Environmental Analysis of Control Strategies for Connected Vehicles

Author: Luana Donato

Supervisors: Dr. Yu Zhang
Dr. Monica Menendez

MSc Thesis **January 2014**

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

USF
UNIVERSITY OF SOUTH FLORIDA

Table of Contents

Abstract

The adoption of *Vehicle2Infrastructure* technology will not only have impact on the traffic flow, but also on the emissions due to that.
This paper proposes an environmental analysis at an intersection governed by *V2I* technology. The car's behavior is described from an algorithm, which should either minimize the total delay or the number of stops during the simulation. These two cases are compared to a standard fixed traffic light.

Simulations were run for different total demand, the results were discussed and compared.

It can be noticed that besides the almost linear correlation between emissions and total demand close to the saturation flow, the algorithm for minimizing delay also pollutes the less, followed by the algorithm for minimizing the number of stops. For extremely undersaturated systems, the standard discharge strategy still seems to represent the best solution.

1 Introduction

« Any man who can drive safely while kissing a pretty girl
is simply not giving the kiss the attention it deserves »
– Albert Einstein –

It is estimated that the world's population is about to double over the next 50 years, with consequences on society, logistics and environment. In the future bigger, higher, louder, overpopulated and highly polluted urban areas, besides the reliability and sustainability of the infrastructures, engineers will have to face new challenges in terms of traffic planning.

New control strategies will further optimize the functions of costs and emissions, in order to provide reasonable solutions to the issue. Hereafter the focus is on the *Vehicle2Infrastructure* technology. The starting assumption is a perfect information transfer between infrastructures and cars equipped with automatic cruise control system. The vehicles transmit their position, speed and acceleration to the infrastructure, which is able to compute a real time demand curve and to communicate to each vehicle the course of the traffic in terms of stop or go.

Recent studies pertaining to this topic confirmed significant "improvements in the efficiency of traffic operations at intersections in terms of minimization of total delay and number of stops" [1] by comparison with a standard fixed-time traffic light.

The goal of this paper is to deepen the knowledge of *V2I* technology from an environmental perspective. The system which has been considered consists of two intersecting one-way streets with no turning. The traffic flow is given with respect to three different criteria:

- Minimum delay optimized *V2I* communication,
- Minimum stops optimized *V2I* communication,
- Traditional fixed-time traffic light.

For these cases, the emissions during a limited simulation time are calculated and compared.

The content covers a literature review of the above mentioned traffic strategies and environmental topics, followed by a description of the developed methodology and the simulation and its results for the sensitivity analysis. A discussion of the results and the conclusions will complete the work.

2 Literature review

The literature consulted is *Using Connected Vehicle Technology to Improve the Efficiency of Intersections* [1]. A brief introduction of the environmental issue is based on researches published on the websites U.S. Department of Transportation [2] and the U.S. Environmental protection Agency [3].

The first paper "proposes algorithms to optimize traffic operations in terms of total delay and number of stops at an intersection consisting of two one-way-streets […] and compares them to more traditional intersection control strategies" [1]. The treated concepts are summarized in following:

- For each car entering the simulation's radius, the virtual arrival time V_c to the intersection is randomly generated assuming an exponential headway distribution. The virtual arrival time V_c is defined as the "time when cars would have arrived to the intersection if there were no queuing and assuming a free flow speed" [1].
  I.e. in the case of the blue car arriving at the end of the queue, its virtual arrival time V_c is generated as if the same car would have stopped at the intersection line (first position in the platoon), travelling at free flow speed until that point (no deceleration time).

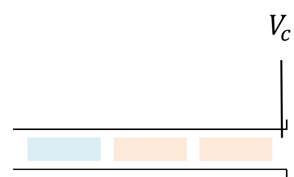


Figure 1: Vehicles approaching from one direction

- The departure is computed "using the information obtained about the cars' arrival times" [1] and the following formula:

$$D_C = \max\left(V_c; D_{c'} + \frac{1}{S_m} + P_{c,k}\right)$$

  where $D_{c'}$ departure of the previous car, S_m saturation flow, $P_{c,k}$ penalty time – which corresponds to the time to cross the intersection. The figures should help this visualization.

  The decision about the next discharge priority takes in consideration all possible combinations of departures including approach 1 and 2.

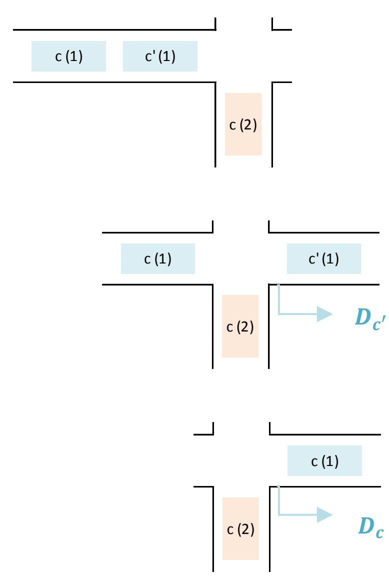


Figure 2: Scheme for the priority decision

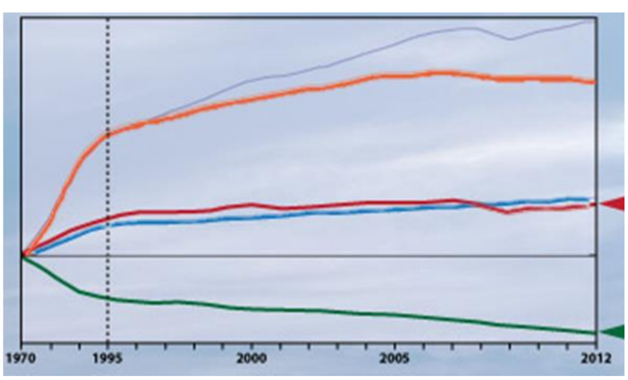
For expamle, if $V_c(c(2)) < D_{c'(1)} + \frac{1}{S_m} + P_{c(1)}$ then the car $c(1)$ will have the priority for the next departure, and its departure time will be $D_{c(1)} = D_{c'(1)} + \frac{1}{S_m} + P_{c(1)}$. But if $V_c(c(2)) > D_{c'(1)} + \frac{1}{S_m} + P_{c(1)}$ the car $c(2)$ will have priority for the next departure, and its departure time will be $D_{c(2)} = D_{c'(1)} + \frac{1}{S_m} + P_{c(1)}$.

- The algorithms find the best solution for the combinations, which also fulfill either the condition of minimizing the total delay or minimizing the number of stops.

The results show:

- Benefits of discharging in platoons;
- Increasing average delay and number of stops with higher total demand, in particular for total demand greater than saturation flow, the increase of average delay and number of stops is exponential;
- No apparent relationship between average delay and demand ratio between the two directions;
- The average platoon size converges for balanced demand ratio between the two directions and increases with higher total demand;
- The algorithm to minimize the total delay often minimizes the total number of stops;
- Both algorithms lead to an improvement in the traffic performances at the intersection if compared to a standard fixed traffic light.

The second part of the literature review focuses on the effects of vehicle emissions on the environment. Sources for these informations are the U.S. Department of Transportation [2] and the U.S. Environmental Protection Agency [3].



+ 165% Vehicles Miles Traveled

+ 53% Population

+ 47% Energy Consumption

- 72% Emissions of commons pollutants

Figure 3: Evolution for emissions of commons pollutants [www.epa.gov]

In order to protect the environment from exponential escalation of the production and from urban development, the U.S. Congress finalized in the early Nineties the *Clean Air Act*. It was the first documentation which stated the "Air Quality standards for pollutants considered harmful to public health and the environment" [3].

