) ** 2	3.441	3.400	6.460	1.012	0.386	0.021	0.055	3.751	0.389	0.723
	(Constant)	6139.204	4794.491		1.280	0.290	844.986	1479.483		0.571	0.608
Power	ln(Emission/Lane (g/ln))	-2.858	2.011	-0.579	-1.421	0.228	0.079	1.669	0.024	0.047	0.965
	(Constant)	8363735.330	8363735.335		0.137	0.897	196.801	1188.377		0.166	0.877
Exponential	Emission/Lane (g/ln)	-0.074	0.055	-0.556	-1.337	0.252	0.004	0.045	0.045	0.090	0.933
	(Constant)	4299.408	8965.404		0.480	0.657	225.267	381.978		0.590	0.587

Table 4.20 shows models summery, it can be seen that the adjusted R square has negative values, because a small sample size was used to build the model, overfitting of model, so the R square was used to evaluate the models.

R square has a higher value of quadratic and cubic relation of the dependent variable intersection delay, 0.566, which considered moderated.

Table 4.20: Model Summary of NO_x Emissions.

Relationship	The dependent variable is ln(Int. Delay (sec)).			The dependent variable is ln(Delay/Veh. (sec/veh)).		
	R	R Square	Adjusted R Square	R	R Square	Adjusted R Square
Linear	0.647	0.418	0.273	0.015	0.000	-0.250
Logarithmic	0.670	0.448	0.310	0.003	0.000	-0.250
Inverse	0.690	0.476	0.345	0.009	0.000	-0.250
Quadratic	0.753	0.566	0.277	0.216	0.046	-0.589
Cubic	0.753	0.566	0.277	0.221	0.049	-0.585
Power	0.579	0.336	0.169	0.024	0.001	-0.249
Exponential	0.556	0.309	0.136	0.045	0.002	-0.247
The independent variable is Emission/Lane (g/ln).						

Figure 4.11 represents the NO_x Emissions versus Intersection delay for the seven proposed mathematical models, it can be seen none of them fits the points, as well as represented in Figure 4.12, NO_x Emissions versus delay per vehicle.

