AN INTEGRATED OFF-RAMP CONTROL MODEL FOR FREEWAY TRAFFIC MANAGEMENT

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ABSTRACT

This study presents a mixed integer model for an integrated control between off-ramp and arterial traffic flows. The proposed study intends to minimize the queue spillback from off-ramp to the freeway mainline that may significantly degrade the performance quality of the entire freeway system. In this study, the Cell Transmission Model (1, 2) is employed to capture the traffic propagation on both freeway an surface streets, and to capture the interactions between those two types of flows within the target control boundaries. An efficient solution method based on Genetic Algorithm is provided along with a numeric case study to demonstrate the benefit of this proposed model.

KEY WORDS: off ramp control, cell-transmission, genetic algorithm

Introduction

To contend with congestion, various control strategies have been explored in the literature, such as speed control, ramp metering (on-ramp metering), etc.. And among these, ramp metering is one of the commonly studied methods.

There exist two major categories of algorithms for ramp metering, i.e., local and system-wide controls. The former includes the use of empirical-based methods(3) and automatic control theory (4-6). An overview of the former category can be found in the study of Papageorgiou and Kotsialos(7). The latter works in the system-wide context.

Wattleworth and Berry (8) were the first attempting to optimize the ramp metering control at the system level. This study and its followers (9) propose a time-invariant linear program to minimize the total travel time for the entire freeway system. These models assume that: freeways operate under free speed; the time-dependent origin-destination (OD) demand information is available; and no diversions from freeways to surface arterial street. In 2000, Lovell and Daganzo (10) extended Wattleworth's model to include time-dependency by employing departure curves and assumed no exit spill-over.

To model the traffic dynamics of the freeway, macroscopic traffic flow models have been employed and combined with optimization theory to obtain optimal control strategies. Papageorgiou (11) proposes a linear optimal-control model including both motorways and signal-controlled urban roads based on the store-and-forward modeling philosophy. Zhang and Recker (12) analyze the state and control relationships, and obtain some general analytical results based on the well-known Lighthill-Witham-Richard (LWR) model. Chang and Li (13) construct a linear dynamic model with a quadratic objective function for integrated-responsive ramp-metering control based on Payne's continuum traffic stream model. Kotsialos and Papageorgiou et al. (14) consider ramp metering, route guidance, and motorway-to-motorway control measures simultaneously in a discrete-time optimal control problem based on the METANET (15) and METACOR(16). Zhang and Levinson(17) propose an analytical framework for ramp metering whose input variables are all directly measurable by detectors in real-time. Gomes and Horowitz (18) propose a nonlinear optimization problem for the on-ramp metering control problem by utilizing the asymmetric cell transmission-link model (ACTM) and solve a simple linear version with certain constraints applied.

But in all those models, queue spillback from off-ramps is not considered since the vehicles will be removed from the system as soon as arriving at an off-ramp. But in reality, this is not always true. As described by Lovell (9), since most drivers do not tend to segregate themselves by destination well in advance of an off-ramp, but rather make most of their lane-changing decisions at the last second. The exit queue of an off-ramp might spread itself laterally upstream of an off-ramp, thereby restricting the mainline flow as depicted in Figure 1.