Engineers ought to stick to these norms in their planning, construction and operative phases. In particular transportation engineers are called to improve the traffic strategies, since a high percentage of the pollution is due to traffic emissions.

The typical combustion process of the engine goes [www.nutramed.com]:

$$Fuel + Air \rightarrow Hydrocarbons + Nitrogen\ Oxides + Carbon\ Dioxide + Carbon\ Monoxide + Water\ .$$

These pollutants will be considered the subjects of study in this paper. The following table provides their short description:

Table 1: Description of the pollutants [3]

C_nH_m	"Hydrocarbon emissions are fragments of fuel molecules only partially burned. These react in the presence of Nitrogen Oxides and sunlight to form Ozone (O_3), a major component of smog. Ozone irritates the eyes, nose, throat and damages the lungs. Some non-reacted Hydrocarbons are also toxic." [www.nutramed.com] Hydrocarbons will not be a concern of this thesis.
CO_2	Carbon dioxide results mostly from burning processes, and gets converted through the photosynthesis into carbohydrates (as sugars), which are crucial for plants' nourishment. But there is too much CO_2 in the atmosphere to be totally converted, in part impacted by the fact that the biological carbon cycle is interrupted during the fall and winter. This leads to high concentrations of CO_2, the most important Greenhouse Gas. As such it contributes to global warming. Its impact is measured by the Global Warming Potential (GWP), which gives information about "the total energy that gets absorbed over a particular period of time (usually 100 years). The larger the GWP, the more warming the gas causes. CO_2 has a GWP of 1. It remains in the atmosphere for a very long time." As of November 2011, carbon dioxide in the Earth's atmosphere is at a concentration of approximately 390 ppm by volume. [4]
CO	"Carbon Monoxide can cause harmful health effects by reducing Oxygen delivery to the body organs."

NO_x	Nitrogen Oxides, especially Nitrogen Dioxde (NO_2), forms quickly from vehicles' emissions, contributing to the formation of Ozone and fine particle pollution. It damages human health mostly causing respiratory problems.
PM	"Particulate Matter is a complex mixture of extremely small particles and liquid droplets, made up of a number of components with a diameter of max. 10 µm. Once inhaled, these particles can affect the heart and lungs." The composition of PM is influenced by the weather conditions. One distinguishes *Inhalable coarse particles*, with a diameter between 2.5÷10 µm, from *Fine Particles*, with a diameter smaller than 2.5 µm (like the ones of smoke).
SO_2	Sulfur Dioxide is a highly reactive gas that causes a number of adverse effects on the respiratory system.

The increment of the energy consumption is also a problem. Indeed, even if the energy is not directly linked to human or environmental damages, its production contributes to each one of the above mentioned issues, including the global warming.

Nevertheless energy is essential, since nowadays it represents the power source of households, industry, technology etc., basically for the civilization.

3 Methodology

3.1 Extrapolation of the speed profiles

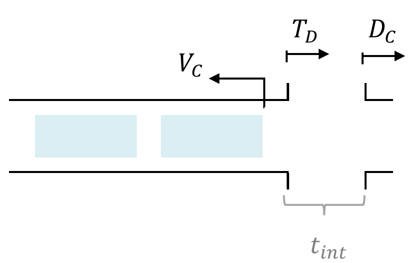
The emissions' simulation is based on the results of the algorithms of [1]. The Matlab-output of the algorithm shows for each car its approach, virtual arrival time, departure time, cumulative delay, car number, number of switches of approach 1, number of switches of approach 2, and cumulative number of stops. The above mentioned outputs were grouped in discharging platoons in order to make the understanding of the results better.

For the environmental analysis, a second-by-second speed profile of each car is required.

<u>*Procedure*</u>

Since the only information about the time for each car are the virtual arrival and the departure, the goal is to extrapolate the timeline of priority switches for each simulation. With the given acceleration rate and free flow speed and taking into consideration acceleration and deceleration time, the timeline will enable to track the trajectory of each car.

- Define T_D as the time at which the vehicle passes the intersection line. Notice that T_D corresponds to the departure time minus the time needed to cross the intersection, or as in the literature previously mentioned *Penalty time*.



$$T_D = D_c - t_{int}$$

Figure 4: Schematic description for T_D and t_{int}

- The following assumptions were taken:
    - T_D of the first car of the platoon corresponds to the beginning of the green time for its cycle, and
    - T_D of the last car of the platoon corresponds to the end of the green time for its cycle.
    - The duration of the cycles is then calculated as $T_{D(\text{last car platoon})} - T_{D(\text{first car platoon})}$.

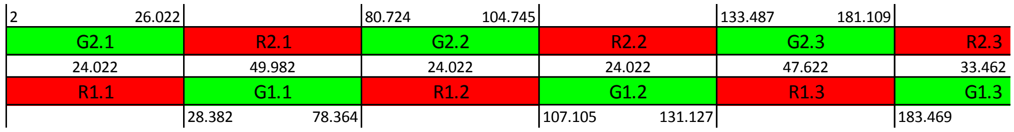


Figure 5: Example of timeline with green and red cycles for both approaches

- Thanks to the platoon grouping and to the number of stops per car, the position of the car at each time step during its whole stay in the system can be found. The next example should help the understanding.

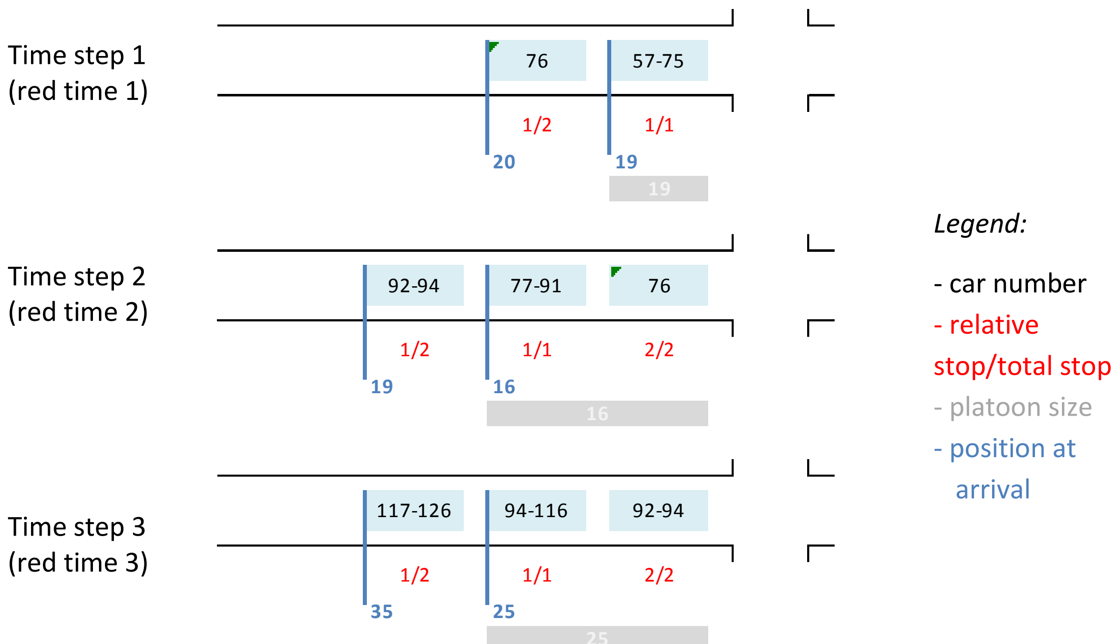


Figure 6: Schematic description of platoon discharge per time step

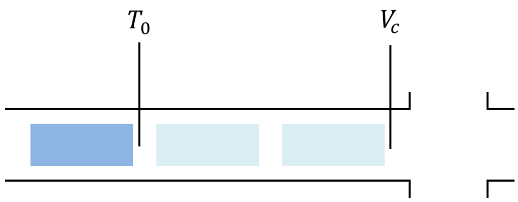
Meaning: The first platoon consists of 19 cars (#57-75), which all stop once. They arrive at the intersection during time step 1, and their initial position corresponds to the platoon position. They all leave the intersection at the next green time.

