2012 15th International IEEE Conference on Intelligent Transportation Systems
Anchorage, Alaska, USA, September 16-19, 2012

Simulation-Based Benefit Evaluation of Dynamic Lane Grouping Strategies at Isolated Intersections

Guoyuan Wu, *Member, IEEE*, Kanok Boriboonsomsin, Liping Zhang, *Senior Member, IEEE*, Matthew J. Barth, *Senior Member, IEEE*

***Abstract*—Unlike conventional traffic signal control strategies, which assume that an intersection's geometric configuration is given as an exogenous input, dynamic lane grouping (DLG) strategies aim to further improve roadway capacity utilization under significant traffic demand variation. This is accomplished by dynamically adjusting the turning movement assignments for each lane. Previous numerical analyses have demonstrated that such a DLG strategy is effective in balancing lane flow ratios and reducing intersection delays. This paper presents an evaluation of a DLG strategy's benefits at an isolated intersection using microscopic traffic simulation. It is demonstrated that such a DLG strategy can provide significant mobility and sustainability benefits over conventional strategies.**

***Index Terms*—Dynamic lane grouping, traffic demand variation, traffic signal control, fuel economy, vehicle emissions**

I. Introduction

Continued growths in travel demand coupled with limited capacities in existing roadway facilities have brought about a variety of challenges to our society, including ever-increasing congestion along with higher energy consumption and emissions. Based on survey data from 439 urban areas in the United States, it has been reported that the annual travel delay in 2010 was 4.8 billion hours and approximately 1.94 billion gallons of fuel was wasted due to traffic congestion [1]. In addition, the U.S. Environmental Protection Agency (USEPA) estimates that nearly 33% of carbon dioxide (CO_2) emissions, 24% of methane (CH_4) emission, and 65% of nitrous oxide (N_2O) emissions resulted from fossil fuel combustion for transportation activities in 2009 [2]. Therefore, mitigating traffic congestion and reducing environmental impacts have been crucial tasks for any sustainable transportation program.

In addition to the deployment of better transit operation and the improvement in vehicle technology (e.g., hybrid vehicles and alternative fueled vehicles [3]), numerous studies have shown that there can also be profound mobility and sustainability (in terms of energy and emissions) benefits from enhancing traffic operations with the introduction of various intelligent transportation system (ITS) technologies, such as active traffic and demand management (ATDM) strategies [4–7]. For arterial, most ATDM strategies and applications have focused on traffic signal control [8], in particular on signal timing optimization at an intersection. However, these optimization strategies assume that traffic movement(s) in each lane of an intersection approach is fixed and given as an exogenous input [9], which may limit the intersection's ability to handle significant variations in traffic demand and achieve even greater operational and environmental performance.

To overcome these limitations in conventional traffic signal control strategies, the idea of dynamic lane grouping (DLG) at signalized intersections has been put forward and its mathematical formulation and numerical analysis was recently provided by Zhang and Wu [10]. It has been demonstrated that such a DLG strategy can be effective in balancing lane flow ratio and reducing traffic delays. This paper aims to evaluate the DLG strategy's benefits more comprehensively in terms of both mobility and sustainability at signalized intersections using microscopic traffic simulation.

The remaining of this paper is organized as follows: In Section 2, background information related to the DLG strategy is presented, followed by the introduction of a microscopic emission estimation model that is used in this study in Section 3. Section 4 elaborates on the setup and the results of traffic simulation scenarios. The last section concludes this paper and describes possible future steps of research.

II. Background

A. Traffic Demand Variation

Variation in traffic demand has always been a major challenge for traffic planning, operation, and control. A signalized intersection may experience considerable day-to-day or within-the-day traffic demand variability [11]. Previous studies on selected sites along urban arterials have revealed that the patterns of traffic demand vary significantly in both temporal and spatial dimensions [12]. During peak hours, the day-to-day variability is as high as the site-to-site variability at some intersections in a city [13]. Such demand variation may lead to the imbalance of lane utilization at conventional intersections where turning lanes have been predetermined and fixed (see Fig. 1 (a)). This motivates the idea of dynamic lane grouping, a strategy of dynamic lane utilization.