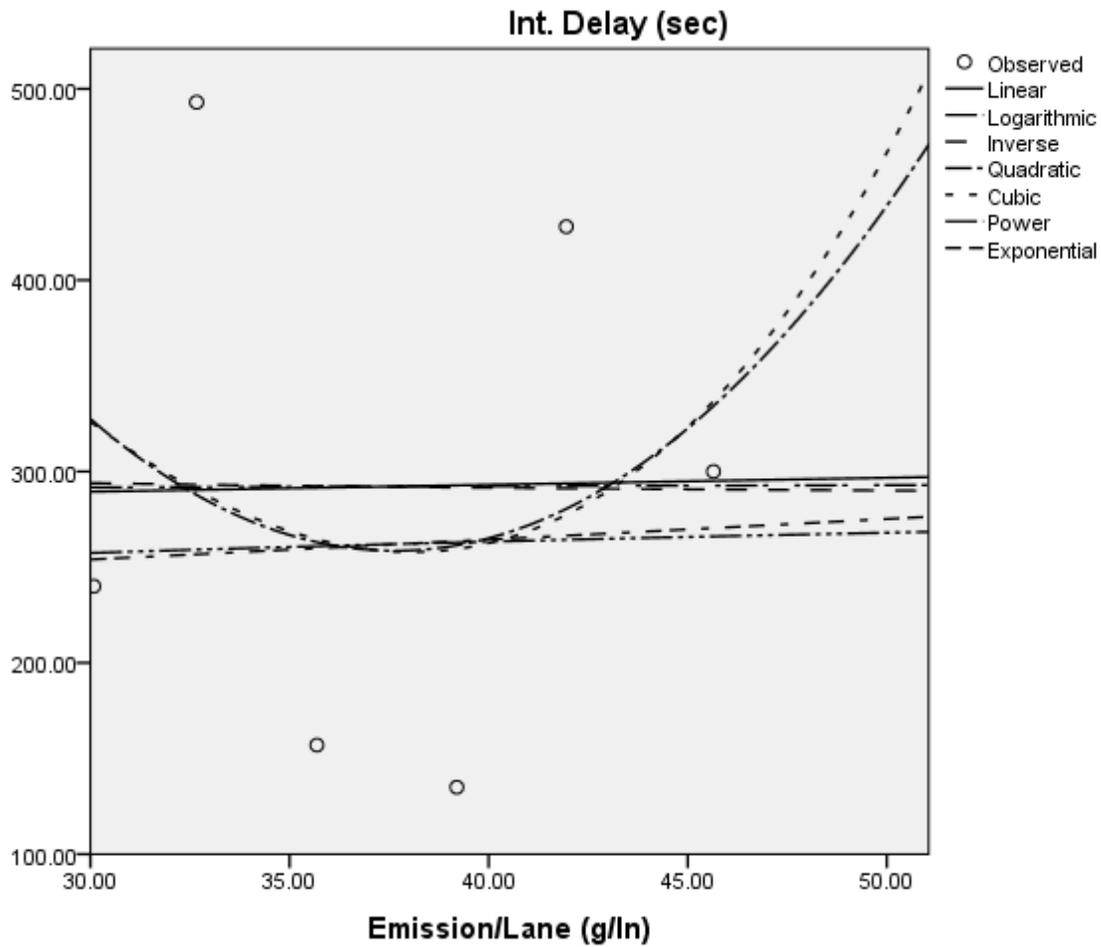


Figure 4.11: NO_x Emissions versus Intersection Delay

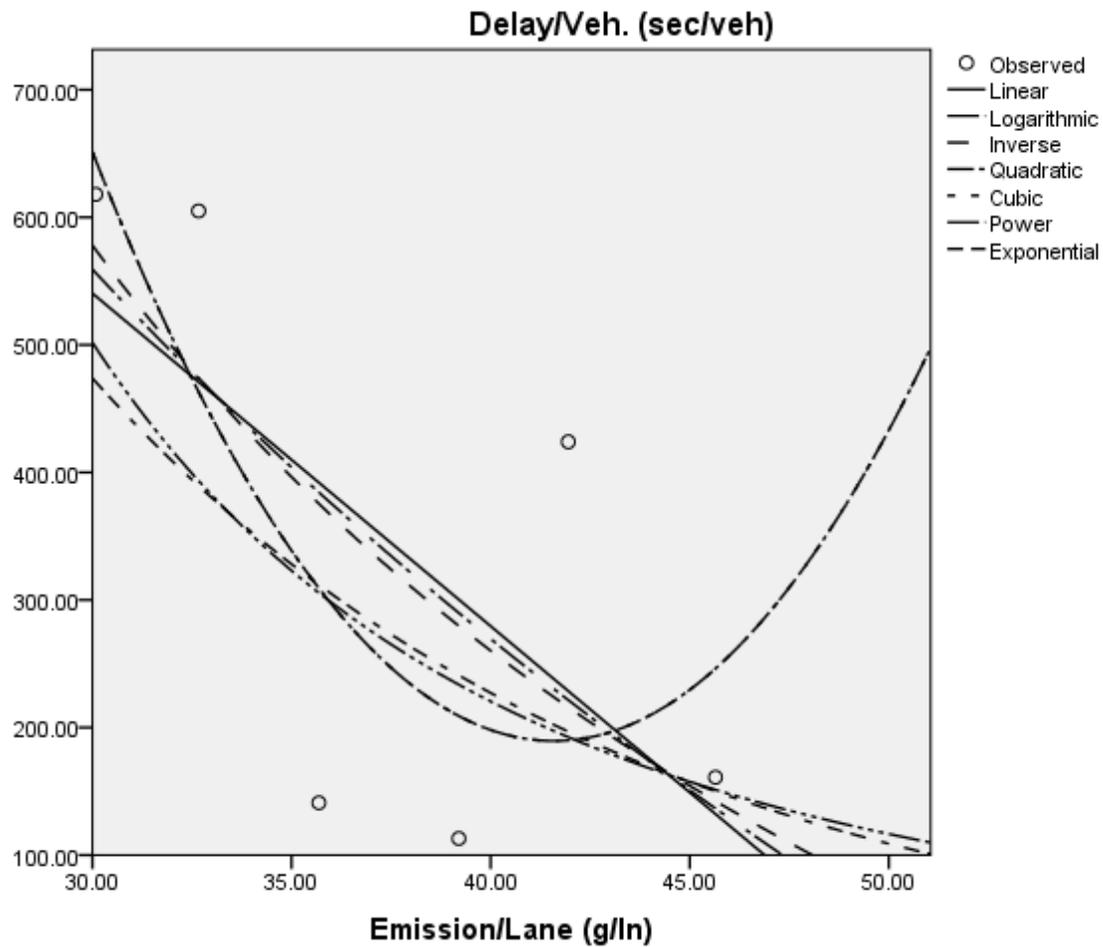


Figure 4.12: NO_x Emissions versus Delay per Vehicle

The models that were developed using SPSS were not significant to represent the relation among gas emissions, intersection delay and delay per vehicle, so other models were developed using Microsoft Excel, logarithmic models of the independent variables, intersection delay and delay per vehicle, to the base of dependent variable, gas emissions. The Microsoft Excel was used since SPSS is only able to analyze the logarithmic model to the base of ten.

Gas emissions are plotted against log (delay per vehicle) to the base of emission per lane, as shown in Table 4.21, for the Hydrocarbon HC, Carbon monoxide CO, and Nitrogen Oxid NO, to

develop mathematical models of $\text{Log}(\text{Delay}/\text{Veh.})$ and emission per lane. The models were developed using the six selected intersections Figures 4.13, 4.14, and 4.15 show the models that fit the data by 89.53%, 85.38%, and 98.08%, of HC, CO, and NO, respectively.

Calibration of the mathematical model has been achieved using the Al-Kindi intersection.

Table 4.21: Input Data of HC Emissions (delay per vehicle)

Intersection	Delay/Veh. (sec/veh)	HC Emissions (g/Lane)	$\text{Log}(\text{Delay}/\text{Veh.})$ Emission/Lane
ALASSAF	618	12.08333333	0.3877432
ELBA HOUSE	797.4	31.16666667	0.3890302
FIRAS SQUARE	747.1	21.8125	0.4665443
JBAHA	402.9	21.76470588	0.520181
PRINCESS ALIAH	79.1	14.4	0.5147903
WIDI SAQRA	744.6	18.1	0.4277484