The second platoon consists of 16 cars (#76-91). They all leave the intersection after the second time step. Since car #76 stops twice, this means that it already arrived during the previous red time, and queued behind the first platoon. Its position at the end of the queue at its arrival is 20. After the first green time, the first platoon will discharge, and car #76 will be the first at the intersection line at time step 2. Cars #77-91 also belong to the same platoon, but they arrive just at time step 2, since their total number of stops is 1.

The same logic is valid for the next platoon (#92-116). Cars #92-94 arrive during time step 2, where they stop for the first time behind the previous ones. Their position during their first red light (time step 2) is 17-19. In the next time they are the first at the intersection line, and the other cars of the discharging platoon (#95-116) follow them. They will all leave the intersection after this third red light.

Etc.

- The above described notion of platoon positions also allows the finding of the arrival time T_0 when the car actually stops for the first time at the end of the queue, instead of considering the given virtual arrival V_c (=: "time when cars would have arrived to the intersection if there were no queuing and assuming a free flow speed until then").

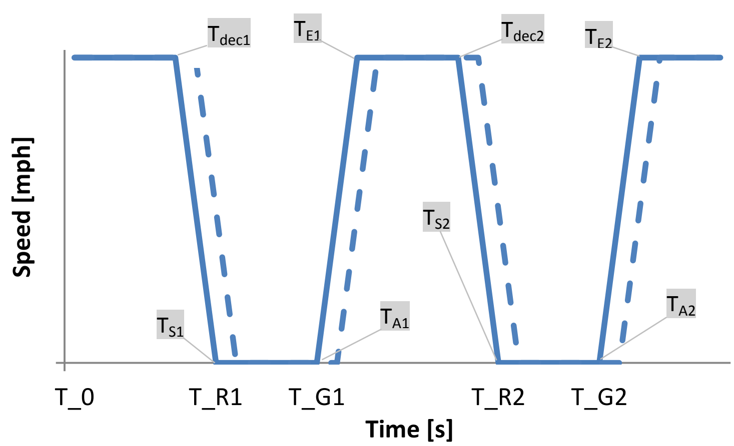


$$T_0 = V_c - \frac{O_{c,0} \cdot L}{v_{FF}}$$

Figure 7: Schematic description of arrival time T_0

where L car + security length (assumed 5 m), $O_{c,0}$ platoon position at the end of the queue, v_{FF} free flow speed.

- The speed profile of a car can then be found using the constant acceleration rate and the free flow speed.



Legend:

$T_{dec,i}$ start deceleration
$T_{R,i}$ red light
$T_{S,i}$ car stationary
$T_{G,i}$ green light
$T_{A,i}$ start acceleration
$T_{E,I}$ FF speed

i: index for number of stop

Figure 8: Speed profile and definition of time references

The continuous line refers to the first car of the platoon, and the dashed line refers to the next one.

In the case of the first car of the platoon $T_{S,i} = T_{R,i}$ and $T_{A,i} = T_{G,i}$, for the followings

$T_{S,i} = T_{R,i} + \frac{O_{c,i} \cdot L}{v_{FF}}$ and $T_{A,i} = T_{G,i} + \frac{O_{c,i} \cdot L}{v_{FF}}$.

$T_{dec,i}$ is obtained subtracting from $T_{S,i}$ the ratio between free flow speed and acceleration rate, which in this case corresponds to 7 seconds.

Between $T_{S,i}$ and $T_{A,i}$ the car is stationary, with a speed equal to 0, and between $T_{E,i}$ and $T_{dec,i}$ the car travels at free flow speed.

3.2 Calculation of the emissions with MOVES

MOVES is a software provided by the U.S. Environmental Protection Agency (EPA) which calculates the motor vehicle emissions for the given simulation's inputs.

In the modeling process, the user specifies vehicle types, time periods, geographical areas, pollutants, vehicle operating characteristics, and road types. These objects make up the 'Run Specification'. The program combines these inputs with its database's record, and then it computes the emissions of the system thanks to a built-in algorithm.

The following table should explain the functions of the Run Specification, in particular the ones chosen for this study case:

Table 2: Description of MOVES' setting

Scale: Project	Project Domain is the finest level of modeling in MOVES. For its use the user has to completely define the individual project, i.e. roadway links. The program utilizes its intrinsic data like fuel library, emission rates and other factors to correctly calculate the emission inventory. [6]
Calculation type: Inventory	Calculation of the quantity of emissions and/or energy used referred to the specified region and time span.

Time spans	The assumed time span is November 2012, Weekday, 10-11AM. Notice that the choice of a weekday, from 10-11AM gives the perception of a non-rush hour time period. In this way it is assured that the calculation of the emissions won't get any boundary influence from that. As well this choice allows to calculate accurately the emissions for a more congested case, where one can associate a greater traffic volume with the requested link. Also here the calculation won't get any boundary influence due to rush-hour effects. The selection of the year should also recall the vehicle type and the fuel composition in the database.
Geographic bounds	The Geographic bound refers to Tampa, FL (US), which belongs to Hillsborough County. In conjunction with the time span, the Geographic bound estimates climate parameters as temperature and relative humidity. These parameters are very important for the impact and the diffusion of the pollutants on the environment. One sample simulation was run with climate parameters according to Zurich (CH).
Vehicles equipment	The only on-road vehicles considered for this simulation are Gasoline – Passenger Cars. The software delivers the fuel formulation, the age distribution and the consumption rates per traffic operation (accelerating, cruising, decelerating, idling).
Road type	For the modelling of the two on-way streets intersecting with no turning possibility, the only road type used is Urban Unrestricted Access.
Pollutants and processors	MOVES is able to calculate a wide range of pollutants' emissions. According to the previous literature review, the ones chosen for this analysis are CO_2, CO, NO_x, NO, PM10, PM2.5 and SO_2. Furthermore the Total Energy consumption has been calculated. "With the processes MOVES describes the mechanisms by which emissions are created. Engine operation creates Running Emissions Exhaust, Start Emissions Exhaust, and Extended Idle Emissions Exhaust." [6]

Figure 9: Summary of MOVES' RunSpec

The definition of 'Links' is straightforward: according to the previous inputs "link is a section of any road where a vehicle is moving" [6]. The user assigns a demand volume and a speed trend to these vehicles.

The algorithm that the program uses to calculate the emissions is supported by the Vehicles Operating Mode ("Running Emissions Exhaust, Start Emissions Exhaust and Extended Idle Emissions Exhaust") and divides them into categories based on Vehicle Specific Power (VSP). This is a good approach to correlate emissions with vehicle speed.

$$VSP = v \cdot (a \cdot (1 + \sum) + g \cdot \phi + g \cdot C_R) + 2 \cdot \rho \cdot C_D \cdot A \cdot v^3 / m$$

where v vehicle speed [m/s], a vehicle acceleration [m/s^2], $\sum$ mass factor accounting for the rotational masses, g acceleration due to gravity [m/s^2], ϕ road grade, C_R rolling resistance coefficient [m/s^2], C_D aerodynamic drag coefficient [1/m], ρ air density [kg/m^3], A frontal area [m^2], m vehicle mass [ton].