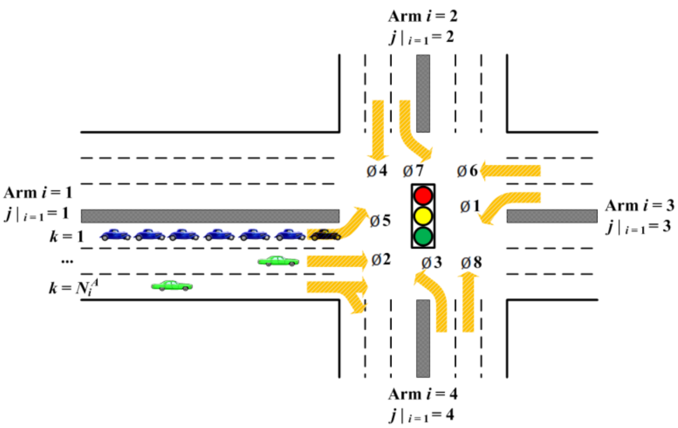
B. Dynamic Lane Utilization

The concept of dynamic utilization of lane resources has been proposed in various forms of ATDM. In the context of freeway management, various strategies have been studied in detail, such as dynamic lane allocation control for different user-classes [14] and even reversible lane use [15].

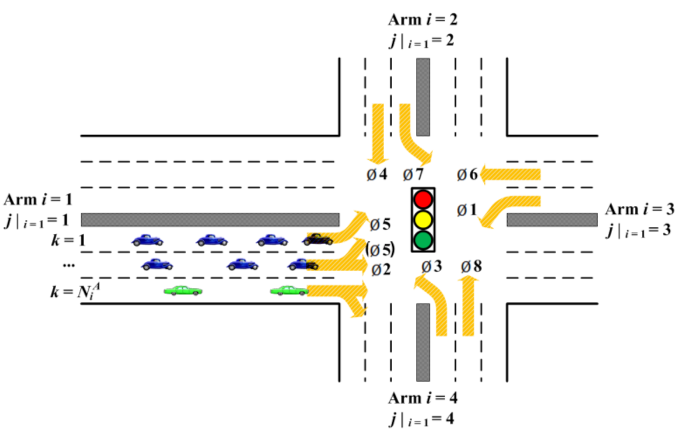
For urban arterials, concepts that have been proposed include dynamic/changeable lane assignment systems [16, 17] and dynamic turn restriction at highway-railroad grade crossings [18]. Another similar concept has also been investigated in the form of a fully automated intersection with autonomous vehicles [19].

C. Dynamic Lane Grouping (DLG)

The basic idea of the DLG strategy is that lane groups at intersections can be adaptive to the variation of traffic demand along each movement. As shown in Fig. 1, if the left-turn traffic on arm 1 increases too much to be accommodated by the single left-turn lane, then the adjacent exclusive through lane can be converted to a shared lane or an exclusive left-turn lane to alleviate the congestion in the left-most lane.



(a) Imbalanced lane utilization due to predefined lane grouping under demand variation



(b) Improved lane utilization due to dynamic lane grouping under demand variation

Fig. 1. Illustration of dynamic lane grouping strategy [10].

Details of the problem formulation and performance analysis of the DLG strategy have been described in [10] and are summarized below. Without loss of generality, the optimal lane grouping on individual arms of an intersection can be obtained by minimizing the maximum lane-level flow ratios of each arm, provided that the intersection experiences time-varying traffic origin-destination (O-D) demands.

If a 0-1 binary function is defined to identify the permitted movement at the lane level for arm i,

$$\delta_{i,j,k} = \begin{cases} 1, & \text{if lane k allows movement from arm } i \text{ to } j \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

then the DLG strategy for the i-th arm can be formulated as:

$$\min \max_k y_{i,k} \tag{2}$$

subject to:

1) For safety reasons, if a movement to arm j is allowed on lane $k+1$, then all movements to $j+1, j+2, \ldots$ are prohibited on lane k,
$$\delta_{i,m,k} \le 1 - \delta_{i,j,k+1} \qquad \forall\, j, k, \text{ and } m > j \tag{3}$$
2) For any lane k_1 and lane k_2 with the same movement(s),
$$y_{i,k_1} = y_{i,k_2} \tag{4}$$
3) For any two lanes, lane k_1 and lane k_2, where movements of lane k_1 is a subset of movements of lane k_2,
$$y_{i,k_1} \le y_{i,k_2} \tag{5}$$
4) Conservation of flow factors on each lane,
$$\textstyle\sum_j f_{i,j,k} = 1 \qquad \forall\, k \tag{6}$$
5) On each lane, traffic flow is allowed only when the associated movement is assigned,
$$0 \le f_{i,j,k} \le \delta_{i,j,k} \qquad \forall\, j \text{ and } k \tag{7}$$

where $y_{i,k} \triangleq \sum_j q_{i,j,k}/s_{i,k}$ is the k-th lane flow ratio along arm i; $q_{i,j,k}$ is the flow rate from arm i to arm j via lane k; and $s_{i,k}$ is the lane-level saturation flow rate. The reader can refer to [20] for a generalized model to estimate $s_{i,k}$. $f_{i,j,k} \triangleq q_{i,j,k}/\sum_j q_{i,j,k}$ is the flow factor, defined as the proportion of traffic flow from arm i to arm j via lane k.