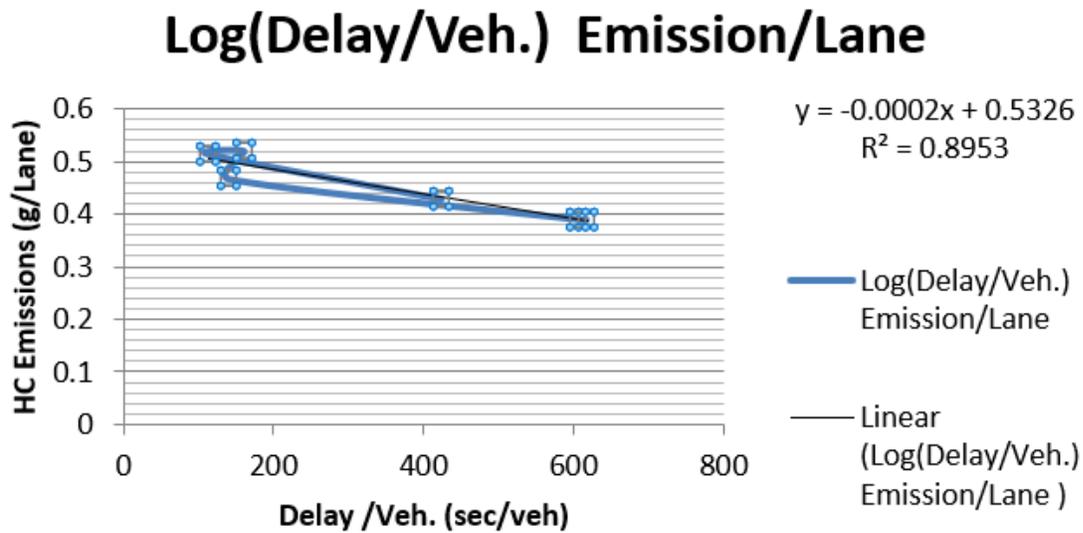


Figure 4.13: The Mathematical Model of HC Emissions as Function of Delay per Vehicle

HC gas emissions = -0.0002 (delay per vehicle)+ 0.5326....Equation 4

Table 4.22: Input Data of CO Emissions (delay per vehicle)

Intersection	Delay/Veh. (sec/veh)	CO Emissions (g)	Log(Delay/Veh.) Emission/Lane
ALASSAF	618	47.25	0.5296783
ELBA HOUSE	797.4	905.3333333	0.5442983
FIRAS SQUARE	747.1	890.875	0.7223629
JBAHA	402.9	1232.294118	0.7519455
PRINCESS ALIAH	79.1	658.3	0.7760473
WIDI SAQRA	744.6	763.4	0.617627

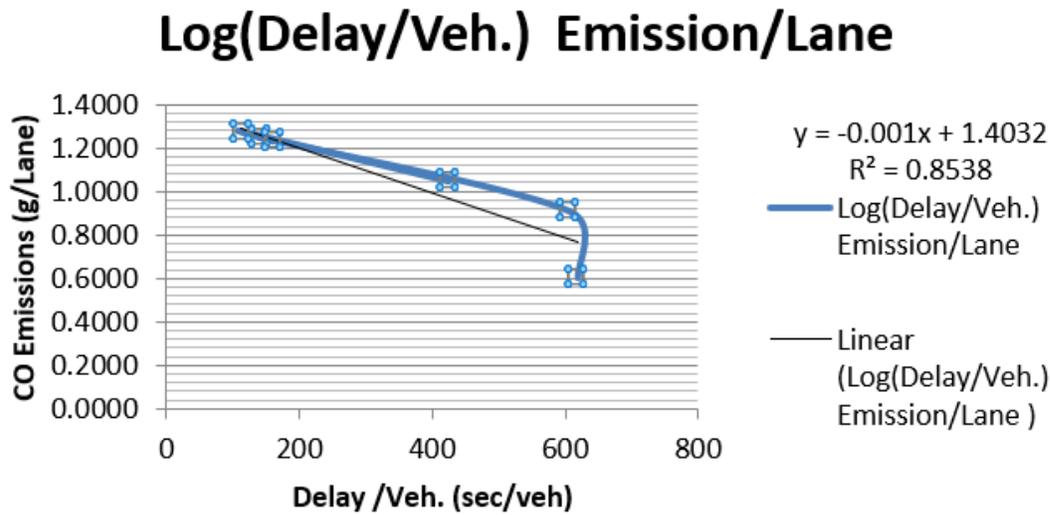


Figure 4.14: The Mathematical Model of CO Emissions as Function of Delay per Vehicle

CO gas emissions = -0.0001 (delay per vehicle)+ 1.4032.....Equation 5

Table 4.23: Input Data of NO Emissions (delay per vehicle)

Intersection	Delay/Veh. (sec/veh)	NO _x Emissions (g)	Log(Delay/Veh.) Emission/Lane
ALASSAF	618	47.25	0.5296783
ELBA HOUSE	797.4	905.3333333	0.5442983
FIRAS SQUARE	747.1	890.875	0.7223629
JBAHA	402.9	1232.294118	0.7519455
PRINCESS ALIAH	79.1	658.3	0.7760473
WIDI SAQRA	744.6	763.4	0.617627

