Work Zone Analysis Model for the Signalized Arterial

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The purpose of this paper is to illustrate new theoretical concepts used to represent traffic flow in work zones. The paper presents the development and applications of a microcomputer program—Work Zone Analysis Tool for the Arterial (WZATA)—for the analysis and evaluation of a system consisting of a lane closure between two signalized intersections. The program consists of two parts: a semi-simulation model to represent and analyze flow between the intersections, and a macroscopic model to represent traffic characteristics at the downstream intersection. New techniques were developed to represent percentage merges and vehicle merge characteristics before the lane closure. The user was provided direct control over the merging of every vehicle. A modified version of the continuum-flow theory was utilized to represent and analyze traffic flow at the downstream intersection. Flow was considered to be composed of two parts: the platoon flow and the non-platoon flow. The techniques of analysis used also considered acceleration, deceleration, and start/stop losses. The program is written in Microsoft BASIC for the IBM-PC/XT/AT and is structured to facilitate easy modification of data as well as analysis of various hypothetical situations. Attempts are being made to include graphical display facilities in the model.

Work zone management constitutes the most common management and maintenance task of any transportation system. Many streets require regular repair or upgrading. Construction and maintenance activities performed often require the closure of at least one lane to traffic. The decrease in the number of lanes usually manifests itself in an increase in traffic congestion and consequent reduction of the level of service. An effort should therefore be made to schedule work zone activities and modify signal characteristics to reduce delay and congestion to the minimum.

A considerable number of analytical and computer techniques and models are available to maintenance personnel to aid in decision making and scheduling of work zone lane closures on the arterial. The drawback to almost all these techniques is that, in the final analysis, an arterial is divided into several segments and each is analyzed individually—with no relation to the other. For example, in a typical analysis of a work zone in an arterial, the arterial is divided into three sections:

1. The intersection;
2. The strip between the intersections, but not including the lane closure; and
3. The work zone, including the lane closure.

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Each section was analyzed individually for the different scenarios, and the final decision was based on a logical combination of the results of all three analyses. To date, while several comprehensive computer programs (such as QUEWZ(*1*) and FREECON(*2*)) have been developed to analyze work zones on freeways, no model has been developed to analyze the arterial system with the work zone as an overall comprehensive unit.

This paper culminates the development of a macroscopic semi-simulation model to analyze the work zone in an arterial system as an overall comprehensive unit.

MODEL DEVELOPMENT

A review of the literature on work zones revealed that a completely macroscopic model would be too approximate to represent conditions of traffic flow in an arterial with a work zone, since the phenomena of merging and diverging before and after lane closure is complex and involves several interrelated parameters. It was therefore decided to develop the model in two parts: a semi-simulation model to represent flow between the intersections and through the lane closure zone, and a macroscopic model to represent traffic characteristics at the downstream intersection. Illustration of a few fundamental theoretical aspects of the developed model follow. A detailed explanation of all aspects of the model can be found elsewhere(*3*).

SEMI-SIMULATION MODEL

A technique utilizing a concept of "real" and "imaginary" vehicles was used to simplify the simulation model to a considerable extent.

Real Vehicles

These vehicles represent actual vehicles in the open lane that follow each other according to the car-following rules. All parameters like delay, travel time, and bandwidth are estimated for these vehicles alone.

Imaginary Vehicles

These vehicles, on the other hand, are not actual vehicles but pseudo vehicles introduced to simulate merging and diverging behavior before and after the lane closure. They could be considered as vehicles originally traveling in the lane about to be closed. Outside the proximity of the lane closure, they have the same characteristics as their real counterparts in the open lane. Within the proximity of the lane closure, however, their characteristics are manipulated to represent the additional headway required by the real vehicles to accommodate the merging of vehicles from the closed lane. Delay and other parameters of interest are not estimated for these vehicles.