This 0-1 binary integer linear programming can be solved efficiently using some commercial optimization solvers, e.g., IBM ILOG CPLEX. It is noted that in this problem formulation, if $\delta_{i,j,k}$ is given (e.g., a pre-defined movement assignment for each lane), then the optimal flow factor $f_{i,j,k}$ can be obtained to minimize the maximum lane flow ratio for arm i. Otherwise, the optimal movement assignment $\delta_{i,j,k}$ and associated flow factor $f_{i,j,k}$ can be derived to equalize all lane flow ratios for arm i.

III. Comprehensive Modal Emissions Model

In order to accurately assess the energy and emission benefits of this DLG strategy, the Comprehensive Modal Emissions Model (CMEM) is used in this study. CMEM is a microscopic emissions model that is capable of estimating second-by-second fuel consumption and tailpipe emissions of greenhouse gas and other pollutants, including CO_2, carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NO_x), based on different modal operations of an in-use vehicle fleet. The latest version of CMEM includes 28 light-duty vehicle/technology categories and 3 heavy-duty vehicle/technology categories, respectively. Please refer to [21–24] for further details on CMEM.

CMEM has been developed primarily for use with micro-scale transportation models that typically produce second-by-second vehicle trajectories (location, velocity, and acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy/emissions estimates. Alternatively, CMEM has also been integrated with traffic simulation models, e.g., PARAMICS [25], in the form of software plug-in developed through the use of an application programming interface (API). The integrated modeling tool has been successfully used in the evaluation of a variety of intelligent transportation systems [26], and therefore, is used in this study.

In this study, the energy/emission estimation is performed for two vehicle categories in CMEM:

1) LDV5, which represents light-duty gasoline vehicles with mileage more than 50,000.
2) HDDV7, which represents heavy-duty diesel vehicles with four-stroke engines.

IV. SIMULATION EVALUATION

In principle, the DLG strategy provides another degree of freedom to accommodate the variation in traffic demand, compared with other conventional traffic signal control strategies. Therefore, mobility and sustainability benefits can be expected of the strategy due to improvements in utilization of roadway capacity. Different measures of effectiveness (MOEs) are used to quantify these benefits.

For mobility, the following MOEs are considered:

1) Average delay per vehicle, where the reference speed is 64 kph or 40 mph; and
2) Average number of stops per vehicle, where the queuing speed threshold is 8 kph or 5 mph.

For sustainability, we consider:

1) Average fuel consumption per vehicle;
2) Average emissions of greenhouse gas (i.e., CO_2) per vehicle; and
3) Average emissions of other pollutants, such as CO, HC, and NO_x per vehicle.

The benefits of DLG have been evaluated by conducting extensive simulation experiments as described in the following subsections.

A. Simulation Setup

High-fidelity microscopic traffic simulation software, PARAMICS, is used as the simulation tool where the CMEM plug-in is applied to estimate the energy consumption and emissions for all vehicles. Another plug-in has been developed to determine the number of stops, trip travel time, and intersection delay for each simulated vehicle.

The simulation model contains an isolated signalized intersection with four arms which are all 300 meters long. Each arm has four lanes per direction with a speed limit of 64 kph or 40 mph (see Fig. 2). The turning movement assignment for each lane is fixed for different traffic O-D patterns in non-DLG scenarios. In the DLG scenarios, the turning movement assignment may vary with traffic demands and the optimal solution can be obtained from the proposed mathematical model presented in Section II. Two types of vehicles, LDV5 and HDDV7, are used in the simulation with a 95:5 split.

The traffic signal follows a typical eight-phase, dual ring control scheme. Some basic settings of the signal timings are as follows:

1) For all scenarios, cycle lengths are 120 seconds based on the recommendations from [27] for intersections with protected left-turn signal;
2) Minimum green times are 12 seconds for all phases;
3) Yellow and all-red clearance intervals are 3 seconds and 1 second, respectively, for all phases;
4) In fixed timing scenarios, signal timings for different demands are the same as those for the baseline demand; and
5) In so-called adaptive timing scenarios, signal timings for different demands may vary and are estimated by using the Quick Estimation Method (QEM) in [28].