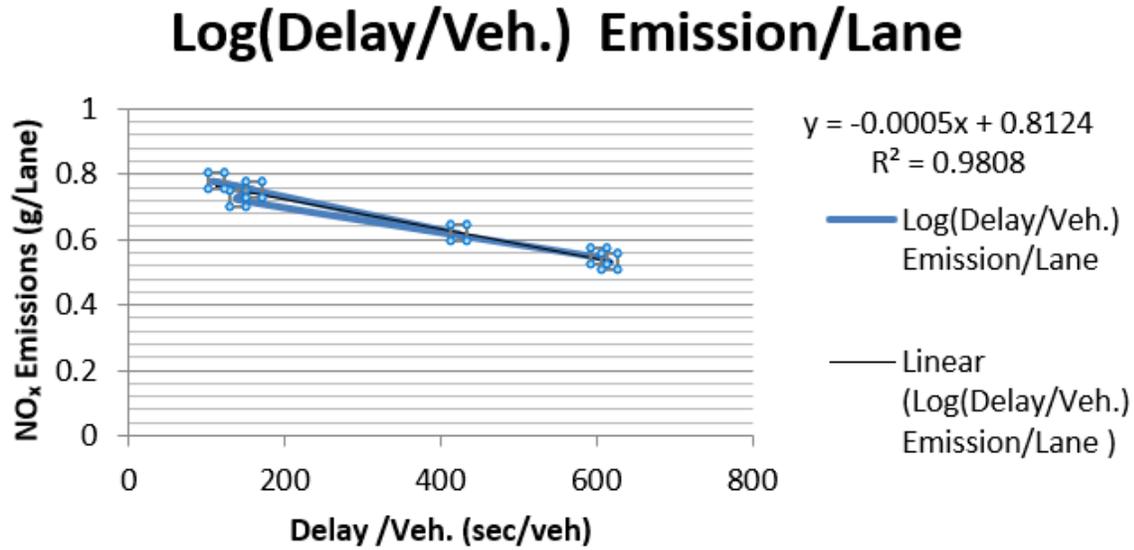


Figure 4.15: The Mathematical Model of NO_x Emissions as Function of Delay per Vehicle

NO_x gas emissions = -0.0005(delay per vehicle)+ 0.8124.....Equation 6

Gas emissions are also plotted against log (intersection delay) to the base of emission per lane, for the Hydrocarbon HC, Carbon monoxide CO, and Nitrogen Oxid NO, to develop mathematical models of Log(intersection delay) and emission per lane. The model is developed using the six selected intersections Figures 4.16, 4.17, and 4.18 show the model that fits the data by 81.37%, 15.56%, and 79.77%, of HC, CO, and NO, respectively.

Table 4.24: Input Data of HC emissions (intersection delay)

Intersection	Int. Delay (sec.)	HC Emissions (g/Lane)	Log(Int. Delay) Emission/Lane
ALASSAF	240.4	12.08333333	0.45466
ELBA HOUSE	843.2	31.16666667	0.4018746
FIRAS SQUARE	449.5	21.8125	0.4566265
JBAHA	356.4	21.76470588	0.4634206
PRINCESS ALIAH	231.2	14.4	0.4961217
WIDI SAQRA	815.5	18.1	0.4270856