The basic assumptions made in the semi-simulation model are as follows:

1. Initial headway of vehicles is assumed to be directly proportional to initial velocity. All vehicles beginning from the upstream intersection have the same initial velocity and therefore the same headway.
2. Vehicles are distributed equally and have similar characteristics in all lanes.
3. Passenger cars constitute 100% of the traffic.
4. When vehicles merge from the closed lane, they merge at equal intervals in such a way that the traffic volume and characteristics upstream from the lane closure are similar in both lanes at all times.
5. All vehicles merging from the closed lanes distribute themselves equally to all open lanes.
6. Only vehicles in the platoon are assumed to experience any sort of delay in travel between the intersections. Non-platoon vehicles are assumed to be able to travel at their desirable speed and hence experience no travel delay.

All the above assumptions were made in an attempt to reduce the complexity of the simulation model without introducing major errors in the estimation of traffic flow characteristics and calculated parameters. Assumption 1 is realistic in an arterial setting that is part of a network, since signals tend to group vehicles together and attribute similar characteristics to them. Assumption 3 is also appropriate in an arterial, since it is well known that traffic in an arterial, in general, constitutes a very low percentage of trucks. Assumptions 4 and 5 are directly related to the default values assumed by the model during execution. Options are provided to alter conditions to analyze situations when some of the assumptions are not valid.

CAR-FOLLOWING RULES USED IN SEMI-SIMULATION MODEL

The basic philosophy adopted for the car-following rules is to provide the following driver enough gap between vehicles so that the status of his vehicle can be brought to that of his leader, without ever reducing the gap between the vehicles to less than a minimum.

Two conditions, those of steady and varying flow, were considered in the development of this model. During steady flow (no acceleration or deceleration of vehicles), vehicles travel behind each other at a distance equal to the product of the reaction time times the velocity plus a minimum headway (headway at zero velocity) between vehicles.

Mathematically:

$$HW = V*C + HW_{min}$$

where:

HW = the distance headway between vehicles,
V = velocity of the vehicle of interest,
C = car-following constant, and
HW_{min} = minimum acceptable headway between vehicles

Under varying flow conditions (acceleration/deceleration of vehicles), different cases are considered based on the relationship between the velocities of the leading and the following vehicles. A more detailed explanation of the car-following rules is provided elsewhere (*3*).

MODEL REPRESENTATION OF TRAFFIC CHARACTERISTICS IN CLOSED AND OPEN LANES

To make the simulation of vehicles less complex, the arterial system (including the work zone) was simplified in a two-stage process.

In stage 1, all arterial segments, with both the total number of lanes and the number of lanes closed having a common divisor, are divided until further "irreducible". For example, a $4-2$ configuration would be reduced to a $2-1$ configuration.

In stage 2, vehicles from the open and closed lanes are combined in one lane and configured to represent a symmetrical and uniform merge situation (default) of vehicles in a single lane at the lane closure.

The two-stage process is illustrated in Table 1. As mentioned earlier, the concept of "real" and "imaginary" vehicles is used to represent vehicles that were initially (before the work zone) in the open or closed lane, respectively. After the default configuration is estimated by the model, the user is provided an option to modify it if necessary.

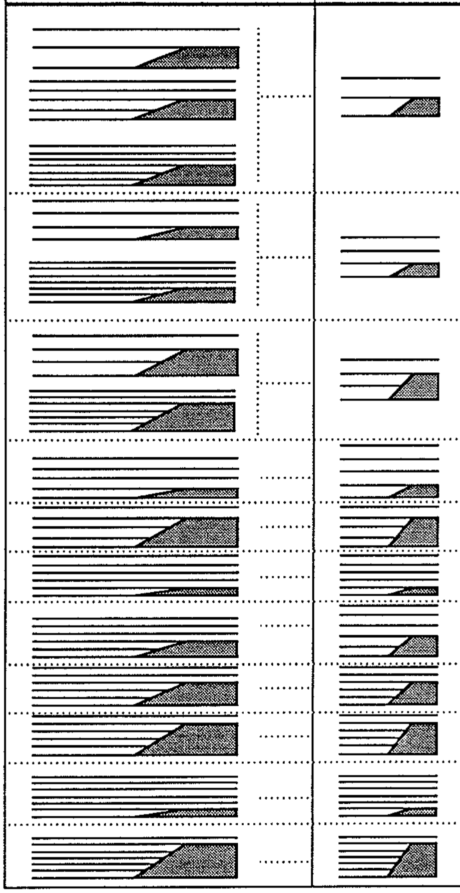
The entire length of roadway between the intersections is divided into five zones, each representing sites of different flow characteristics.