The duration for each simulation run is 60 minutes, but the first 30 minutes is used as a "warm-up" period.

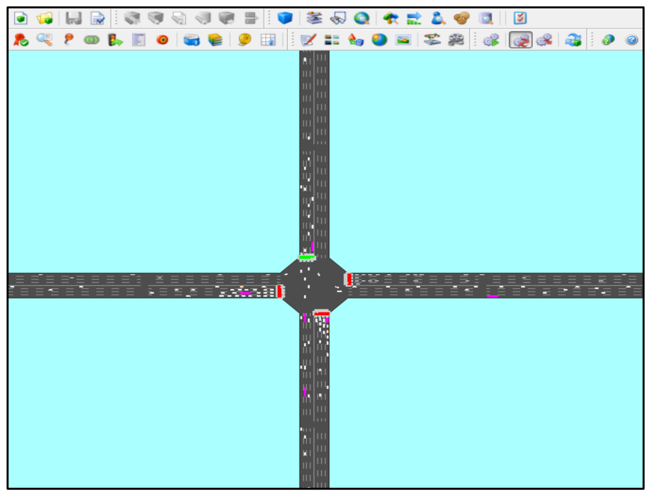


Fig. 2. Simulation network in PARAMICS.

B. Strategy Evaluation

To evaluate the benefits of the implementation of DLG and the changes in signal timings, the traffic demand pattern of the four-lane intersection in [10] is used in the simulation. In the baseline model, the demand matrix is:

$$\begin{pmatrix} arm & LT & TH & RT \\ \boldsymbol{i=1} & 375 & 600 & 225 \\ 2 & 600 & 600 & 150 \\ 3 & 300 & 750 & 150 \\ 4 & 300 & 750 & 150 \end{pmatrix}.$$

It is further assumed that, for each arm, there is one exclusive left-turn lane, one left-turn and through shared lane, one exclusive through lane, and one through and right-turn shared lane, i.e.,

$$\delta_i = \begin{pmatrix} \text{lane index} & \text{k} = 1 & 2 & 3 & 4 \\ \text{LT} & 1 & 1 & 0 & 0 \\ \text{TH} & 0 & 1 & 1 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}, i = 1, \dots, 4$$

TABLE I: Summary of numerical and simulation results for different strategies

Demand Model	Strategy Scenario	Numerical Analysis Delay (sec) [a]	Simulation Study						
			Delay (sec)	No. of Stops	CO2 (g)	CO (g)	HC (g)	NOx (g)	Fuel (g)
Baseline	Baseline	53.02	53.48	1.02	343.16	17.40	0.314	1.124	116.54
Perturbed	Scenario I	61.73	59.65	1.15	358.16	17.76	0.324	1.156	121.43
	% vs. Baseline	16.43	11.54	12.23	4.37	2.08	3.13	2.81	4.20
	Scenario II	58.48	58.09	1.12	354.64	17.51	0.319	1.154	120.20
	% vs. Baseline	8.84	8.63	9.11	3.35	0.66	1.60	2.62	3.14
	Scenario III	53.46	54.31	1.03	345.07	17.46	0.316	1.129	117.17
	% vs. Baseline	0.75	1.56	0.21	0.56	0.36	0.50	0.45	0.54
	Scenario IV	53.45	53.67	1.01	343.30	17.38	0.314	1.123	116.57
	% vs. Baseline	0.80	0.36	-1.47	0.04	-0.12	0.07	-0.12	0.03

[a]Some results have been shown in [10].

For illustration purpose, it is assumed that only the traffic demand on arm 1 will change in the perturbed model, which is the same as in [10] and specified as follows.

$$\begin{pmatrix} arm & LT & TH & RT \\ \boldsymbol{i=1} & 816 & 168 & 216 \\ 2 & 600 & 600 & 150 \\ 3 & 300 & 750 & 150 \\ 4 & 300 & 750 & 150 \end{pmatrix}$$

However, extensions to the demand variation on other arms are straightforward and further improvements can be obtained by optimizing their turning movement assignment.

In addition to the baseline model, different strategies have been applied to the perturbed model and simulated:

1) Scenario I: There is no change in lane grouping and signal timings.
2) Scenario II: There is no change in lane grouping but signal timings are adjusted based on QEM.
3) Scenario III: The lane grouping is optimized but signal timings kept intact.
4) Scenario IV: Both lane grouping and signal timings vary with the perturbed traffic demand.