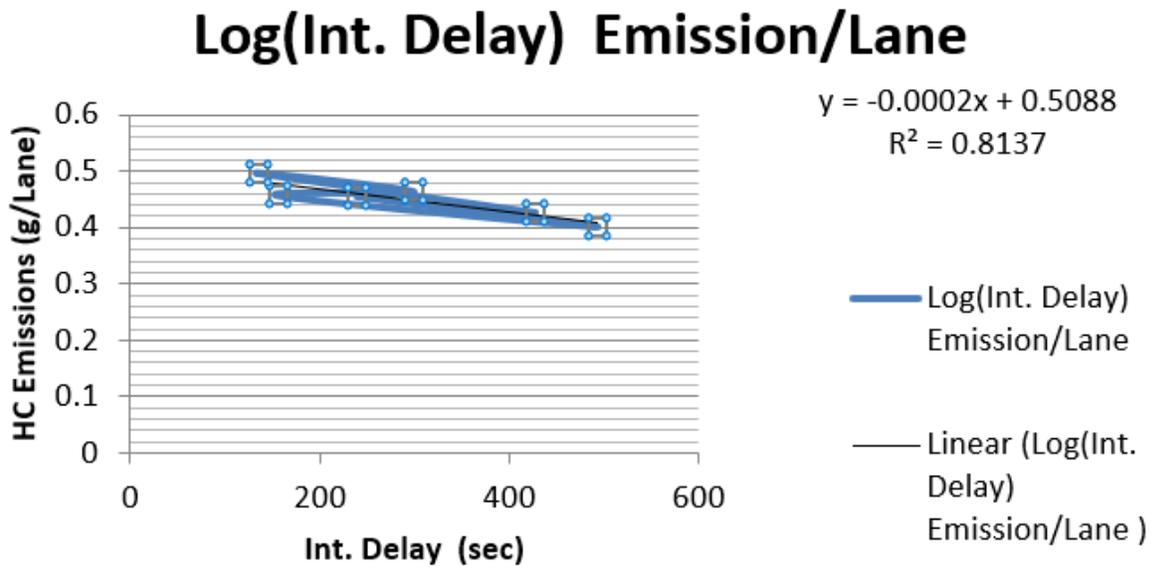


Figure 4.16: The Mathematical Model of HC Emissions as Function of Intersection Delay

HC gas emissions = -0.0002 (intersection delay)+ 0.5088.....Equation 7

Table 4.25: Input Data of CO emissions (intersection delay)

Intersection	Int. Delay (sec.)	CO Emissions (g)	Log(Int. Delay) Emission/Lane
ALASSAF	240.4	47.25	0.7035
ELBA HOUSE	843.2	905.3333333	0.9367
FIRAS SQUARE	449.5	890.875	1.2193
JBAHA	356.4	1232.294118	1.0945
PRINCESS ALIAH	231.2	658.3	1.2282
WIDI SAQRA	815.5	763.4	1.0425

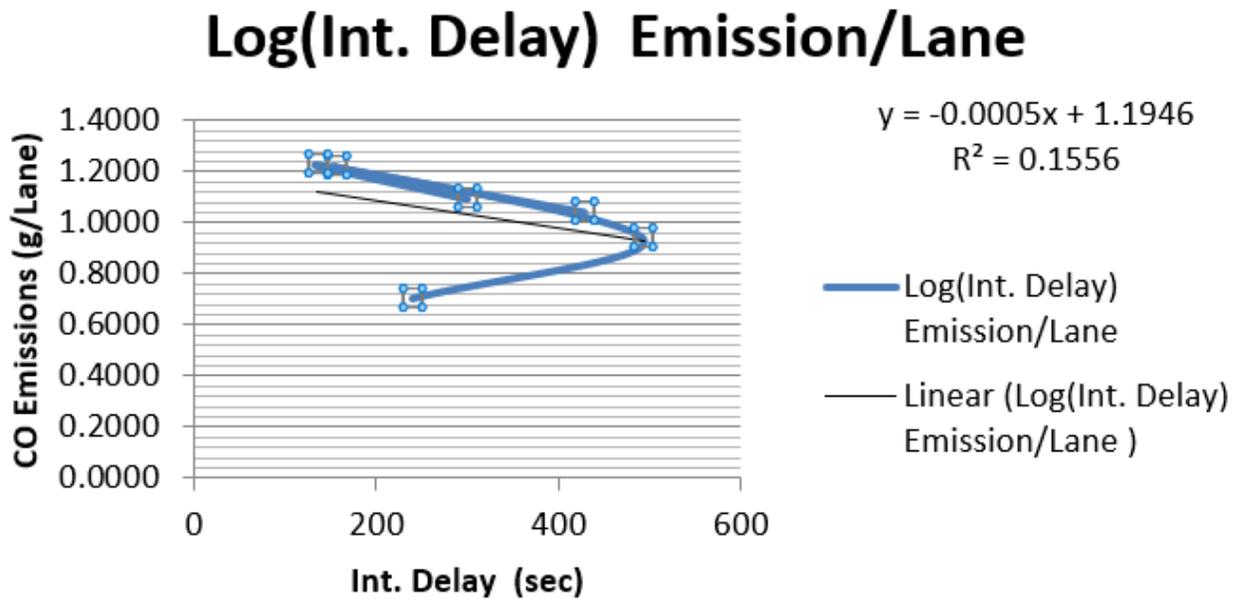


Figure 4.17: The Mathematical Model of CO Emissions as Function of Intersection Delay