Zone 1 represents the length of roadway before the work zone where there is no modification of flow characteristics directly due to the existence of a lane closure ahead. Characteristics of the imaginary vehicles are exactly the same as those of their counterpart real vehicles in the open lane.

Zone 2 represents that part of the roadway where the driver is directly influenced by the work zone ahead, but not yet alongside, the actual lane closure. A logical beginning of this zone could be either the distance at which the warning sign is visible, the distance at which the lane closure itself is visible, or the distance at which the drivers are expected to react to the effect of the work zone ahead. Characteristics of the imaginary vehicles in this zone begin to differ from their counterpart real vehicles in the open lane. This is to slowly introduce additional headway between the real vehicles to accommodate prospective mergers.

Zone 3 is the zone actually constituting the lane closure alone. The configuration referred to in the previous section and displayed in column 3 (model default) of Table 1 represents actual vehicle positions of merged (imaginary) and real vehicles in this zone, as depicted by this model. Imaginary vehicles begin to follow real vehicles in the open lane according to the normal car-following rules. This is the only zone

TABLE 1 ILLUSTRATION OF THE TWO STAGE SIMPLIFICATION PROCESS OF A ROAD SEGMENT WITH THE WORK ZONE



WORK ZONE CONFIGURATION	MODIFIED	MODEL DEFAULT
		RIRIRIRIRIRIR
		RRIRRIRRIRRI
		RIIRIIRIIRIIRI
		RRRIRRRIRRRI
		RIIIRIIIRIIIRII
		RRRRIRRRRIRR
		RRIRIRRIRIRRI
		RIIRIRIIRIRIIRI
		RIIIIRIIIIRIIIIR
		RRRRRIRRRRRI
		RIIIIIRIIIIIRIII

in which the imaginary vehicles behave exactly like the real vehicles in terms of following vehicles in front of them.

Zone 4 is the zone beginning at the end of the lane closure and extending to a location where all the merged vehicles are assumed to have diverged back into their original respective lanes. This location is user-defined; and if selected judiciously with the "diverge constant" (explained later), it could represent any "diverge" behavior after the lane closure. Behavior of imaginary vehicles in this zone is similar to that in zone 2.

Zone 5 is the "normal" zone where vehicles are no longer influenced by the work zone behind them. Behavior of imaginary vehicles in this zone is similar to that in zone 1.

TRAFFIC CHARACTERISTICS AT THE FIVE ZONES

The configurations discussed previously in their unmodified form (column 3, Table 1) are a representation of all merged (imaginary) and already existing (real) vehicles in the open lane of the lane closure (zone 3). All vehicles follow the one in front, whether real or imaginary, according to the normal car-following rules in this zone. Differences in characteristics of traffic flow as existing in each of the other four zones are illustrated below.

Zones 1 and 5 represent locations with no direct effect of the conditions in the work zone. Hence, no merging operations should take place; and the configuration would represent just the real vehicles following each other, and not an imaginary vehicle that may exist between them. This modification is accomplished by assigning to all the imaginary vehicles that follow the real vehicle in this zone the same velocity and distance as that of the closest real vehicle ahead. A configuration like RIRIRIRIRIRI, as represented in Table 1, would therefore be equivalent to an RRRRRR configuration in zones 1 and 5 (Figure 1a).

Zones 2 and 4 represent zones where the effect of the work zone is being sensed, resulting in a general reaction reflected in terms of the merging or diverging of vehicles. To represent this behavior, a two-step manipulation of the parameters of the original configuration is undertaken, as follows:

Step 1: The imaginary vehicles are first attributed velocities equal to the real vehicle ahead and closest to them. Headway is then calculated using steady flow analysis.