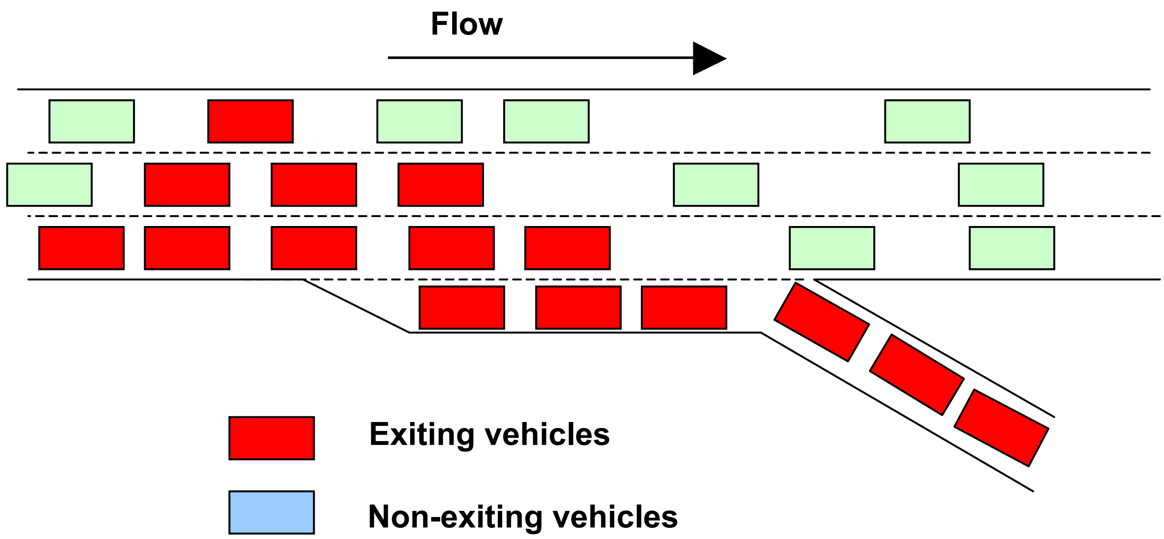

Figure 1 Lateral spreading of an exit queue upstream of an off-ramp.

A similar observation was made from the simulation experiments conducted by Jia et al (19) where cellular automaton model was applied to study the traffic characteristics near off-ramps. The authors investigated cases with and without an auxiliary lane and the influence of the length of exit lane on the traffic flow was studied. The freeway section with the off-ramp was divided into four sections: freeway mainline upstream of ramp, exit lane, off-ramp and freeway downstream of off-ramp. Two peaks were observed in the density profile: The first peak was observed at the start of the exit section where vehicles start to decelerate to exit the freeway and the second peak was at the end of the exit section where vehicles wait to enter the off-ramp. From the simulation results, it was deduced that even in the presence of very long exit sections, a saturated condition in the off-ramp will lead to observable disturbances in the mainline traffic. The same observation was made in cases with an auxiliary right lane also, but with a lesser magnitude.

M. J. Cassidy et al (20) studies the exiting queue of an off-ramp using field data from video-tapes, and find that a bottleneck with a diminished capacity arises on a freeway segment whenever queues from the segment's off-ramp spilled-over and occupied its mandatory exit lane and the lengths of these exit queues are negatively corrected with the discharge flows in the freeways segment's adjacent lanes, i.e., longer exiting queues from over-saturated off-ramp are accompanied with lower discharge rates for the non-exiting vehicles.

To depict the above fact, a simulation study of the MD97@I495 interchange is presented in the remaining of this section. Figure 2 is a sketch of the study size. In the peak hours, the off-ramp volume (off-ramp A) from I495 west bound to MD97 south bound is very high. Long exiting queue and heavy congestion are observed. Currently, the off ramp from I495 west to MD97 (off-ramp A) is controlled by a signal and the other two are controlled by yield signal. Since off-ramp A is an observed bottleneck during peak hour, this study focus on off-ramp A. To evaluate the effect of exiting queue on upstream mainline traffic, the demands from each enter links are fixed and only the exit volume at off-ramp A increase from 1500 vph to 2000 vph.