Based on the mathematical model in Section II, the optimal lane grouping for Scenario III and IV is,

$$\delta_1 = \begin{pmatrix} \text{lane index} & \text{k}=1 & 2 & 3 & 4 \\ \text{LT} & 1 & 1 & 1 & 0 \\ \text{TH} & 0 & 0 & 1 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}$$

The simulation results are summarized in Table I. It can be observed that when the traffic demand varies, the DLG strategy with QEM-based adaptive signal timings (Scenario IV) provides the most mobility and sustainability benefits. The changes in different MOEs are trivial in comparison with the baseline scenario whose lane grouping and signal timings have been optimized accordingly. On the contrary, the non-DLG strategy with fixed signal timing (Scenario I) performs the worst, where the average vehicle delay and number of stops increase as much as 11.54% and 12.23%, respectively. In addition, although improvements in MOEs can be obtained by changing signal timings, it is more effective to adjust the turning movement assignment (Scenario III vs. Scenario II), especially in the cases where traffic demand varies significantly among different movements (e.g., left-turn vs. through). It is also noted that, as shown in Table 1, the average vehicle delays obtained from the simulation are comparable with those from the numerical analysis in the previous study.

For further reference, the actual green splits for the different scenarios are listed in Table II. It is noted that both left-turn and through phases of an arm share a common green split due to the shared-lane use. Also, the total green time within a cycle is 100 seconds, because the total lost time (yellow and all-red) is assumed to be 20 seconds.

TABLE II
ACTUAL GREEN SPLITS FOR DIFFERENT SIMULATION SCENARIOS

Scenario	Green Time for Different Phases [a] (sec)			
	Ø2 or Ø5	Ø4 or Ø7	Ø1 or Ø6	Ø3 or Ø8
Baseline	25	28	24	23
Scenario I	25	28	24	23
Scenario II	27	25	26	22
Scenario III	25	28	24	23
Scenario IV	24	28	24	24

[a]Refer to Fig. 1 for definition of each phase.

C. Sensitivity Analysis

To further investigate the benefits of the DLG strategy, a sensitivity analysis on different left-turn traffic volume proportion has been conducted on both non-DLG and DLG strategies with adaptive timings. In the baseline model, the traffic demand matrix is

$$\begin{pmatrix} arm & LT & TH & RT \\ \boldsymbol{i=1} & 240 & 810 & 150 \\ 2 & 300 & 750 & 150 \\ 3 & 300 & 750 & 150 \\ 4 & 300 & 750 & 150 \end{pmatrix},$$

and the turning movement assignment matrix for each arm is

$$\delta_i = \begin{pmatrix} \text{lane index} & \text{k}=1 & 2 & 3 & 4 \\ \text{LT} & 1 & 0 & 0 & 0 \\ \text{TH} & 1 & 1 & 1 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}, i = 1, \dots, 4$$

Simulation runs have been performed with four levels of left-turn traffic volume proportions,

$$p_{1,LT} \triangleq \sum_k q_{1,2,k} / \sum_j \sum_k q_{1,j,k},$$

on arm 1 only ($p_{1,LT} = 0.2$, 0.4, 0.6 and 0.8) while keeping the total traffic volume and right-turn traffic volume to be 1,200 veh/hr and 150 veh/hr, respectively. More specifically, the optimal turning movement assignment for each left-turn volume proportion is:

1) For $p_{1,LT} = 0.2$, the same as the baseline model.
2) For $p_{1,LT} = 0.4$,

$$\delta_1 = \begin{pmatrix} \text{lane index} & \text{k}=1 & 2 & 3 & 4 \\ \text{LT} & 1 & 1 & 0 & 0 \\ \text{TH} & 0 & 1 & 1 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}$$

3) $p_{1,LT} = 0.6$;

$$\delta_1 = \begin{pmatrix} \text{lane index} & \text{k} = 1 & 2 & 3 & 4 \\ \text{LT} & 1 & 1 & 1 & 0 \\ \text{TH} & 0 & 0 & 1 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}$$

4) $p_{1,LT} = 0.8$;