Step 2: The ratio of the distance traveled by the real vehicle involved, from the beginning of the concerned zone to the total zone length, is then estimated. The headway as calculated in step 1 is then multiplied by this term, raised to some power (user-defined). The resulting term is again multiplied by the total number of vehicles between the imaginary vehicle concerned (including itself) and the closest real vehicle ahead of it.

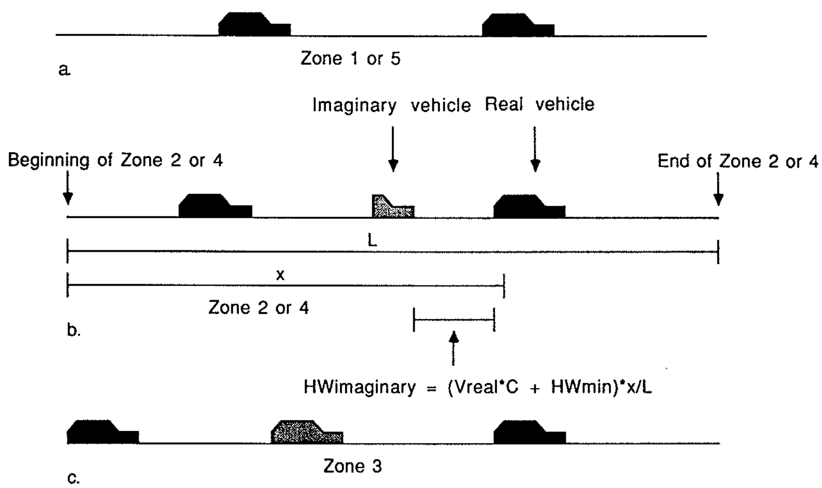


FIGURE 1 Illustration of traffic characteristics in the different zones.

Mathematically, the resulting term for Zone 2 is

$$HW_{\text{imaginary}} = (V_{\text{real}}*C + HW_{\text{min}})*rm*n$$

For Zone 4,

$$HW_{\text{imaginary}} = (V_{\text{real}}*C + HW_{\text{min}})*(1 - rl)*n$$

where

- r = the ratio as explained above,
- n = number of vehicles between itself and the real vehicle closest and ahead of it (including itself),
- m and l = coefficients > 0 and $< \alpha$ that represent merging and diverging behavior of vehicles.

Physically, r varies from 0 (when the real vehicle is at the beginning of the concerned zone) to 1 (when at the end of it).

To illustrate the principle, let a real vehicle be at a distance x from the beginning of the zone 2, which has a total length L. The ratio r, using the above definition, is x/L. The first imaginary vehicle behind the real vehicle will be placed at a distance:

$$HW_{\text{imaginary}} = (V_{\text{real}}*C + HW_{\text{min}})*(x/L)^{m}*1$$

Assuming $m = 1$, (input by the user), the final expression is:

$$HW_{\text{imaginary}} = (V_{\text{real}}*C + HW_{\text{min}})*x/L \quad \text{(Figure 1b)}$$

REPRESENTATION OF DIFFERENT "MERGE LOCATION CONFIGURATIONS"

In the above illustration, m is considered to be equal to 1. The resulting term increases linearly with increase in x. Therefore, it could be perceived that, for example, at a location midway in zone 2 (between the work zone warning and the lane closure), only "half a vehicle" has merged into the open lane. This is the case for all the vehicles in the closed lane. Another way of perceiving the situation is to assume only half the total number of vehicles have managed to merge completely, while the other half are still in the closed lane at that location. Thus, the merging phenomena can be assumed to be occurring uniformly all along the zone, between the lane closure warning and the lane closure. Different merging characteristics, including early and late merging, can be represented by manipulating the value of m (Figure 2).