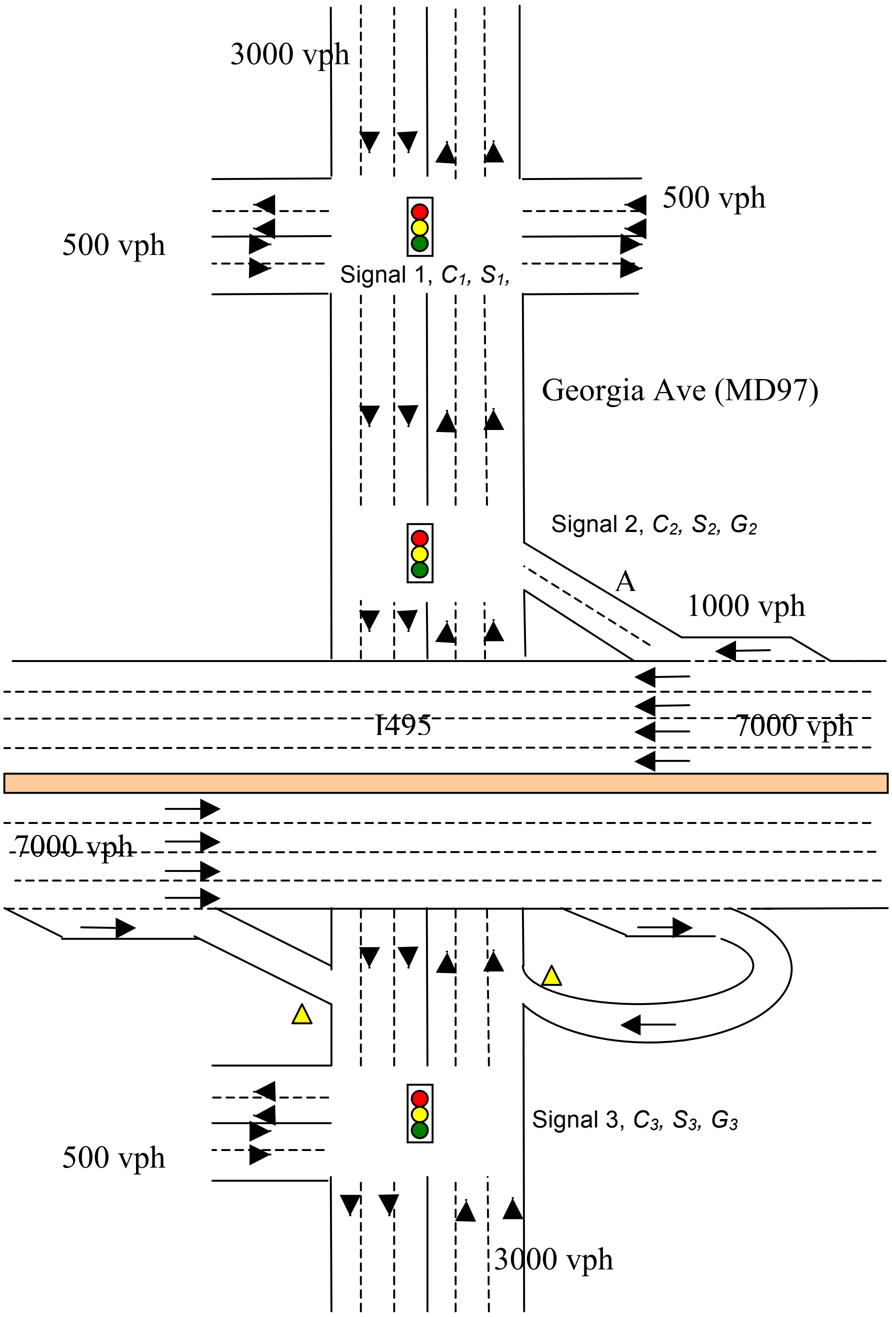

Figure 2 MD97@I495 Interchange Sketch

The simulation results from CORSIM program are listed in Table 1, which indicates that the queue spillback effect on upstream mainline traffic increases dramatically in terms of average delay and average speed when off-ramp volume increases from 1500 vph to 2000 vph. There are two main causes. One is the increment in the lane-change frequency, and the other is the spillback of exiting queue. Hence, in the attempt to minimizing the delay for a corridor control, it is essential to include the off-ramps and the connected surface street intersections in an integrated control system.

The remaining part of this paper is organized as follows. Section 0 will present the details of the model, its formulation and solution algorithm. A case study with results will be described in Section 0 and conclusions are presented in Section 0.

Table 1 The impact of off-ramp queue on its upstream mainline freeway traffic performance

Off Ramp Volume (vph)	Average Delay (Sec/VEH)	Average Speed (Mile/Hr)
2000	96.4	7.3
1800	68.1	9.87
1700	41.7	14.69
1600	9.7	36.05
1500	1.4	57.95

Off ramp control model

Model overview

The following model employs the cell transmission model (1, 2) to capture the traffic propagation and formulate a mixed integer program to find the optimal signal timing for the target control area.

