into the estimation process.

5. A process of contingency table analysis that incorporates vehicle exposure is desirable to allow more detailed investigation of the impact of exposure on important interactions among accident variables and thus on accident causation.

6. A process of contingency table analysis that incorporates the economic costs of accidents more directly than it was possible to do in this study should also be developed.

ACKNOWLEDGMENT

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REFERENCES

1. L. L. Philipson, P. Rashti, and G. A. Fleischer; University of Southern California. Statistical Analyses of Commercial Vehicle Accident Factors: Volume 1—Technical Report. National Highway Traffic Safety Administration, U.S. Department of Transportation, Rept. DOT HS-803-418, Feb. 1978. NTIS: PB 284 436/3SL.
2. G. A. Fleischer and L. L. Philipson; University of Southern California. Statistical Analyses of Commercial Vehicle Accident Factors: Volume 2—Summary Report. National Highway Traffic Safety Administration, U.S. Department of Transportation, Rept. DOT-HS-803-419, March 1978. NTIS: PB 284 437/1SL.
3. J. D. Thorpe. Calculating Relative Involvement Rates in Accidents Without Determining Exposure. Traffic Research Review, Vol. 11, 1967, p. 308.
4. F. A. Haight. Induced Exposure. Accident Analysis and Prevention, Vol. 5, No. 2, June 1973.
5. R. E. Scott and others; University of Michigan. Statistical Analysis of Truck Accident Involvements. National Highway Traffic Safety Administration, U.S. Department of Transportation, Dec. 1971.
6. J. Hedlund. The Severity of Large Truck Accidents. National Highway Traffic Safety Administration, U.S. Department of Transportation, Tech. Note DOT HS-802322, April 1977.

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Analysis of Bicycle Delays at Intersections and Crossings by Computer Simulation

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Computer simulation models were developed to analyze the delay to bicycles and motor vehicles at crossings and intersections where the two types of vehicles interact. The objective was to generate some understanding of the level of delay to each type of vehicle under various methods of traffic control and combinations of traffic conditions. Observational experiments on bicycle traffic behavior and interactions between bicycles and motor vehicles were carried out in the field, and the models were structured based on these data. The basic elements and assumptions of the simulation models are presented, and the behavior of bicyclists observed in traffic in the field is reported. Results of the simulation of traffic delays to bicycles and motor vehicles under various traffic conditions and controls are discussed in relation to traffic control strategies.

In areas where there is relatively heavy use of bicycles as a mode of transportation, it is often difficult to develop traffic control plans that will satisfy both bicyclists and motorists. The problem lies in trading off the time and safety of the bicyclist for the convenience, fuel economy, and time of the motorist.

In the city of Davis, California, a situation in which a bicycle path crossed a one-way street generated heated debate and was not resolved for a period of more than two years. In the end, motorists were controlled by a stop sign and bicyclists were not controlled. The use of bicycles has been promoted in Davis by provision of safe and convenient bicycle facilities because the bicycle is more energy and transportation efficient than the motor vehicle. On the other hand, it is undesirable to stop motor vehicles unnecessarily because they consume fuel and emit more pollutants when stopped. Guidelines and standards would be useful in similar future situations.

In 1974, a survey was mailed to 45 individuals whose work was connected with bicycle traffic. The objective of the questionnaire was to determine what considerations were given to bicycles in traffic control. Twenty-five responses were received. The respondents were unable to report any specific warrants in use that gave consideration to bicycle traffic. Two of the respondents commented that bicycles should be treated as pedestrians, and one alluded to the concept that a bicycle is a vehicle and should be treated as a motor vehicle when warrants for traffic control devices are established. Neither approach is satisfactory, however, because of differences in the traffic behavior of motor vehicles, bicycles, and pedestrians.

A more satisfactory basis needs to be established to resolve issues of traffic control at intersections and crossings where motor vehicles and bicycles interact. Although it is desirable to construct bicycle facilities that are completely separated from motor vehicle traffic, the high costs are prohibitive except in rare circumstances and in communities that have a strong bicycle orientation. There are a number of less expensive traffic control methods for maintaining safe and convenient crossings for bicycles and motor vehicles. These require separating conflicting traffic streams by allocating the use of the crossing area and therefore result in delays. Where a bicycle path crosses a motor vehicle path, stop or yield signs can be posted on either path. For a crossing at which traffic is heavy, a traffic signal can be installed. Where bicycles and motor vehicles share the same roadways, as at most urban intersections, stop sign or signal control can be used.