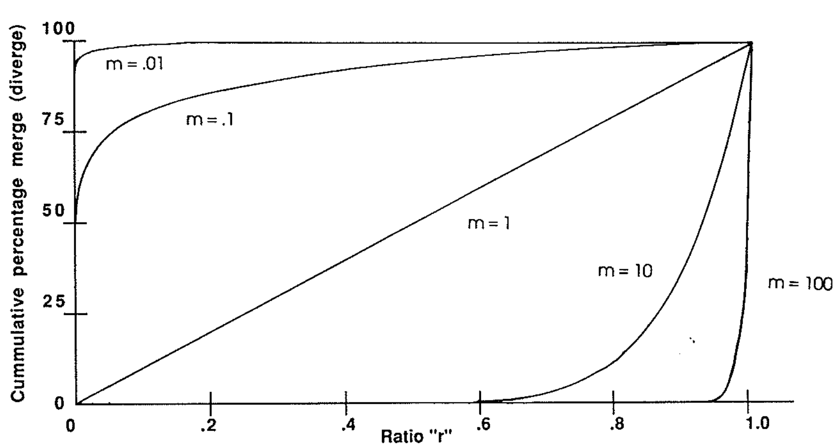


FIGURE 2 Relationship between ratio r, and the cumulative percentage of vehicles that have merged (or diverged) from the closed (open) lane.

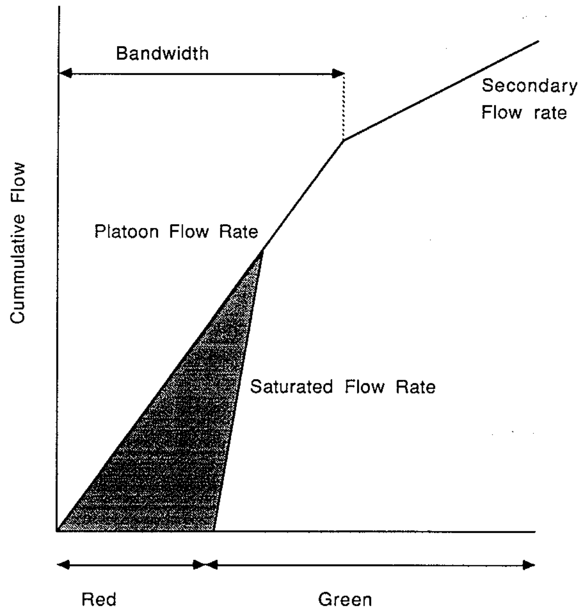


FIGURE 3 Modified continuum model to introduce two flow rates.

INTERSECTION DELAY MACROSCOPIC MODEL

The conventional continuum model was modified and a new model was developed to more realistically represent the characteristics of platoon flow. The fundamental concept of this model was borrowed from an idea originally developed by Rouphail (*4*). Instead of assuming a single average flow rate (as in uniform flow), two different flow rates were considered, one representing the average platoon flow rate and the other representing the secondary flow rate.

ESTIMATION OF INTERSECTION DELAY AND RELATED PARAMETERS

The macroscopic model uses a continuum model as depicted in Figure 3. Configurations like the one depicted in the figure can be defined by relationships between three attributes: signal (green time and cycle time), bandwidth, and offsets. It is not possible to establish a general formula to calculate the delay and other related parameters. The model is therefore split into several sub-models, and distinct formulas are derived for each of these sub-models. All parameters obtained from the semi-simulation model either serve as direct input or are used to estimate parameters required for input to the macroscopic model at the intersection. Formulas are also derived to actually introduce losses due to the reaction time and acceleration of vehicles after the start of the green. Detailed illustration of the formulas and method of estimation of parameters can be found elsewhere (*2, 3*).

INPUT REQUIREMENTS AND MODEL APPLICATIONS

The input requirements for execution of the program are divided into five sections. They are listed below with respect to a typical arterial system with a work zone (Figure 4).

1. Traffic Characteristics:
   a. Initial velocity = 20 mph.
   b. Desired velocity = 45.
   c. Desired velocity in the work zone = 45.
   d. Maximum allowable acceleration = 7 ft/sec^2. This parameter is only used with respect to the first vehicle, to develop its velocity profile.
   e. Maximum allowable deceleration = 21. This param-