Daganzo and Newell [4] explain the microscopic correlation of the energy consumption per unit time for transit vehicles, on which MOVES bases its algorithm.

$$P = (k_1 + k_2 v + k_3 v^2) \cdot v \cdot w + v \cdot (grade) \cdot w + v \cdot \frac{a}{g} \cdot w$$

where k_i constants, v vehicle speed [m/s], a acceleration [m/s^2], w weight of the vehicle [ton]. The first term is due to the rolling and air friction, the second term to the grade and the last term to the acceleration of the vehicle.

For transit vehicles with stop at stations, the energy consumed on a round trip is

$$E = f(v) \cdot L \cdot w + k_4 \cdot N_s$$

where L route length [m] and N_s number of stops. With a proper selection of $f(v)$ and k_4 the effects of acceleration and deceleration can be captured.

4 Simulation

4.1 General considerations

The three operations to calculate the emissions of the system are:

- Matlab code to obtain the virtual arrival and the departure times, as well as the car sequence and stop number;
- Extrapolation of speed profiles with Matlab and Excel;
- Calculation of the emissions with MOVES.

For the first Matlab code a simulation of 15 minutes is considered. The total demand (total input flow) varies between 1000 and 2000 vehicles per hour. The only case considered is the one of a perfectly balanced demand (demand ratio equal 1). It has been prooved, that "for unbalaned unbalanced demands, a larger portion of the delay is due to stochastic fluctuations in the arrival process." [1] Further inputs are:

Input	
Simulation time	15 min
Saturation flow	1'800 veh/h
Free flow speed	50 km/h
Acceleration rate	2 m/s²
Length of conflict zone	5 m

Figure 10: Summary of Matlab simulation

The code was ran for the three different discharge strategies, minimizing the total delay (MD), minimizing the total number of stops (MS) and fixed-time traffic signal (FT). "The fixed-time traffic signal is assumed to have a fixed cycle length of 60 seconds and the green ratios are determined according to splits of the demand with a minimum green time of 5 seconds." [1]

The second step is to extrapolate the speed profiles with the procedure described in Chap. 3.1.

The simulation with MOVES was firstly done using the accurate second by second speed profiles of each vehicle. The vehicles were classified with respect to their number of stops. For each different number of stops a different simulation was run, for which the link volume corresponded to the total amount of cars belonging to that group.

In a next step, the emissions related to average speed intervals were researched. The results were grouped in 5 mph speed intervals and the link volume corresponded to their number was displayed.

Comparing the two simulations should explain the impact of the method of grouping on the calculation of the average speed and therefore on the calculation of the emissions.

In order to give the system a deterministic background, a sample case with random generated acceleration rates for the following behavior within a platoon was studied. The range of the acceleration rate is 1.5-2.5 m/s^2. In an abstract way this randomness represents the human behavior of drivers. Comparing these results with the previous ones will give an idea about the effects on the control strategies.

As above mentioned, the results for the city of Zurich (CH) will also be calculated for a sample case. The impact of temperature and relative humidity on the emissions and their diffusion should be verified.

NB: Despite the randomness of the arrival curves, the simulations are run just once.

4.2 Sensitivity analysis

A sensitivity analysis for a total demand equal 1000-1200-1400-1600-2000 veh/h for each discharge strategy was run.

The following tables show the average results of the first Matlab program for platoon size, cycle length, delay, stop time, speed and the number of cars grouped after their stops.

Observations:

- Average platoon size increases with higher total demand. For FT it is almost constant.
- Cycle gets longer when there are more cars in the system. For FT of course they are constant.
- The average delay increases with the link volume.
- The number of cars per stop decreases with growing total demand. Within the same simulation 0 stops and the highest number of stops register the fewer number of cars.
- The average speed per stop per car increases with the total demand.
- The number of cars per speed interval increases with the total demand.

The expected results with MOVES are:

- High emissions for fixed-time traffic light, since it generally shows a greater total delay and total number of stops for a total demand greater than 1400 veh/h;
- Increasing emissions with the total demand, more significantly close to the saturation flow.

Table 3: Averaged results

	Avg. platoon size	Avg. cycle length	Avg. delay
MD1000	5.90	17.26	13.10
MS1000	9.33	11.98	9.80
FT1000	8.06	21.97	15.43
MD1200	3.65	8.06	5.70
MS1200	5.51	14.55	13.87
FT1200	10	25.12	27.58
MD1400	14.87	35.58	24.44
MS1400	9	23.75	21.26
FT1400	10.61	26.32	71.70
MD1600	14.24	35.29	45.91
MS1600	13.52	32.30	53.32
FT1600	10.53	25.22	114.23
MD1800	17.68	42.16	121.25
MS1800	13.81	33.16	151.54
FT1800	10.71	26.46	190.15
MD2000	15.38	36.73	157.27
MS2000	14.91	35.60	207.78
FT2000	10.64	24.42	211.98

Table 4: Number of cars per number of stops

 # CARS

stops	0	1	2	3	4	5	6	7	8
MD1000	155	87							
MS1000	140	102							
FT1000	116	134							
MD1200	210	82							
MS1200	164	127	1						
FT1200	103	179	18						
MD1400	164	178							
MS1400	166	176							
FT1400	30	148	160	12					
MD1600	68	164	10						
MS1600	90	260	42						
FT1600	27	116	103	100	42	12			
MD1800	46	160	181	55					
MS1800	37	112	120	119	104				
FT1800	26	64	66	79	63	72	62	18	
MD2000	26	161	93	137	74	1			
MS2000	19	72	108	115	128	50			
FT2000	20	65	78	63	93	57	64	59	1

Table 5: Average speed per number of stops

AVG. SPEED

stops	0	1	2	3	4	5	6	7	8
MD1000	30.75	4.25							
MS1000	30.70	3.15							
FT1000	30.84	5.35							
MD1200	30.61	4.08							
MS1200	30.22	4.93	3.52						
FT1200	30.40	7.34	6.99						
MD1400	30.10	7.34							
MS1400	30.25	5.99							
FT1400	30.24	9.80	8.34	7.57					
MD1600	30.17	9.60	7.96						
MS1600	30.80	10.07	9.23						
FT1600	30.19	9.15	8.72	8.97	8.92	8.59			
MD1800	30.52	10.41	11.43	13.74					
MS1800	29.71	10.51	9.78	13.01	9.62				
FT1800	30.36	8.93	9.37	9.10	8.80	8.97	8.55	8.64	
MD2000	30.33	11.06	11.40	13.21	10.52	10.34			
MS2000	29.23	14.48	9.83	13.21	10.33	10.47			
FT2000	30.68	9.00	8.77	8.97	9.20	8.69	8.58	9.07	10.24

Table 6: Number of cars per speed interval

CARS PER SPEED INTERVAL

speed	0-5	5-10	10-15	15-20	20-25	25-30	30-FF
MD1000	51	18	7	0	1	14	144
MS1000	81	16	5	0	0	14	126
FT1000	78	29	23	4	1	7	108
MD1200	58	22	10	4	5	15	170
MS1200	78	30	15	5	4	33	127
FT1200	68	73	45	11	5	9	89
MD1400	76	46	35	21	11	19	134
MS1400	85	55	27	9	9	18	139
FT1400	30	188	85	13	3	5	26
MD1600	28	53	77	16	2	12	54
MS1600	55	103	101	38	5	9	81
FT1600	32	209	125	7	1	4	22
MD1800	33	100	184	69	13	2	41
MS1800	26	143	164	66	8	8	27
FT1800	16	266	137	4	1	4	21
MD2000	22	170	162	100	13	2	23
MS2000	27	179	229	27	19	8	12
FT2000	14	296	159	11	0	2	18

5 Results

In this chapter the results of the sensitivity analysis are shown and discussed. First the results for emissions will be looked at. Then the MD and the MS will be compared to the standard FT strategy and their percentage difference plotted in bars. A correlation of the results for emission as a function of the total demand will also be suggested.