Definition of basic traffic variables

Parameters:

τ *: time step*

d_i^t *:demand of cell i at time interval t*

s: exit cell set

x_i^t *: vehicle number in cell i at time interval t*

y_{ik}^t *: vehicle number moving from cell i to cell k at time interval t*

R_i^t *: receiving capacity of cell i at time interval t*

S_i^t *: sending capacity of cell i at time interval t*

Q_i *: saturation flow rate of cell i*

l: cell length

K: saturation density

$N_i^t = l \times K$ *:holding capacity of cell i*

$\Gamma(i)$ *: downstream cell set of cell i*

: upstream cell set of cell i

MinG: minimum green time

MinC: minimum cycle length

MaxC: maximum cycle length

$$r_{kj}^{i} = \begin{cases} 1, if\ the\ jth\ movement\ of\ signal\ k\ is\ green\ at\ time\ t \\ 0, \quad otherwise \end{cases}$$

L_m *: maximum queue length allowed on link m*

$\psi(m)$ *: cell set of link m*

$Q_{kj,}$*: adjusted saturation flow rate of jth approach of signal k.*

$S_{kj,}$*: sending capacity of jth movement of signal k.*

$X_{kj,}$*: sending capacity of jth movement of signal k.*

$E_{kj,}$*: entering vehicles number of the last cell of signal k approach j*

ratio$_{kj,}$*: turning ratio of jth movement of signal k.*

C_k *: circle length of signal i*

Decision variables:

S_k*: offset of signal k*

$g_{kj,}$*: green time of jth approach of signal k.*

Model formulation

(1)

$$Max \quad \sum_{t=1}^{T} \sum_{s} y_{\Gamma(s),s}^{t} \qquad (2)$$

The purpose of the objective function (1) is to minimize total delay of all the vehicles moving through the control area. Alternatively, this study also proposes a second objective function (2), which maximizes the total throughput during over saturated traffic conditions.

There are two categories of constraints for the above objective function. One represents the traffic propagation on the links, and the other represents traffic dynamics at merge and diverge. Among the link traffic propagation constraints, Equation (3) represents the flow conservation law. Equation (4) is designed to capture the vehicles entering the network. Equation (5) and (6) state that the total number of vehicles entering and exiting a cell during an time interval cannot exceed its entering and sending capacity, which are defined in equation (7) and (8) respectively.

(3)

(4)

(5)

(6)

$$R_i^t = \min\{Q_i^t, N_i^t \mid x_i^t\} \quad (7)$$

$$S_i^t = \min\{Q_i^t, N_i^t\} \quad (8)$$

For signal control, NEMA coding method is employed to describe the split information (see Figure 3). To represent the signal control strategy, at each time step, for movement j of signal k, a binary variable $\mathbf{r}_{kj}^{t}$ is defined to indicate whether or not the corresponding movement is green. Equation (9), (10), (11), (12) intend to make $\mathbf{r}_{kj}^{t}$ equals to 1 for green or 0 for red.

(9)

(10)

(11)

(12)