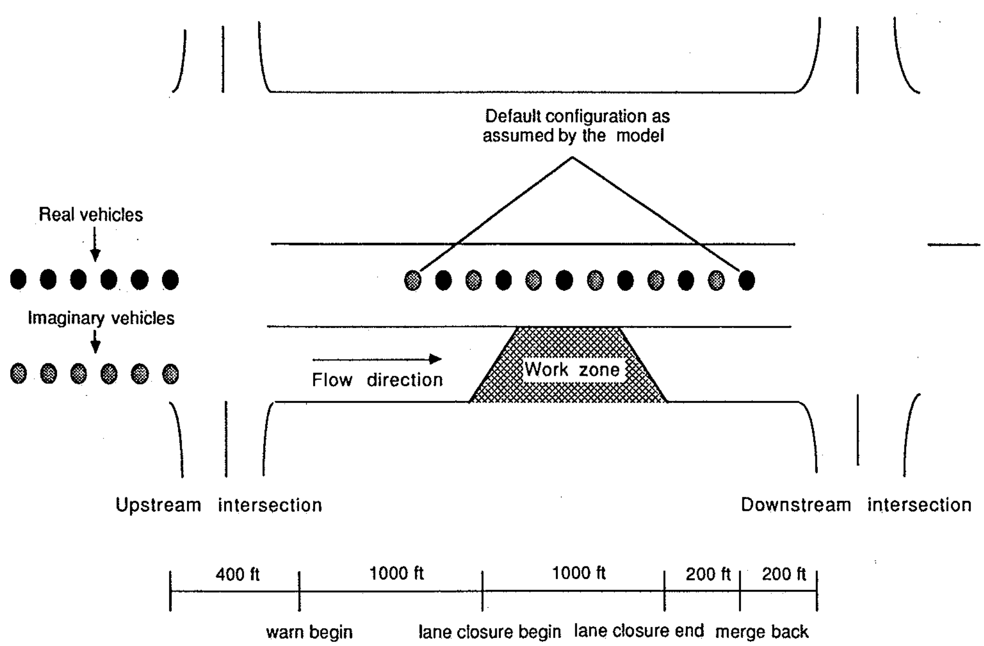


FIGURE 4 Typical arterial with a work zone.

eter is used with respect to all vehicles and is related to basic vehicle characteristics.

f. Minimum headway = 16 ft. This parameter represents an allowable distance between the front or back end of two average vehicles, when stationary.

2. Intersection/Work Zone Characteristics:
   a. Lane closure warning location = 400 ft. This parameter defines a location with respect to the upstream intersection, from which point the vehicles are directly aware of the lane closure ahead. It should be selected with caution. The program considers this location as the beginning point of zone 2, where all merges originate.
   b. Lane closure "begin" location = 1400. This parameter represents the location, with respect to the upstream intersection, of the beginning of the lane closure (zone 3).
   c. Lane closure "end" location = 2400. This parameter represents the location of the end of the lane closure with respect to the upstream intersection (beginning of zone 4).
   d. Post-lane closure merge-back completion location = 2600. This parameter represents the location, downstream of the lane closure, at the end of which all vehicles that had merged are assumed to have merged back into their respective lanes. This parameter can be manipulated to represent different merging behavior.
   e. Total number of lanes = 2.
   f. Number of closed lanes = 1.
   g. Downstream intersection location = 2800.
   h. Average grade = 0.
3. Signal Characteristics:
   a. Cycle time = 60 sec.
   b. Green time = 30.
4. Platoon Characteristics:
   a. Saturation flow rate = 2000 veh/hr/lane (at the downstream intersection).
   b. Secondary flow rate = 200 (non-platoon flow rate at the downstream intersection).
   c. Number of vehicles per lane = 6 (in the platoon).
5. Options:
   a. *C* value outside the work zone = 1.45. This parameter represents a constant for car following [discussed in detail elsewhere (*3*)].
   b. *C* value in the work zone = 1.45. This parameter is used instead of the above only in the work zone. Caution should be used when selecting this parameter, since it would differ from the value used outside the work zone only for specific situations [discussed in detail elsewhere (*3*)].
   c. Constant for merging behavior = 1. This parameter is responsible for the merging behavior before the lane closure. All positive values are acceptable. (See Figure 2.)
   d. Constant for diverging behavior = 1. This parameter represents diverging or merging back of the "imaginary" vehicles into the original lanes, and operates similar to the parameter discussed above.
   e. Time step for simulation = 1 sec.
   f. Listing of simulation process = *N*.
   g. Optimize offsets = *Y*
   h. Listing of the optimization process = *N*.
   i. Direct run = *N*.