N.B.: In order to better interpret the trends some insensibly out of range results have been excluded from the outputs. These were mostly the results for the emissions of the last stop, which were approximately zero. The reason of it can be attributed to a mistake in the algorithm programming or solution.

5.1 Emissions for MD, MS, FT

The following charts show the emissions for the designated systems. For total demand 1800 veh/h – corresponding to saturation flow – and for total demand 2000 veh/h and 1600 veh/h – respectively greater and smaller then saturation flow – the results are displayed for the three strategies. The values correspond to the total emission for a 1h simulation time averaged over the total number of cars per number of stops.

The choice of the characterization criteria for the results comes from the following observation: By plotting the average emissions grouped with respect to the number of stops one would obtain the following results, with an average emission per car and hour of 943.25 g for Total Demand 2000 veh/h (Figure 11(a)). Looking at the total emission per average speed range (which also include contemplations about the stops of the car), the results would look like Figure 11(b), with a total average emission of 1500.60 g.

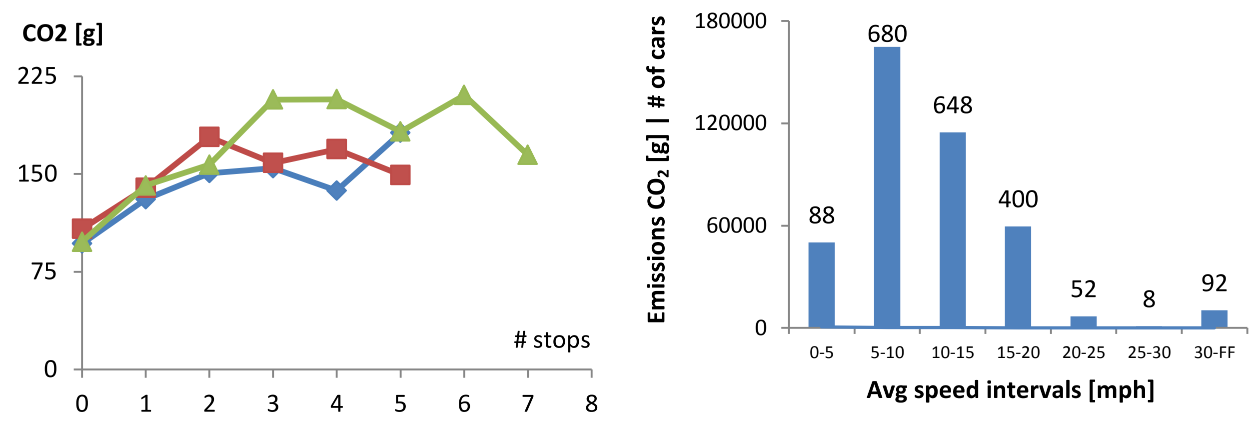


Figure 11(a,b): Emissions for total demand 1'800 veh/h, characterization after number of stops (left) and average speed (right)

Comparing Figure 11(b) with Table 5, one can suppose that the cars with a high average speed didn't have to stop at all, and that the average speed increases with the total demand.

The interpretation of the three curves of figure 11(a) shouldn't confuse the reader: the comparison of the strategies make sense just if considered punctual. Indeed, it is correct to state for example that for 0 stops the average emissions for MD are worse than the ones of FT. But to compare the performance of the strategies, the integral underneath the whole function line must be taken, which will result in a much higher total average emission for FT since it has more stops.

The trends of CO_2 and of Total Energy are affine, since they refer to the same burning process.

Total Demand 1800 veh/h

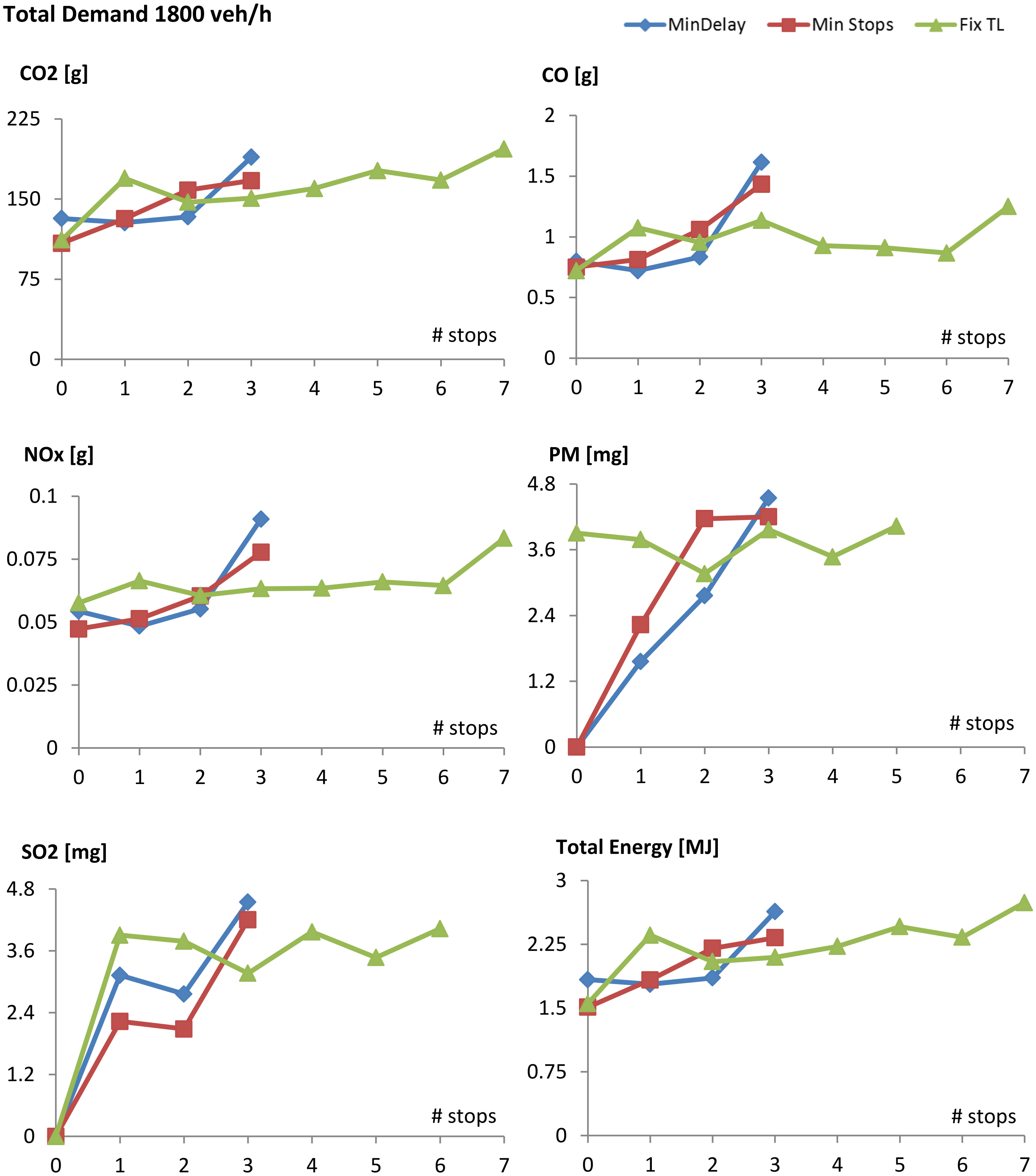


Figure 12(a-f): Emissions for total demand 1'800 veh/h

Discussion (Total Demand 1800 veh/h):

- Figure 12(a) shows a growing trend for the CO_2 emissions. This is reasonable, since more stops usually mean more delay, more time spent at the intersection, and therefore more emissions.
- For the emissions of CO, NO_x and Total Energy (Figures 12(b), 12(c), 12(f)) the same observations as for CO_2 are valid.
- Simulations for lower total demand resulted in better results for FT compared to the other strategies. No logical pattern could be observed from those.
- The trends for PM and SO_2 start from the origin of the coordinates.