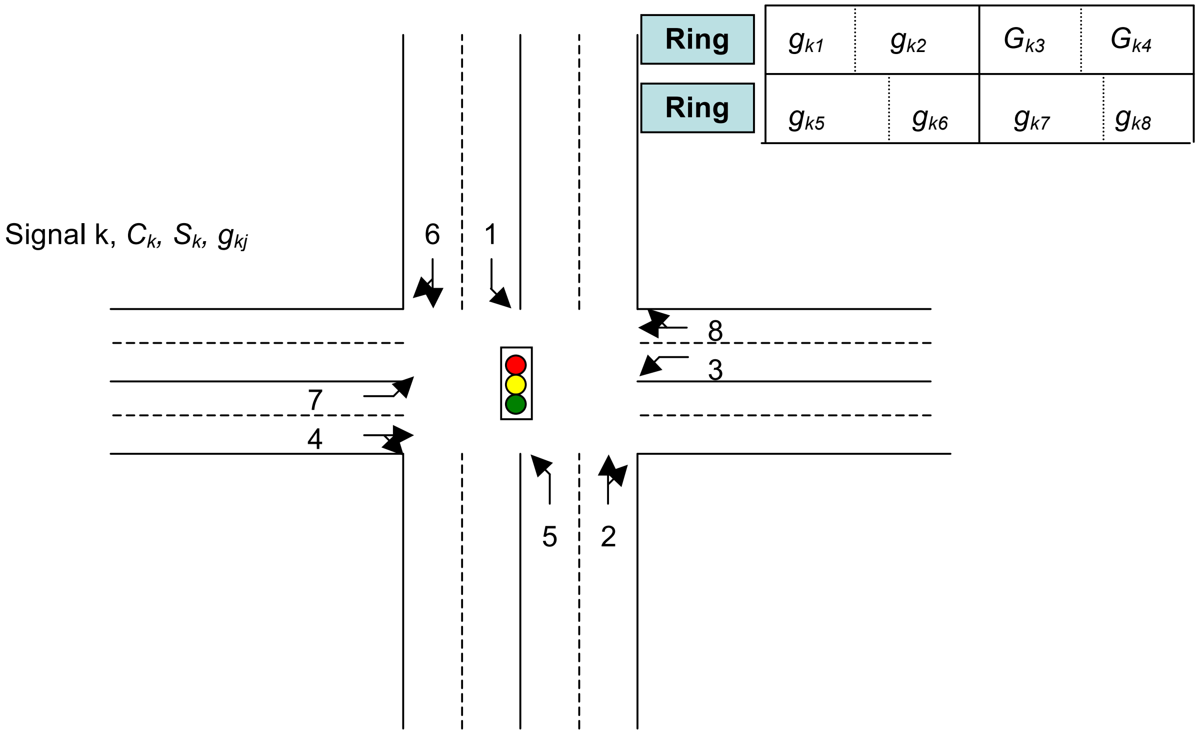

Figure 3 NEMA coding for a signalized intersection

Equation (13), (14) state the existence of barrier, which means that the green time summation of phase 1 and phase 2 should be equal to that of phase 3 and phase 4. By equation (15), only one of the four phases, i.e., phase 1 to phase 4, is allowed to be green.

$$r_{k3}^{t} + r_{k4}^{t} = r_{k7}^{t} + r_{k8}^{t} \qquad (13)$$

$$r_{k1}^{t} + r_{k2}^{t} = r_{k5}^{t} + r_{k6}^{t} \qquad (14)$$

$$r_{k1}^{t} + r_{k2}^{t} + r_{k3}^{t} + r_{k4}^{t} = 1 \qquad (15)$$

Equations (16) , (17) , (18) , (19) , (20) , (21) , (22) translate the split information into the time points in equation (9), (10), (11), (12).

$$G_{k0} = 0 \qquad (16)$$

$$G_{k1} = g_{k1} \qquad (17)$$

$$G_{k2} = g_{k1} + g_{k2} \qquad (18)$$

$$G_{k7} = g_{k1} + g_{k2} + g_{k3} \qquad (19)$$

$$G_{k5} = g_{k5}\ G_{ki} \qquad (20)$$

$$G_{k6} = g_{k5} + g_{k6} \qquad (21)$$

$$G_{k7} = g_{k5} + g_{k6} + g_{k7} \qquad (22)$$

To apply the minimum green time, minimum cycle length and maximum cycle length constraints, constraints (23) and (24) are employed.

$$g_{kj} \geq MinG \tag{23}$$

$$MinC \leq C_j \leq MaxC \tag{24}$$

To avoid spill-over of the exiting queue to the freeway mainline and no spillback to upstream intersection, Equation (25) is presented.

(25)

Solution algorithm

As presented above, the model is a mixed integer program and certainly can be solved by general Integer Program algorithm such as Branch and Bound. But there will be 4 variables per cell each time step and more than 10 variables per intersection per time step. One can expect that the typical Integer Program Algorithm will be very slow. To obtain to an almost optimal solution quickly, the Genetic Algorithm (GA) is employed in this study.

GA has been considered to be more and more promising for solving the real-world problems in the past decades. As a probabilistic search approach, GA is founded on the ideas of evolutionary processes and based on the Darwinian principle of survival of the fittest.

An initial population is created containing a predefined number of individuals, each represented by a genetic string. Each individual has an associated fitness measure. The concept that the fittest (or best) individuals in a population will produce a fitter offspring is then implemented in order to reproduce the next population. Selected individuals are chosen for reproduction (or crossover) at each generation, with an appropriate mutation factor to randomly modify the genes of an individual, in order to develop a new population. The result is another set of individuals based on the original population leading to subsequent populations with better fitness and those with lower fitness will naturally get discarded from the population.