CO gas emissions = -0.0005 (intersection delay)+ 1.1946.....Equation 8

Table 4.26: Input Data of NO emissions (intersection delay)

Intersection	Int. Delay (sec.)	NO _x Emissions (g)	Log(Int. Delay) Emission/Lane
ALASSAF	240.4	47.25	0.6210902
ELBA HOUSE	843.2	905.3333333	0.5622692
FIRAS SQUARE	449.5	890.875	0.7070069
JBAHA	356.4	1232.294118	0.6698957
PRINCESS ALIAH	231.2	658.3	0.7479044
WIDI SAQRA	815.5	763.4	0.6166698

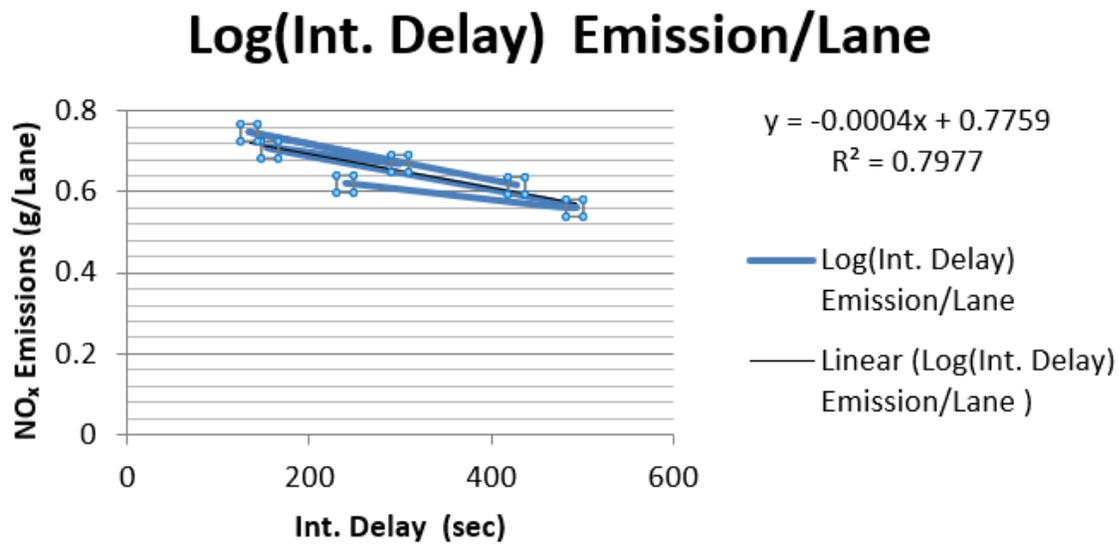


Figure 4.18: The Mathematical Model of NO_x Emissions as Function of Intersection Delay

NO_x gas emissions = -0.0004(intersection delay)+ 0.7759.....Equation 9

It worth mentioning that the capacity is implicitly considered since the dependent variable, gas emission is substituted by gas emission per the number of lanes.

Site Selection: Six highly congested signalized intersections in Amman were selected for analysis.

a. Data Collection: Traffic volume counts, signal timings, and geometric design data were collected for both the main intersections and their surrounding arterial roads.

Simulation and Validation: Microscopic simulation models of the current traffic conditions were developed using SYNCHRO 8 software.

a. Model Validation: The simulated throughput volumes were validated against observed field data using VISSIM software, with all percent differences falling within an acceptable 15% margin of error.