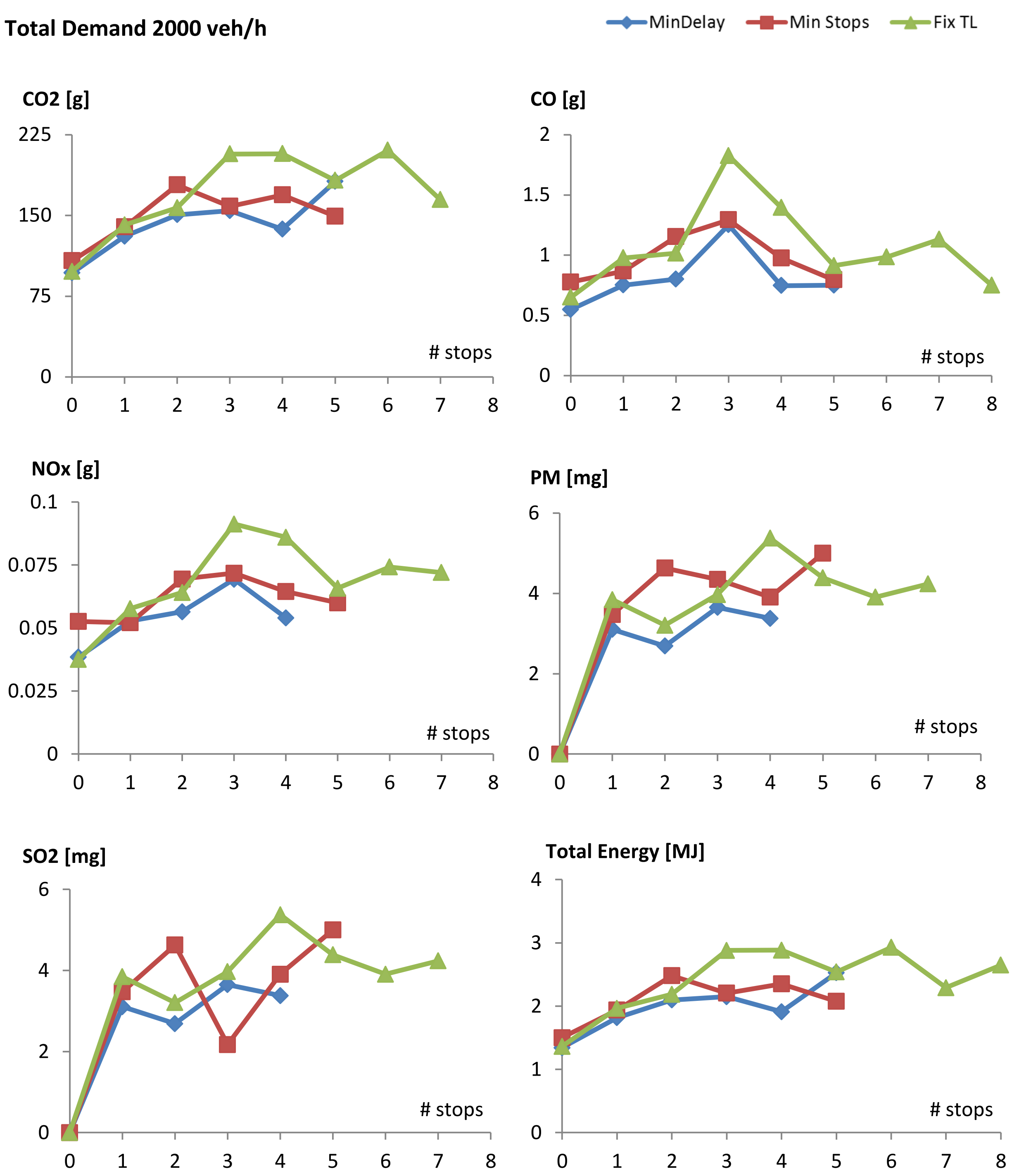


Figure 13: Emissions for total demand 2'000 veh/h

Discussion (Total Demand 2000 veh/h):

- For an oversaturated system the average emissions are roughly the same, but since there are more stops the total amount of emissions will result evidently higher, as there are more cars in the system.
- Some trends show peaks. There can be several explanations to this phenomenon: besides errors in the program, one can consider the stopped time that cars spend at the intersection. According to MOVES emission's rate, cars pollute the most when they are idling. To explain this assertion in the next figure are displayed emissions for the case of CO_2 for one vehicle with respect to the speed.

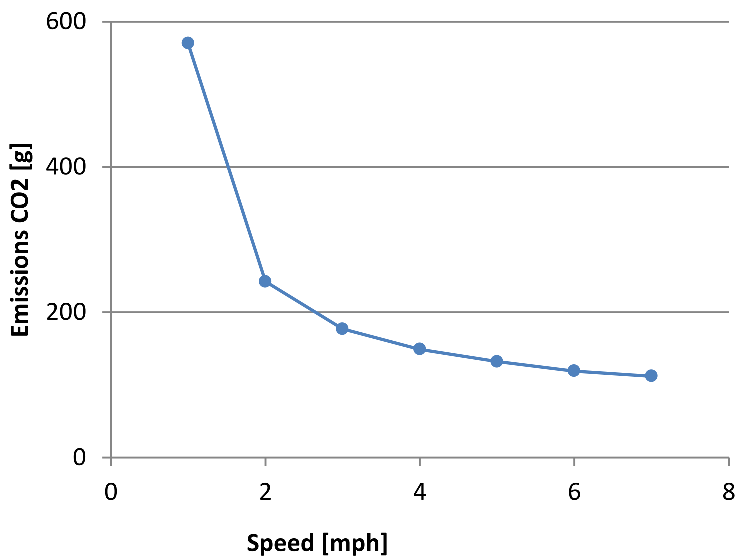


Figure 14: Emission rate per car (CO_2)

It can be observed that the highest emissions result from low speed. The following table shows the average idling time for each stop, strategy and total demand.