The signal timing settings are the only decision variables in the Off Ramp Integrated Control Model (ORICM). So in this study, a GA individual presents a set of signal timings. The GA solution procedure can be illustrated as follows: The first population is generated randomly and each individual is decoded to a set of signal plan. Then Cell Transmission Procedure will compute the performance indices of one hour. The corresponding fitness measure can be obtained from these performance indices. Based on the fitness evaluation, the crossover and mutation procedure are processed. This procedure will continue until the stop criterion is satisfied.

To accommodate the traffic signal optimization constrains, a fraction-based decoding scheme (21) is employed based on the NEMA phase's structure as shown in Figure 4.

$$C_j = MinC + (MaxC - MinC) \times \lambda_{j1}$$

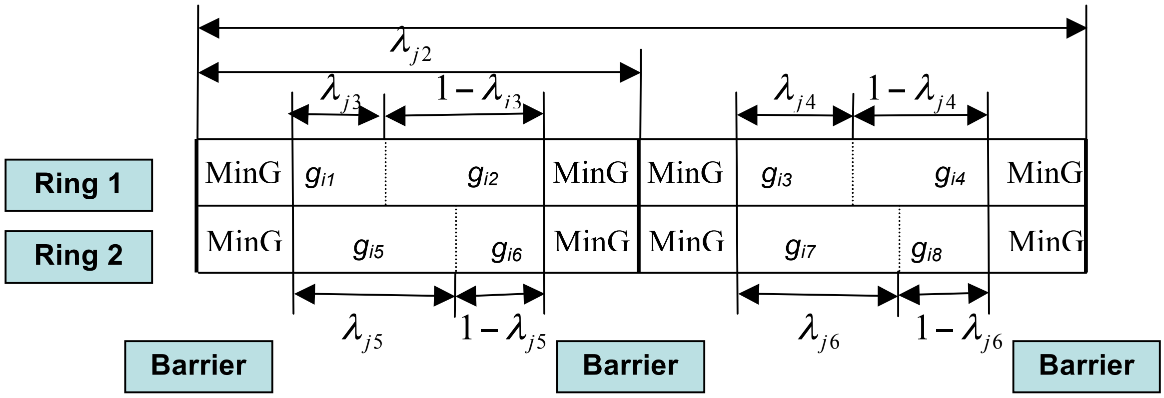

Figure 4 signal fraction-based decoding scheme

As illustrated in Figure 4, six fractions are needed to describe the cycle length and split, and an additional one for offset. So, totally 7 fractions are needed for a four-leg NEMA coding signal scheme. Once the 7 fractions are generated, a signal plan can be decoded easily.

After the signal plans are generated, they are input into the cell transmission procedure to compute the maximum queue length, total throughput and total delay, which are used to evaluate the fitness of each signal plan.

Case study

In this study, the I495@MD97 (see Figure 2) interchange is employed to test the performance of the proposed model. The signal plan from the proposed model is compared with TRANSYT-7F release 9, which is commonly used in signal timing studies.

To compare the results, a microscopic simulation, CORSIM, is employed as performance index provider. For off-ramp volume from 600 vph to 2000 vph, timing plans from TRANSYT-7F and the proposed Off-Ramp Integrated Control Model (ORICM) are input into CORSIM simulation and the simulation results comparison of one hour are listed below.

Table 2 Network Total Delay* Comparison (Vehicle Hour)

Off Ramp Volume (vph)	*Transyt 7F*	*ORIC**	*Transyt 7F - ORIC*	*[Transyt 7F - ORIC]/Transyt 7F*	*95% confidence interval*
600	147.37	146.74	0.63	0.43%	[-3.20, 4.46]
700	149.04	149	0.04	0.03%	[-3.77, 3.85]
800	149.39	151.2	-1.81	-1.21%	[-5.42, 1.80]
900	152.81	154.21	-1.4	-0.92%	[-5.00, 2.20]
1000	160.45	156.85	3.6	2.24%	[-0.34, 7.54]
1100	174.55	162.11	12.44	7.13%	[8.38, 16.50]