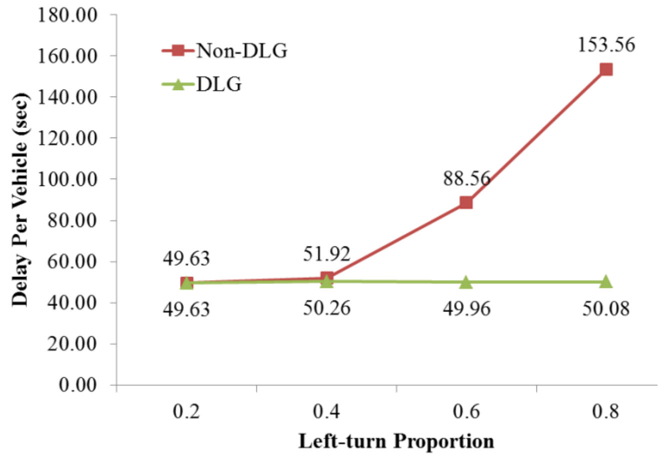
$$\delta_1 = \begin{pmatrix} \text{lane index} & \text{k} = 1 & 2 & 3 & 4 \\ \text{LT} & 1 & 1 & 1 & 1 \\ \text{TH} & 0 & 0 & 0 & 1 \\ \text{RT} & 0 & 0 & 0 & 1 \end{pmatrix}$$

In both non-DLG and DLG scenarios, the QEM-based green splits for different phases may vary with different demand profiles and are presented in Table III. It can be observed that, without changing the lane grouping of arm 1, the green time of Ø2 or Ø5 in the non-DLG strategy has to be reserved for longer as the left-turn volume proportion increases in order to clear the queuing vehicles as soon as possible. If the cycle length is fixed, then the green times for other phases have to be shortened. Thus, the average delay and number of stops may increase on other arms, so do the fuel consumption and emissions. On the other hand, the green splits for different phases, however, are very close to each other in the scenarios with the DLG strategy because the traffic volumes on different arms are equal (i.e., 1,200 veh/hr) and the flow ratios in the lanes can be well balanced by the DLG strategy. In addition, such balance in flow ratios may facilitate the design of traffic signal coordination. It should be pointed out that all signal timings in this study are obtained based on QEM, which focuses on handling the critical movement or the movement with the largest flow rate. Other tuning methods with different considerations may result in different signal timings although the results are expected to be similar.

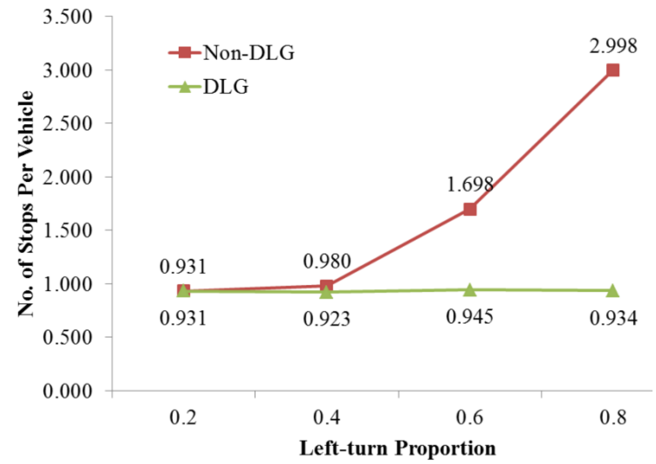
TABLE III
ACTUAL GREEN SPLITS FOR DIFFERENT LEFT-TURN VOLUMES

p_{LT}	Scenario	Green Time for Different Phases (sec)			
		Ø2 or Ø5	Ø4 or Ø7	Ø1 or Ø6	Ø3 or Ø8
0.2	Non-DLG	24	25	26	25
	DLG	24	25	26	25
0.4	Non-DLG	31	22	25	22
	DLG	25	25	25	25
0.6	Non-DLG	38	19	25	18
	DLG	26	25	25	24
0.8	Non-DLG	44	16	24	16
	DLG	26	25	25	24