Few studies have sought to provide data on the relations between motor vehicle delay and bicycle delay under various types of traffic control. Controlled experiments and field studies were limited by the availability of sites and conditions that cover the full spectrum of the variables. Suitable sites that have a wide range of bicycle flows are not common, especially sites that have heavy bicycle flows. Instead of relying wholly on field data, this study uses computer simulation to investigate the relation between bicycle delay and motor vehicle delay at intersections. After simulation outputs have been adequately verified by field data, the computer models allow the extrapolation of the field data to cover all conditions that affect intersection operation. This approach has been shown to be useful in a preliminary study (1).

The objective of this study was to develop a simulation model for studying bicycle and motor vehicle delays at crossings and intersections. The simulation model should be useful for quantifying benefits and trade-offs for various schemes of separating bicycles and motor vehicles. Because the data used in calibrating the various model parameters were data observed in Davis, California, for bicycle traffic composed of the general population of the city, care must be used in interpreting the results presented here for situations that may involve only child or adult bicycle traffic.

The basis of the computer simulation models is presented, and the simulation results are discussed. Various traffic control strategies have been studied, and their performances for different mixes of bicycle and motor vehicle traffic are compared. Field data collected to validate the simulation models are also reported. It is hoped that the simulations and field observations reported here will provide information that will be useful in planning bicycle crossings and intersections that have substantial bicycle traffic.

SIMULATION MODELS

Two simulation models have been developed in FORTRAN by using the Burroughs 6700 computer at the University of California, Davis. One model is used to study the performance of an intersection controlled by stop signs; the other model simulates delays at a signalized intersection. Both models simulate 1 h of traffic at an intersection by using common, simple geometry and four approaches. Symmetrical traffic inputs are assumed for opposite traffic flows on the same roadway. One lane of motor vehicle traffic is provided on each approach. The remaining space of the approach is assigned to bicycle traffic that is moving to the right of the motor vehicles. By not allowing motor vehicle traffic on one roadway and not allowing bicycle traffic on the other, the models represent a bicycle crossing situation.

The detailed mechanical aspects of the simulation will not be discussed here. Emphasis is given to those elements in the models that are important in interpreting the simulation experiments. Simplifying assumptions are made to facilitate the computer operations and analysis. Although it is believed that these assumptions would not affect the reality of the outputs, an understanding of the assumptions used is essential in any simulation study.

Model for Stop-Sign Control

Assumptions

The basic assumptions for the model for a two-way stop-sign-controlled intersection are that

1. Bicycles in crossing streams do not delay one another.
2. Most bicyclists treat a stop sign as a yield sign, stopping only when conflicting motor vehicle traffic is present.
3. When right-of-way is not clearly defined, motor vehicle traffic will yield to bicycle traffic.
4. The delays to side-street traffic caused by crossing conflicts with other side-street traffic may be neglected since the delays caused by cross conflicts with main-street traffic are considerably larger.
5. Bicycles are not susceptible to queueing delays.

There are two major components in the simulation model. The first determines a service time distribution for vehicles when they come to the head of a queue. Service time is defined as the time between the arrival of the vehicle at the intersection and the start of its movement through the intersection. The other component in the model combines service time, queueing time, and time lost in stopping and starting to estimate the delay time for each simulated vehicle. Breaking down the complex stochastic process that governs the operation of the entire intersection into a series of simpler processes greatly reduces the computer storage requirement for bookkeeping purposes and makes the computer operation more efficient.

Service Time Distributions

Different service time distributions are determined for each vehicle type (bicycle or motor vehicle), approach (main or side), and directional movement of the simulated vehicle (through, left turn, or right turn). When the elements that govern service time are known, it is possible to determine the traffic streams with which the simulated vehicle must interact while passing through the intersection. The selection of these conflicting streams is based on the assumptions that govern the model. Arrivals in the conflicting traffic streams are generated by headway distributions, which are described later in this paper. These conflicting streams of arrivals are then combined into a single sequential series of arrivals for the various circumstances experienced by a delayed vehicle. Service time for delayed vehicles is determined from the process of arrivals in the composite conflicting stream by using the gap acceptance function. The gap acceptance function gives the minimum time gap that a simulated vehicle operator is willing to accept in crossing conflicting traffic streams.

The arrival of the delayed vehicle for the purpose of establishing the service time distribution is generated randomly to occur with uniform probability within the simulated hour of arrivals. If the time between the arrival of the vehicle to be serviced and the next arrival in the conflicting traffic exceeds the minimum gap, the vehicle is allowed to pass with zero delay. Should this first gap be unacceptable, the vehicle is held until an acceptable gap in the conflicting traffic stream exists. The service time is then calculated by subtracting the vehicle arrival time from the first time an adequate gap exists.