1200	211.66	175.77	35.89	16.96%	[30.31, 41.47]
1300	253.14	192.21	60.93	24.07%	[54.93, 66.93]
1400	298.48	231.86	66.62	22.32%	[59.68, 73.56]
1500	349.53	278.83	70.7	20.23%	[60.85, 80.55]
1600	424.54	351.25	73.29	17.26%	[59.75, 86.83]
1700	485.27	453.05	32.22	6.64%	[17.78, 46.66]
1800	566.29	552.19	14.1	2.49%	[-0.72, 28.92]
1900	631.58	653.77	-22.19	-3.51%	[-37.97, -6.41]
2000	705.54	758.86	-53.32	-7.56%	[-72.81, -33.83]

*Network total delay: freeway and surface streets

*ORIC: Off-Ramp Integrated Control

The total delay of the entire network is listed in Table 2 and Figure 5. These delays are the mean value based on 100 simulation runs. As the sample size is large than 30, the large sample theory is applicable here. And the 95% confidence intervals are computed based on large sample theory.

From the above results, one can fairly confidently conclude that for off-ramp volume range from 1100 vph to 1700 vph, the proposed model performs better that the TRANSYT-7F in terms of lower delay. To provide a close look of what occurs, the total delay of freeway and surface streets are presented in **Error! Reference source not found.**, **Error! Reference source not found.** respectively and are also illustrated in **Error! Reference source not found.**, **Error! Reference source not found.**.

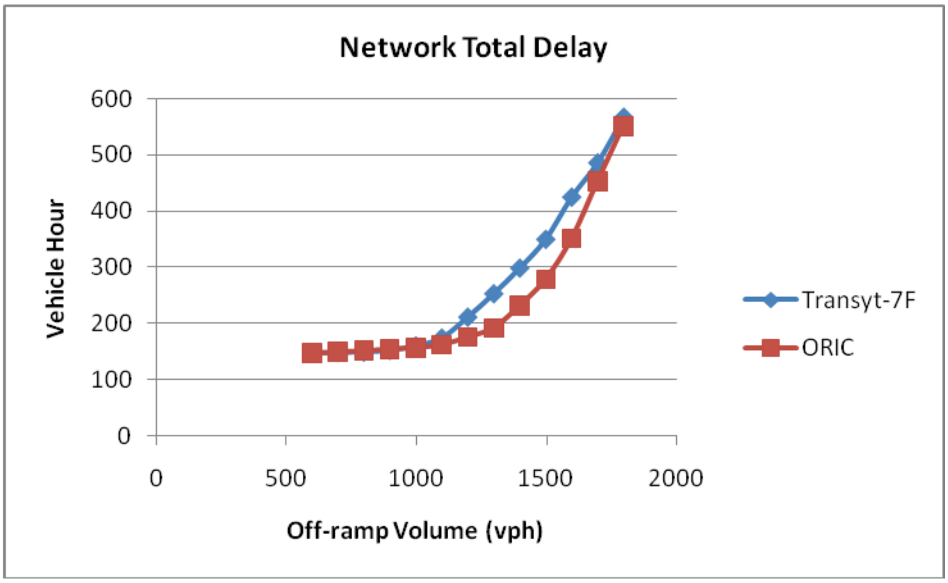

Figure 5 Network Total delay comparison

Conclusions

In this study, a mixed integer version of Integrated Off-Ramp Control Model and the GA based solution algorithm are proposed. To demonstrate the advantage of this proposed model, the MD97@I495 interchange is employed as a numerical case study site. The resulting signal plans are compared with those from TRANSYT-7F by CORSIM simulations. A detailed comparison shows that the proposed model outperforms TRANSYT-7F model in terms of total delay and average delay over a reasonable range of off ramp volume.

Further research along this line is to take into account the inevitable queue spillback on the freeway if both the off-ramp and arterial volume have caused oversaturated conditions at surface street interactions. The control objective function should then consider the trade-off between freeway speed reduction and traffic delay at local intersections. A reliable traffic flow model to capture the intersection between freeway mainline and ramp flows as well as its resulting impacts will certainly be essential for such an integrated control.

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