The program has an option of directly estimating intersection delay without going through the simulation process.

The results of a run with the above data are tabulated in column 1 of Table 2.

SPECIAL APPLICATIONS

Analysis of Flow Without Work Zone

Analysis of flow without the presence of a lane closure between the intersections can be conducted by placing all four parameters that define the work zone before the upstream intersection or after the downstream intersection. Since the upstream intersection is located at the reference point for all other distances (zero distance), attributing negative values to all the parameters that define the work zone would place it before this intersection.

TABLE 2 ILLUSTRATION OF MODEL OUTPUT FROM THE ANALYSIS OF DIFFERENT SCENARIOS AT THE SAME WORK ZONE

Configuration	RIRIRIRIRIRI	RRRRRR	RRRRIIIRRIII	IIIIRRRIIRRR
Work zone present	Y	N	Y	Y
Platoon Flow Rate (veh/hr)	1731	2886	1990	1667
Delay Between Intersections (secs)	5.87	1.64	3.33	8.40
Delay at Intersection (sec)	5.64	5.96	5.80	5.50
Total Delay (sec)	11.51	7.59	9.13	13.90
Travel Time of Bandwidth(sec)	44.12	44.12	44.12	44.12
Bandwidth length (sec)	16.15	7.69	12.77	17.91
Optimized Offset Range (sec)	34.8 40.1	26.1 40.1	31.5 40.1	36.1 40.1
Total Length of Queue (cars)	0 *	0 *	0 *	0 *
Longest Time in Queue (sec)	0 *	0 *	0 *	0 *
Queue Dissipation Time (sec)	7.78	7.78	7.78	7.78

* Only with respect to the platoons (zero because offset considered is optimized)

Four input parameters were modified in the above example to analyze conditions without the lane closure:

1. Lane closure warning location (ft) −2400,
2. Lane closure "begin" location −1400,
3. Lane closure "end" location −400, and
4. Post-lane closure merge completion location −200.

The results obtained after running the program are tabulated in column 2 of Table 2.

Analysis of Asymmetrical Flow

The model can be used to analyze a situation with asymmetrical or non-uniform merging, or that of traffic flow that displays distinct differences in characteristics in both lanes. To illustrate the procedure, consider the work zone described in the previous section. (See Figure 4.) For the sake of simplicity, assume that the number of vehicles in both lanes is equal and that only the merge configuration is asymmetrical. The first two cases illustrate flow when the vehicles are merging uniformly in such a way that flow characteristics upstream of the intersection are always symmetrical in both lanes, *i.e.*, if *R* represents vehicles in the open lane and *I* represents vehicles in the closed lane, then the configuration of vehicles in the open lane at the lane closure appears as follows:

R I R I R I R I R I R I

← (traffic direction)

This is the default condition assumed by the model. However, if this is not the case, the user can alter the configuration. Assume that the configuration at the lane closure after the merge is as follows:

R R R R I I I R R I I I

(traffic conditions not conducive to uniform merging of closed vehicles)

The results obtained when the program is run for this configuration are listed in column 3 of Table 2.

It is obvious that, for the above configuration, there would be asymmetrical flow characteristics just upstream of the intersection. The vehicles merging from the closed lane would certainly experience a greater delay than the vehicles that were already in the open lane. Since the model is only capable of representing the average delay of all the vehicles in the open lane (*R*), the aforementioned delay is only with respect to the vehicles in the open lane (the "real" vehicles). To estimate the average delay for the vehicles in the closed lane, the model is "tricked" by running it again—this time, with all the designations of the vehicles interchanged (easily done using the mirror command on the original configuration of the same data set). The new configuration is as follows:

I I I I R R R I I R R R

The results obtained after the run with this configuration are tabulated in column 4 of Table 2 and represent the average delay of vehicles in the closed lane.