This process is repeated until 500 service times have been determined. These service times form the cumulative distribution for that particular vehicle type, approach, and direction of movement. A total of 12 such distributions are required for a case in which there is combined motor vehicle and bicycle traffic on all approaches. Second-order polynomial fits of the cumulative service time distributions are then used in estimating delays in subsequent steps of the simulation.

Headway Distributions

A shifted exponential distribution is used to generate random (stochastic) arrivals of both bicycles and vehicles. The general form of this headway distribution is

$$
\begin{aligned}
P(h \leq t) &= 1 - \exp\left[-(t-\tau)/(\bar{h} - \tau)\right] && \text{for } \tau \leq t \\
&= 0 && \text{otherwise} \qquad (1)
\end{aligned}
$$

The left-hand term [$P(h \leq t)$] is the probability that a headway h is less than or equal to time t. Average headway $\bar{h}$ is a function of the desired arrival rate, and τ is a minimum allowable headway. The value of τ causes the distribution to be shifted. A value of 1.3 is used for motor vehicles, and no shift is assumed for bicycles. Thus, it is possible that several bicycles may arrive at nearly the same time. The shifted exponential arrival function has been widely used in traffic simulation and has been found to represent headway distributions of real traffic. Groth (2) has found good agreement between exponential arrivals and observed arrivals for bicycle traffic. However, Groth's data show that for low rates of flow there is a greater proportion of short gaps than would be expected from the exponential distribution. Figure 1 shows the behavior of the bicycle arrivals observed in Davis in comparison with the exponential distribution.

Gap Acceptance Functions

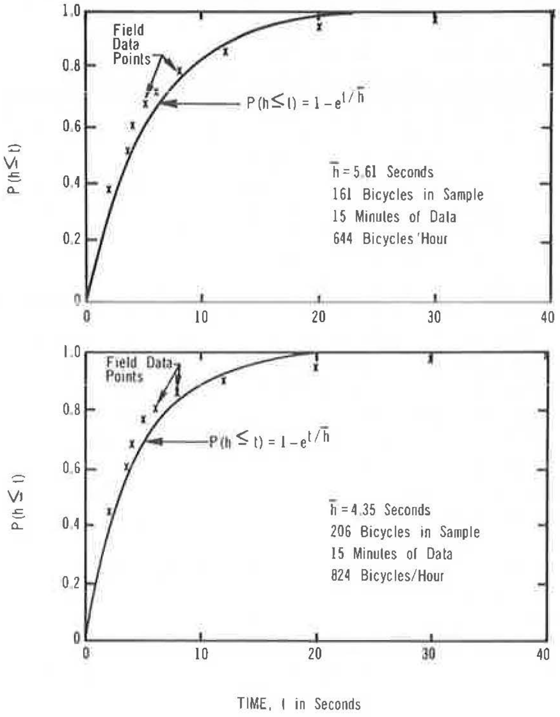
The gap acceptance function for motor vehicles that is used in the model is derived from existing literature. Here, a gap is defined as the interarrival time between two vehicles in a traffic stream. The term "lag" is often used to define the time from an arbitrary instance to the arrival of the first vehicle in the traffic stream. In these models, lags and gaps are treated as synonymous. Most studies have indicated that a linear function can be used satisfactorily to describe gap acceptance behavior. If P(A) denotes the probability that a gap of size G or less will be accepted by the driver of a vehicle, then the linear gap acceptance function is given by

$$
\begin{aligned}
P(A) &= (G - G_{min})/(G_{max} - G_{min}) && \text{for } G_{min} \leq G \leq G_{max} \\
&= 0 && \text{for } G < G_{min} \\
&= 1 && \text{for } G_{max} < G \qquad (2)
\end{aligned}
$$

The minimum gap G_{min} and the maximum gap G_{max} define the entire function.

For motor vehicles that are crossing a motor-vehicle-only traffic stream, a G_{min} of 3.0 s and a G_{max} of 8 s are used. Data were collected in Davis to determine the gap acceptance behavior of motor vehicle drivers as they crossed bicycle traffic. The data were collected at intersections or crossings of two-lane streets. Street widths varied between 8.5 and 10.4 m (28 and 34 ft), which excluded the width allocated to parking. The data were collected for different directional movements of gap-accepting motor vehicles. Figure 2 shows the data and the functions used in the simulation for motor vehicles in bicycle traffic.