SECOND REQUIREMENT: EMISSIONS MODEL DEVELOPMENT PROCESS

The process for creating the emissions models involved several critical steps.

Firstly: Variable Selection and Preliminary Analysis

The primary measures of effectiveness (MOEs) identified for model development were 'Delay per Vehicle' and 'Intersection Control Delay'.

a. Initial integrated regression models were developed using the SPSS software platform to explore the combined effect of both delay variables on emissions.

Simple Regression Models: Seven different model types (Linear, Logarithmic, Inverse, etc.) were tested for each gas and each independent variable separately.

a. Due to the small sample size, the R-squared value was prioritized over the Adjusted R-squared for model evaluation.

Secondly: Final Model Calibration

Given the limitations of the preliminary models, logarithmic models were developed using Microsoft Excel to better fit the data.

a. The general form of the model was: $\text{Log}(\text{Delay}) = f(\text{Emission}/\text{Lane})$. This approach yielded a significantly better fit to the observed data.

THE SECOND TOPIC : ANALYSIS OF RESULTS AND DISCUSSION

This topic presents the findings from the statistical analysis, discusses the performance of the developed models, and explores their practical implications.

FIRST REQUIREMENT: STATISTICAL MODEL PERFORMANCE

The final mathematical models demonstrated a high level of accuracy in predicting emissions.

Firstly: Model Form and Accuracy

The relationship between 'delay per vehicle' and emissions was found to be a strong inverse linear correlation once transformed logarithmically.

a. The coefficient of determination (R^2) values, as shown in Table 1, confirm the high explanatory power of the models, especially for NO_x .

The resulting mathematical equations for predicting emissions based on delay per vehicle are as follows:

- a. HC: $\text{Log}(\text{Delay}/\text{Veh.}) = -0.0002(\text{HC g/Lane}) + 0.5326$ ($R^2 = 0.8926$)
- b. CO: $\text{Log}(\text{Delay}/\text{Veh.}) = -0.0001(\text{CO g/Lane}) + 1.4032$ ($R^2 = 0.8749$)
- c. NO_x : $\text{Log}(\text{Delay}/\text{Veh.}) = -0.0005(\text{NO}_x \text{ g/Lane}) + 0.8124$ ($R^2 = 0.9804$)

SECOND REQUIREMENT: INTERPRETATION AND PRACTICAL IMPLICATIONS

The findings have significant meaning for the field of transportation and environmental planning.

Firstly: Interpretation of the Inverse Relationship

The inverse relationship indicates that as delay decreases, emissions per lane increase. This seems counterintuitive but is explained by the resulting increase in vehicle travel distance when traffic flow is improved via alternative intersections.

a. Shorter idling times (less delay) are offset by longer driving distances, leading to a net increase in fuel consumption and emissions.

This highlights a critical trade-off that traffic engineers must consider: operational improvement versus environmental impact.

Secondly: Application of the Models

The models provide a simple tool for planners to estimate the environmental footprint of a traffic project by using a single, easily obtained metric—average delay.

a. They are particularly useful for conducting rapid preliminary assessments before committing to more complex and data-intensive simulation studies.

Conclusion:

The study successfully achieved its objective by developing robust mathematical models that link traffic delay to vehicle emissions at signalized intersections. The key conclusion is that a strong inverse linear relationship exists, allowing for the accurate prediction of HC, CO, and NO_x emissions using delay per vehicle as a primary input. These models serve as a practical

tool for transportation engineers and environmental planners to quickly assess the emissions impact of traffic management schemes. It is recommended that future research applies and validates these models in different urban contexts and incorporates vehicle fleet composition data to enhance their generalizability.

Tables:

Table 1: Coefficient of Determination (R^2) for Emission Models Based on Delay per Vehicle

Emission Type	Coefficient of Determination (R^2)	Model Strength
HC	89.26%	Strong
CO	87.49%	Strong
NO _x	98.04%	Very Strong

The source of the statistics is the author's calculations based on simulation output data from SYNCHRO 8 and statistical analysis in Microsoft Excel.

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