In some cases, it may not be possible for vehicles both to be merged according to the configuration specified and, at the same time, to satisfy the car-following rules. Such a situation is flagged as a "crash" between vehicles, and the program is terminated. The user should then adjust the configuration to one that is more likely under the circumstances.

SUMMARY AND CONCLUSIONS

The model developed was found to be a very flexible tool; and when calibrated accurately, it can be used as an effective tool to analyze almost any situation of a work zone in an arterial. Analysis of work zones with asymmetrical flows in lanes or with no work zone at all can also be conducted using simple manipulative procedures in running the program. Work is at present being conducted to implement graphical facilities into the model. Preliminary validation of the model indicated general agreement with the commonly witnessed traffic behavior in work zones.

Model Advantages

Several advantages of the model developed are apparent from the initial runs and validation, as follows:

1. Since vehicle travel is actually simulated between the two intersections, direct effects of various parameters—like distance of the warning to the lane closure, location of the lane closure in between the intersections, length of the lane closure, initial speed of vehicles, flow rate at the lane closure, characteristics of the merging phenomena, and offsets between intersections on delay, among others—can be studied.
2. The user has complete control of vehicle merging. He or she actually inputs the likely configuration of vehicles at the single open lane of the lane closure.
3. Unlike conventional simulation models, where merges are based on the philosophy of gap acceptance, this model actually "forces" gaps between vehicles in the open lane for vehicles in the closed lane to complete their merge procedures. This is based on the generally observed fact that, in arterials, where the speeds are not as high as on freeways, merges commonly occur for two reasons: (a) Vehicles from the closed lane "force" themselves into the open lane, assuming that the following driver would automatically reduce his/her speed and adjust the headway to accommodate the merging vehicle; and (b) drivers in the open lane reduce their speed prior to the actual merge phenomena, thereby providing acceptable gaps for drivers from the closed lane to complete their merge.
4. The user has complete control over the merging locations of the vehicles. By altering a single parameter in the input data, a whole new vehicle merge location configuration can be represented.
5. The macroscopic model is accurate in principle since it is developed along the lines of continuum models, which are based directly on first principles. Additional accuracy is obtained by representing flow at the intersection as a composite of two flows and rather than, as in conventional continuum models, one.
6. The model provides an option to analyze the system for an unlimited set of offsets. Since there is no relation between the offset and the travel time delay between the intersections,

only the macroscopic section of the program is to be executed to test for different offsets. The analysis of different offsets is therefore rapid and simple. The model also provides an option to estimate the offset range wherein the delay at the intersection is the least (optimized offset).

7. Special techniques are used to include the deceleration, acceleration, and start losses in the overall estimation of delay at the intersection. Thus, a major disadvantage of conventional continuum models is removed.

8. The model is completely menu-driven and the user has total control over the manipulation of parameters and the execution of the program at all times. Further, there are the advantages associated with microcomputer programs over the main-frame counterparts.

Model Shortcomings

The shortcomings associated with the model in general are listed below.

1. All vehicles are initiated at a constant uniform velocity and a constant headway. No initial distributions of either headway or velocities can be analyzed.
2. No merging phenomena are allowed to occur anywhere outside either the lane closure warning distance or the post-lane closure merge distance.
3. The whole phenomenon of merge initiation is user-dependent and not model-generated. Thus, the user should obtain some prior information on the flow characteristics in the system. When more information and data are available in this respect, it could be possible to perceive patterns and form regression equations; these regression equations might then be directly implemented in the model.
4. Delay between the intersection is not estimated for non-platoon flows. All vehicles constituting the "non-platoon" are considered to travel through the work zone without any delay. Delay at the intersection is, however, estimated for both platoon and non-platoon flow.
5. The macroscopic model is only capable of analyzing pretimed signal control systems.
6. The macroscopic model is only capable of analyzing symmetrical flows at intersections. If flow as estimated by the simulation of vehicles before the intersection is asymmetrical, then an average flow is estimated and considered for further analysis.
7. The macroscopic model is not capable of analyzing oversaturated conditions, because the delays associated with oversaturated conditions are never constant and increase with the cycle length.

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Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.