Table 7: Average idling time

AVG. STOP TIME

stops	0	1	2	3	4	5	6	7	8
MD1000	0.41	17.48							
MS1000	0.31	13.34							
FT1000	0.26	17.97							
MD1200	2.16	5.89							
MS1200	0.77	15.88	4.67						
FT1200	0.66	22.97	19.62						
MD1400	1.09	20.09							
MS1400	2.47	23.35							
FT1400	0.82	31.95	65.24	95.06					
MD1600	1.41	37.37	68.68						
MS1600	3.97	31.68	76.61						
FT1600	0.95	28.83	70.39	107.78	146.24	171.61			
MD1800	0.51	43.98	96.24	142.16					
MS1800	1.73	42.82	92.17	141.15	131.19				
FT1800	0.74	26.36	67.31	106.56	145.16	179.67	224.33	245.88	
MD2000	0.78	40.05	93.45	134.70	179.48	204			
MS2000	4.42	36.22	85.41	140.88	192.3	218.9			
FT2000	0.42	29.49	67.09	116.26	147.33	179.81	198.18	184.82	168.00

Total Demand 1600 veh/h

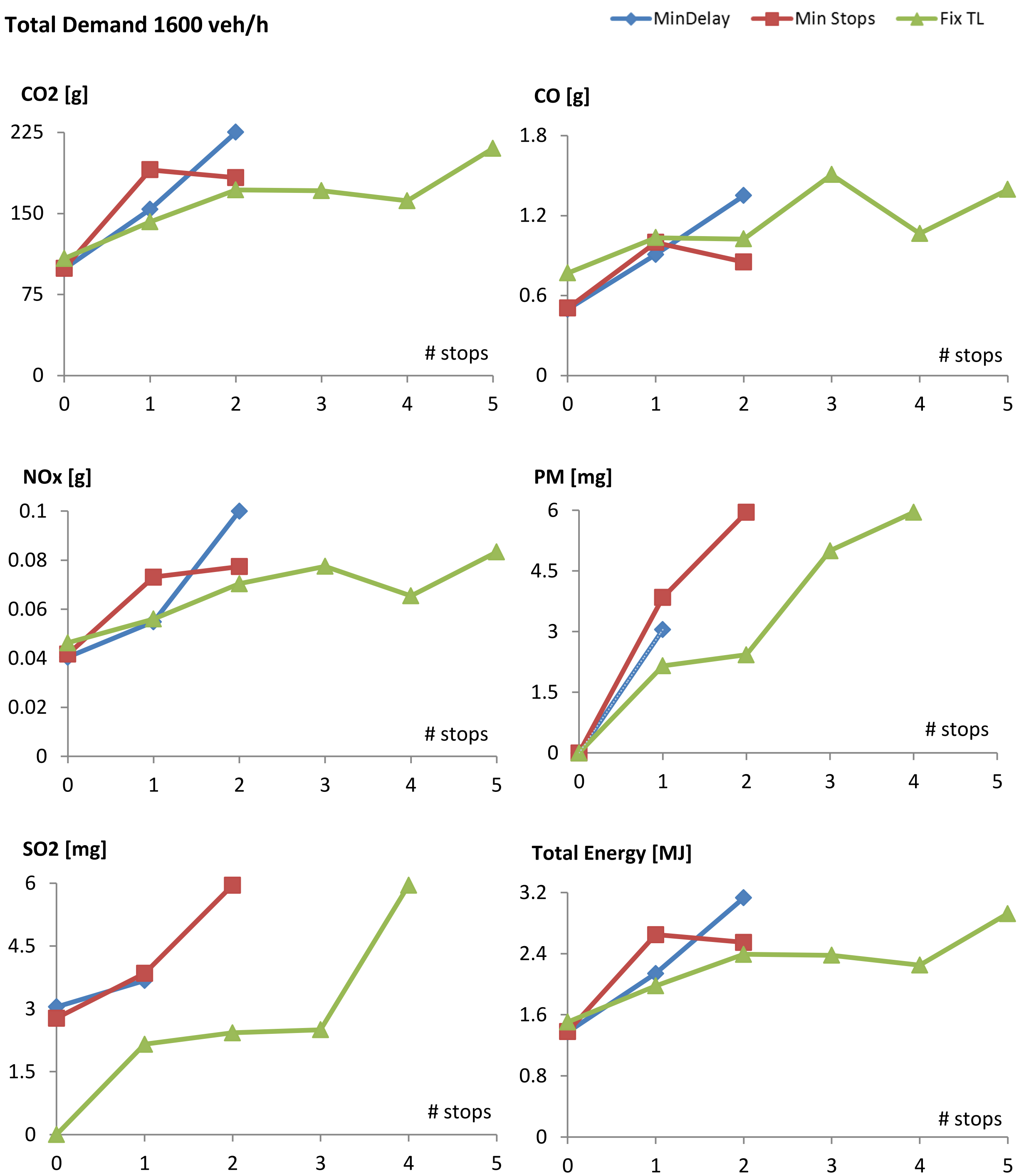


Figure 15: Emissions for total demand 1'600 veh/h

Discussion (1600 veh/h):

- Once again the tendency of increasing emissions with the number of stops can be confirmed. Though the number of stops is lower, resulting from a smaller total demand.
- For undersaturated conditions, less emissions result from less volume.
- MD and MS result with significantly lower number of stops compared to FT, while the discrete average emissions per number of stops are approximately the same, as one could expect.

5.2 Correlation of Total Emissions

The integral of the previous emission lines gives back the total averaged emission. Plotting the total emission for each strategy and for different total demand values, a pattern can be observed.

The following trends will be very meaningful to compare the discharge strategies form the environmental point of view.