Figure 1. Cumulative distribution of arrival gaps in bicycle traffic in Davis.



Two investigations were made to study the gap acceptance behavior of bicyclists as they crossed motor vehicle traffic. One involved moving bicycles and the other stopped bicycles. In both cases, the motor vehicles were moving at right angles to the bicycle movements and the street had two 4.3-m (14-ft) lanes. As Figure 3 shows, there is little difference between the behavior of moving and stopped bicycles. In a study carried out in East Germany by Saitz (3), the critical gap size (the gap size with an equal number of acceptances and rejections) for bicycles crossing two-way vehicle traffic was found to be 8.25 s. That study was done at an urban intersection that had crossing distances of 7.0 and 25.0 m (22 and 82.5 ft).

In reality, it is often necessary for a motor vehicle to accept a gap in several traffic streams that are composed of both bicycles and motor vehicles. A model for this gap acceptance situation was used in the simulation. This gap acceptance takes the form of Equation 2, but the G_{min} and G_{max} used are averages of the values in the motor vehicle and bicycle gap acceptance functions, weighted by the vehicle proportions in the combined traffic stream. For example, $G_{min} = 0.33$ s and $G_{max} = 4.93$ s for motor vehicles crossing a bicycle stream and $G_{min} = 3.00$ s and $G_{max} = 8.00$ s for motor vehicles crossing a motor vehicle stream.

If the combined conflicting traffic stream has 40 percent bicycles and 60 percent motor vehicles, the model uses a gap acceptance function for motor vehicles that has the following parameters: $G_{min} = (0.40)(0.33\ s) + (0.60)(3.0\ s) = 1.93\ s$; $G_{max} = (0.40)(4.93\ s) + (0.60)(8.0\ s) = 6.77\ s$. This procedure is a simplification of reality. The simplification was done to maintain the simple linear gap acceptance function in the model. Theoretically, the resulting gap acceptance function tends to underestimate the delays of motor vehicles. In most cases of mixed

Figure 2. Gap acceptance criteria for motor vehicles in bicycle traffic.

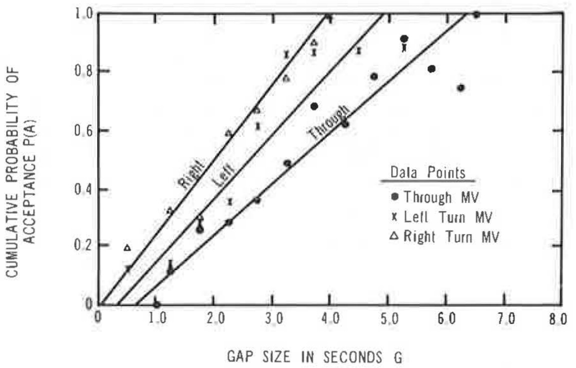


Figure 3. Gap acceptance criteria for bicycles in motor vehicle traffic.

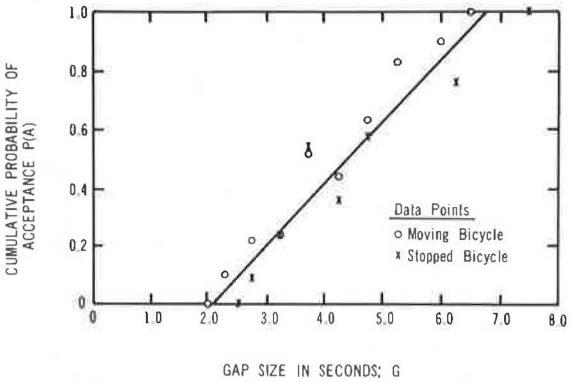
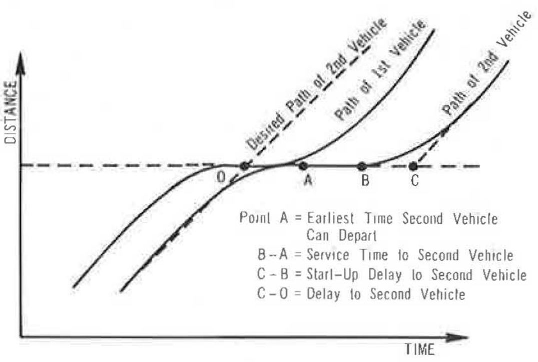


Figure 4. Delay to second or subsequent motor vehicle in a queue (no traffic control).



traffic, however, bicycles generally make up only a small portion of the traffic stream and generally yield the right-of-way to crossing motor vehicles. The size of the underestimation would probably be small.