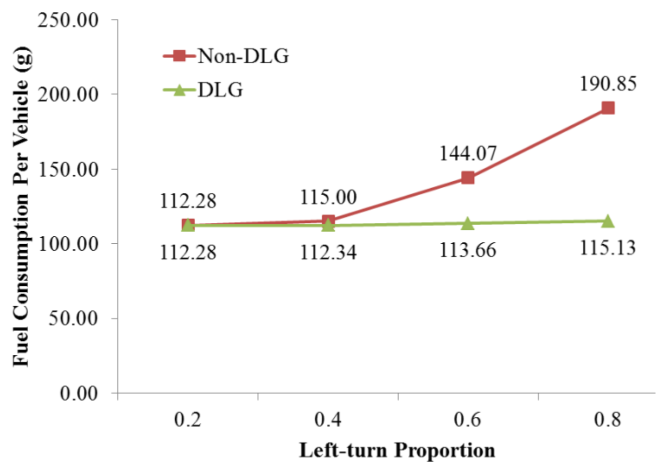
Simulation results on average delay, number of stops and fuel consumption are depicted in Fig. 3. As the left-turn volume deviates from the baseline model (i.e., 240 veh/hr or 20% of total volumes on arm 1), all the MOEs increase considerably for the non-DLG scenarios while the changes in these MOEs are trivial for the DLG scenarios. In particular, when the left-turn volume reaches 960 veh/hr (i.e. $p_{1,LT} = 0.8$), the average delay and number of stops are three folds for the non-DLG scenarios, and the fuel consumption doubles, compared with the DLG scenarios.



(a) Average vehicle delay



(b) Average number of stops



(c) Average vehicle fuel consumption

Fig. 3. Comparison of system performance between non-DLG and DLG strategies with QEM-based adaptive timings under different left-turn traffic volume proportion on arm 1.

Table IV summarizes the results on vehicle emissions. As can be seen from the table, the emissions of CO, HC, and NO_x are reduced by as much as 4.75%, 18.45%, and 32.94%, respectively, if the DLG strategy is applied.

TABLE IV
SIMULATION RESULTS FOR POLLUTANT EMISSIONS

Pollutant	Strategy Scenario	Left-Turn Traffic Volume Proportion			
		0.2	0.4	0.6	0.8
CO2 (g)	Non-DLG	330.11	338.38	430.56	578.91
	DLG	330.11	329.98	333.97	338.71
	% change	0	-2.48	-22.43	-41.49
CO (g)	Non-DLG	17.07	17.34	17.68	18.28
	DLG	17.07	17.24	17.39	17.41
	% change	0	-0.57	-1.60	-4.75
HC (g)	Non-DLG	0.306	0.312	0.339	0.382
	DLG	0.306	0.309	0.311	0.312
	% change	0	-0.731	-8.145	-18.451
NOx (g)	Non-DLG	1.082	1.106	1.327	1.676
	DLG	1.082	1.075	1.098	1.124
	% change	0	-2.802	-17.231	-32.943

V. CONCLUSIONS AND FUTURE WORK

This paper presents an evaluation of the benefits of DLG strategy at an isolated intersection using microscopic traffic simulation. The results have verified that the improvements in mobility performance, i.e., reductions in average vehicle delay and number of stops, due to DLG implementation increase as the traffic volumes for the different turning movements deviate from the baseline demand pattern. This finding is consistent with those of previous studies. In addition, compared with QEM-based adaptive signal control strategies, the DLG strategy is more capable of handling significant traffic demand variations among the turning movements. By balancing traffic flow at the lane level, DLG strategy can provide significant energy/environmental benefits as shown in this paper.

Potential extensions of this study may include:

1) Development and validation of the DLG strategy for corridors with more complex urban networks (e.g. coordinated signalized corridors).
2) Implementation of an online DLG algorithm based on estimated traffic O-D patterns or other MOEs.
3) Evaluation of safety performance and possible capacity reduction due to DLG-induced weaving maneuvers.
4) Integration of other ATDM strategies such as mid-block pre-signals [29] and reversible lane use to further improve the utilization of roadway capacity under varying traffic conditions.

REFERENCES

[1] D. Schrank, T. Lomax and B. Eisele, "TTI's 2011 urban mobility report". September, 2011.

[2] U.S. Environmental Protection Agency, "Inventory of U.S. greenhouse gas emissions and sinks: 1990 – 2009". Final report, EPA 430-R-11-005, April, 2011.

[3] California Energy Commission, "Option to reduce petroleum fuel use, second edition", Staff report CEC-600-2005-024-ED2, July, 2005

[4] T. Le, C. Cai, and T. Walsh, "Adaptive signal-vehicle cooperative controlling system". 14th International IEEE Conference on Intelligent Transportation Systems, Washington D. C., 2011, pp. 236 – 241.

[5] S. D. Beevers and D. C. Carslaw. "The impacts of congestion charging on vehicle emissions in London". Atmospheric Environment, Vol. 39, 2005, pp. 1 – 5

[6] C. Li and S. Shimamoto, "An open traffic light control model for reducing vehicles' CO2 emissions based on ETC vehicles". IEEE Transaction on Vehicular Technology, Vol. 61, No. 1, 2012, pp. 97 – 110.