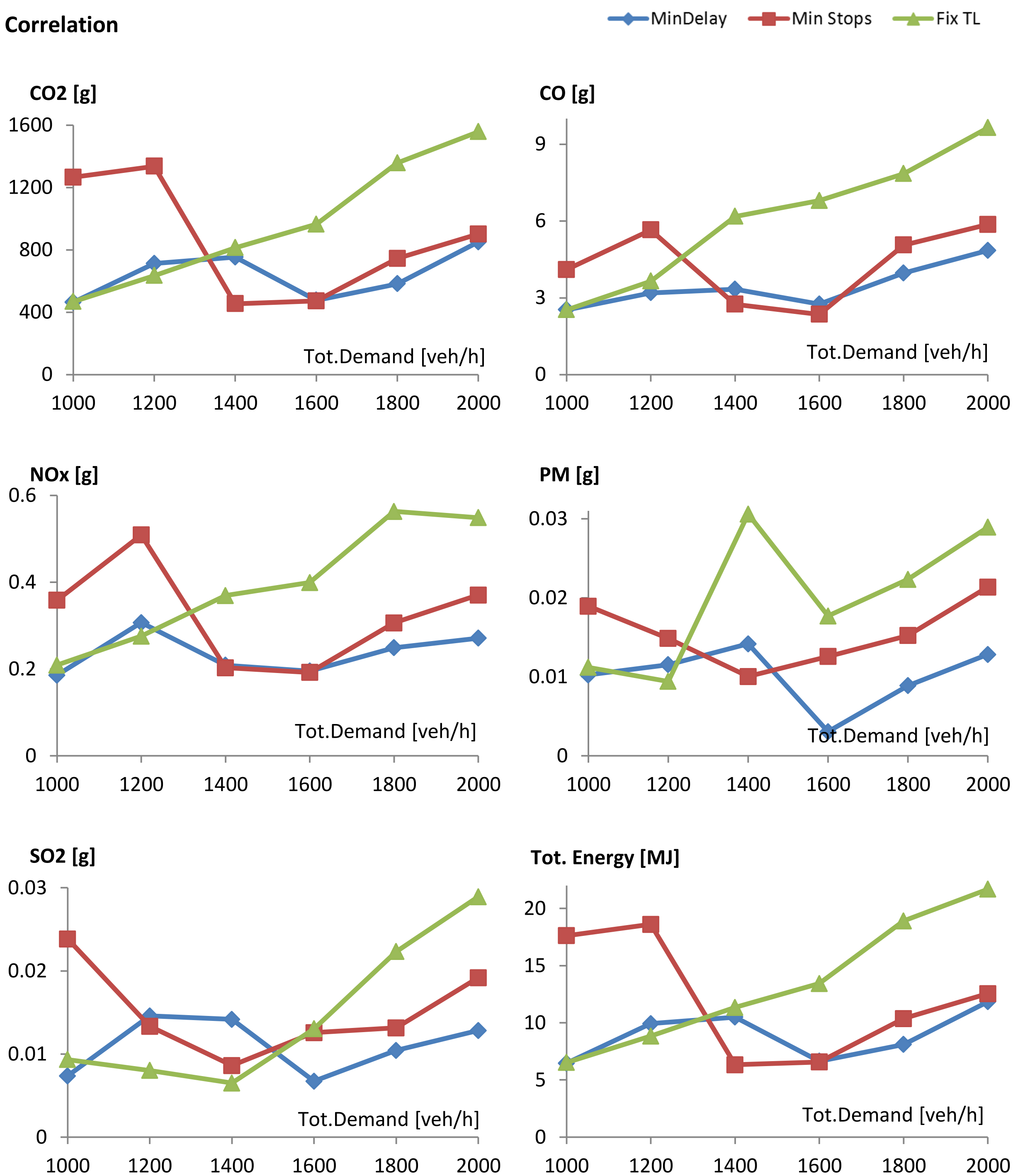


Figure 16: Correlation of the results for total demand 1'000 – 2'000 veh/h

Discussion:

- The simulations don't apparently show correlation for extremely undersaturated systems for MD and MS. This is reasonable, since the algorithms penalize the many switches of discharge priority and encourage platoon discharge. With a standard FT, even if the algorithm is not focused on minimizing the total delay or the number of stops, the results for total emission deriving from the traffic flow are lower. One can then also consider it as good selection for the practical use.
- The high values of total emission for stops 0 and 1 cannot be explained with the total idling time. The total idling time for those cases is lower than 5 seconds, a high emission due to that is excluded. It is still reasonable to suppose mistakes in the input data, particularly for MS.
- A higher total emission for increasing total demand is also confirmed. This makes sense, since greater total demand means more cars, and therefore more pollution.
- For the cases close to saturation flow (total demand 1600, 1800, 2000 veh/h) a smooth almost linear pattern can be observed. This result is very important for this paper. Lower emissions are shown using the MS algorithm, while the MD algorithm shows better results. The FT leads always to the highest emissions (and also traffic profiles).

5.3 Comparison of the discharge strategies

The above mentioned results for 1600, 1800 and 2000 veh/h are further reported here. The percentage enhancement resulting from the discharge strategy as compared to the standard FT is reported (green values).

Table 8: Comparison of the discharge strategies

CO2	1600	1800	2000
MD	477.34 (**-50.5%**)	582.33 (**-54.5%**)	850.84 (**-45.4%**)
MS	472.34 (**-51.0%**)	745.11 (**-41.8%**)	902.1 (**-42.1%**)
FT	964.9	1358.5	1558.4
CO	1600	1800	2000
MD	2.7 (**-59.5%**)	3.97 (**-49.4%**)	4.85 (**-49.7%**)
MS	2.35 (**-65.4%**)	5.06 (**-35.5%**)	5.86 (**-39.2%**)
FT	6.80	7.85	9.64
NOx	1600	1800	2000
MD	0.20 (**-51.1%**)	0.25 (**-52.6%**)	0.27 (**-50.6%**)
MS	0.19 (**-51.9%**)	0.31 (**-41.7%**)	0.37 (**-32.5%**)
FT	0.40	0.56	0.55
PM	1600	1800	2000
MD	0.003 (**-80.4%**)	0.009 (**-60.3%**)	0.013 (**-55.7%**)
MS	0.012 (**-36.9%**)	0.015 (**-31.8%**)	0.021 (**-26.7%**)
FT	0.003	0.022	0.029
SO2	1600	1800	2000
MD	0.007 (**-48.4%**)	0.010 (**-53.3%**)	0.013 (**-55.7%**)
MS	0.013 (**-3.5%**)	0.013 (**-41.1%**)	0.019 (**-33.7%**)
FT	0.013	0.022	0.029
Tot.Energy	1600	1800	2000
MD	6.64 (**-50.5%**)	8.10 (**-54.5%**)	11.84 (**-45.4%**)
MS	6.58 (**-51.0%**)	10.37 (**-41.8%**)	12.55 (**-42.1%**)
FT	13.43	18.90	21.69

Once again it is confirmed that MD and MS result in lower emissions compared to fixed traffic light. Intuition would suggest a higher improvement for higher total demand, but this is not the case. As a matter of fact, the emissions for minimal delay algorithm leads to the lowest emission.

Changing the parameters and simulating climate the situation of Zurich (CH) it was found, that the influence of temperature and relative humidity on the vehicle emissions is just marginal, or even irrelevant for some pollutants.

By adding a random acceleration rate in the following behavior of the platoon one can observe lower emissions for idling conditions and slightly greater for stops 1 and more. This makes sense for the case where the random acceleration affects the idling time of the car reducing it. Besides, the more time the car will spend travelling at low speed, the greater the emissions will be (Figure 14). These results must be further investigated.

6 Conclusions

In this paper the environmental impact of different discharge strategies was researched. The emissions at an intersection for a standard traffic light were found, and then compared to the ones resulting from the algorithms proposed in [1], which were developed to minimize the total delay and total number of stops.

The results showed:

- Increasing emissions with increasing total demand,
- No pattern for extremely undersaturated systems,
- Almost linear correlation close to saturation flow,
- MD algorithm results always with the lowest emissions,
- FT results always with the highest emissions (and stops),
- The climate impacts emissions (higher emissions for higher temperature and relative humidity),
- Idling cars pollute the most.

The discharge strategies can also be discussed from the point of view of the efficiency: indeed, for the case of total demand 1800 veh/h, the three options lead to the same emissions for 2 stops, but comparing their average speed (always for 2 stops, 1800 veh/h total demand, Table 5) the values are 11.43 mph for MD, 9.78 mph for MS and 9.37 mph for FT. The algorithm for minimizing the total delay also lead to faster systems, which are usually more accepted by drivers.

For further work, the consistency of the results is to be tested, by repeating the simulations at least 5 times and comparing their averages. Different demand ratios can also be considered, even though according to [1] “for unbalanced demand a larger portion of the delay is due to stochastic fluctuations in the arrival process”.

Since it is a very primitive stage, the simulation has to be implemented with more lanes and bending options, and the dynamicity of the traffic flow can also be improved in the algorithms.

Nevertheless the human factor is to consider. The human behavior can show skepticism in the adoption of such technologies. But of course the use of new discharge strategies which not only would improve the traffic flow but also lower the pollution would also represent interesting developments for the political, social and technological scene.

One must also keep in mind that changing the discharge strategy is not the only way to reduce the emissions. New fuel composition and vehicle technologies can result as better option, such as discharge strategies focused on minimizing emissions algorithms, with the risk of a worse traffic flow.

7 References

[1] *Using Connected Vehicle Technology to Improve the Efficiency of Intersections*, I. Guler, L. Meier, M. Menendez, 2013

[2] www.fhwa.dot.gov

[3] www.epa.gov

[4] *Methods of Analysis for Transportation Operations*, C.F. Daganzo and G.F. Newell, 2007

[5] en.wikipedia.org

[6] User Guide for MOVES2010b, EPA, 2012