[7] G. Wu, K. Boriboonsomsin, W-B Zhang, M. Li and M. J. Barth, "Energy and emission benefit comparison between stationary and in-vehicle advanced driving alert systems". Transportation Research Record. No. 2189, 2010, pp. 98 – 106.

[8] A. Stevanovic, "Adaptive traffic control systems: domestic and foreign state of practice – a synthesis of highway practice". NCHRP Synthesis 403, 2010

[9] W. H. K. Lam, A. C. K. Poon, and G. K. S. Mung, "Integrated model for lane-use and signal-phase designs". ASCE Journal of Transportation Engineering, Vol. 123, 1997, pp. 114 – 122.

[10] L. Zhang and G. Wu, "Dynamic lane grouping at isolated intersections – problem formulation and performance analysis". Transportation Research Record: Journal of the Transportation Research Board, 2012 (to be published).

[11] W. A. M. Weijermars, "Analysis of urban traffic patterns using clustering". Ph. D. Thesis, University of Twente, Netherlands, 2007

[12] X. Zhou, X. Qin, and H. Mahmassani, "Dynamic origin-destination demand estimation with multiday link traffic counts for planning applications". Transportation Research Record: Journal of the Transportation Research Board, No. 1831, 2003, pp. 30 – 38.

[13] A. P. Tarko and R. I. Perez-Cartagena, "Variability of peak hour factor at intersections". Transportation Research Record: Journal of the Transportation Research Board, No. 1920, 2005, pp. 125 – 130.

[14] S. P. Hoogendorn and P. H. L. Bovy, "Dynamic lane allocation control: a model based approach". European Transport Conference, 1999.

[15] Transportation Research Board (TRB), "Convertible roadways and lanes – a synthesis of highway practice". NCHRP Synthesis 340, 2004

[16] K. Jella, S. R. Sunkari, W. L. Gisler, N. J. Rowan, and C. J. Messer, "Space management: an application of dynamic lane assignment". TTI Research Report 1232-18, College Station, Texas, February, 1993.

[17] A. P. Voigt and M. E. Goolsby, "Evaluation of changeable lane assignment system for daily operations". TTI Research Report 2910-1, College Station, Texas, December, 1999.

[18] Federal Highway Administration (FHWA), "Innovative intersection safety improvement strategies and management practices: a domestic scan". Research Report FHWA-SA-06-016, September, 2006.

[19] K. Dresner and P. Stone, "A multiagent approach to autonomous intersection management". Journal of Artificial Intelligence Research, Vol. 31, No. 1, 2008, pp. 591 – 656.

[20] C. K. Wong and S. C. Wong, "Lane-based optimization of signal timings for isolated junctions". Transportation Research Part B: Methodological, Vol. 37, No. 1, 2003, pp. 63 – 84.

[21] M. J. Barth, et al., "Analysis of modal emissions from diverse in-use vehicle fleet". Transportation Research Record: Journal of the Transportation Research Board, No. 1587, 1997, pp. 73 – 84.

[22] M. J. Barth, et al., "The Development of a comprehensive modal emissions model". Final report for NCHRP Project 25-11, April 2000.

[23] M. J. Barth, G. Scora, and T. Younglove, "Modal emissions model for heavy-duty diesel vehicles". Transportation Research Record: Journal of the Transportation Research Board, No. 1880, 2004, pp. 10 – 20.

[24] M. J. Barth, et al., "Measuring and modeling emissions from extremely low emitting vehicles". Transportation Research Record: Journal of the Transportation Research Board, No. 1987, 2006, pp. 21 – 31.

[25] Pitney Bowes Software, "Quadstone Paramics". http://www.paramics-online.com/, accessed on February 13th, 2012.

[26] K. Boriboonsomsin and M. Barth, "Impacts of freeway high-occupancy vehicle lane configuration on vehicle emissions". Transportation Research Part D: Transport and Environment, Vol. 13. No. 2, 2008, pp. 112 – 125.

[27] P. Koonce, et al., "Traffic signal timing manual". Final report for Federal Highway Administration (FHWA), FHWA-HOP-08-024, June, 2008.

[28] Transportation Research Board, "Highway capacity manual 2000 (HCM2000)", 2001.

[29] Y. Xuan, V. V. Gayah, M. J. Cassidy, and C. F. Daganzo, "Using a pre-signal to increase intersection capacity: theory and experiment", Transportation Research Record: Journal of the Transportation Research Board, 2012 (to be published)