Motor Vehicle Delays

The second component of the model determines total delays by including waiting time in queue and starting and stopping delays in service time. Queueing time is determined from the difference in cumulative service times and cumulative arrival times by the order of arrivals. The time lost by a main-street motor vehicle in accelerating or decelerating is 3.65 s or half the service time lost in starting from a stopped position and reaching 40.23 km/h (25 mph) at an acceleration of 1.52 m/s^2 (5 ft/s^2). The smaller start-up loss associated with a short service time accounts for the fact that the vehicle may not be required to come to a complete stop so that less time is lost. For a queued vehicle, a minimum lost time of 1.3 s is assumed because that is the minimum headway for successive vehicles that are departing from a stop sign. The basis for the computation of delay is shown schematically in Figure 4.

A side-street motor vehicle that is turning right must accept a gap in both the main-street motor vehicle traffic stream and the bicycle traffic stream that is advancing on the approach to its left. Side-street motor vehicles that are turning left must, in addition, accept gaps in the opposite main-street motor vehicle stream. Motor vehicles that are proceeding straight through the intersection must accept gaps in all main-street traffic streams. Three distributions of service time are established by the model so that the crossing requirements of the three turning options can be considered.

The delay encountered by each side-street motor vehicle when it arrives at an intersection first in a queue is its service time plus its lost times for stopping and starting. The time lost in starting is 3.0 s. This is the time lost in coming to a stop from a speed of 40.23 km/h (25 mph) at a braking deceleration of 1.82 m/s^2 (6 ft/s^2). The time lost in starting is the same as that for motor vehicles on the main street.

Delay for a second or subsequent vehicle in a queue is determined by first calculating the earliest time the vehicle can arrive at the stop line. This arrival time is 1.3 s later than the time at which the preceding vehicle initiates its movement through the intersection. Total delay for the second vehicle is determined by subtracting its desired arrival time from its actual arrival time at the stop line and adding the service time and a penalty for starting delay.

Bicycle Delays

Bicycles that approach an intersection on the main street are not delayed unless they intend to make a left turn. The left-turning main-street bicycle must accept a gap in the motor vehicle traffic on both main-street approaches.

Delay to the bicycle depends on which of two ways the turning movement is executed. The bicycle may emerge through a gap in the motor vehicles in the same approach and then cross the motor vehicle traffic that is advancing from the opposite direction. Alternatively, the bicycle may proceed to the far side of the intersection and cross both motor vehicle streams at a right angle. In both cases, gaps must be accepted in two motor vehicle streams. The delay is computed based on the time spent waiting for an acceptable gap. In addition, a starting penalty of 2.0 s or half the service time, whichever is less, is added to the delay time. A bicycle that starts from a complete stop has been observed to suffer a time loss of this amount in comparison with a bicycle that is moving at a constant speed of 19.3 km/h (12 mph). Shorter penalties are allowed for bicycles that encounter short service times since they are not required to come to a complete stop.

When a yield sign controls the bicycles on the side-street approach, right-turning bicycles are not delayed. Observations indicate some slowing down, but this is caused by the right-turn maneuver and not by the traffic conditions or the controls. Left-turning and through bicycles are delayed by the absence of acceptable gaps in motor vehicle traffic on the main street as determined by the service time functions. A start-up penalty identical to that for main-street bicycles is used.

Some special treatment is necessary for stop-sign control. Reported data (4) indicate that only 17.5 percent of the bicyclists observed came to a complete stop at stop signs by placing at least one foot on the ground when there was no motor vehicle traffic conflict. The model applies a 3.5-s stopping and starting delay to a random sample of 17.5 percent of the bicycles that are not delayed by other traffic at the stop sign.

Model for Signalized Intersection

Assumptions

Fewer simplifying assumptions were used in developing the signalized-intersection model than in developing the model for stop-sign control. Under signalized operation, a major part of the delay is caused by the traffic signal. The signal condenses the traffic flow so that at certain periods there are few conflicting movements and at other times flows that may conflict with a particular turning movement are considerably higher than the average hourly input flows modeled.

The basic assumptions in the model structure are the following:

1. Through bicycles and motor vehicles are served on the green at uniform rates.
2. Right-turning bicycles proceed without delay unless the queue of bicycles exceeds six. When the queue exceeds six, the right-turning bicycle is served as a through bicycle.
3. Left-turning bicycles are served after the motor vehicle queues on their approach have cleared. Once the queues are cleared, the bicycles must accept gaps in the adjacent and opposite motor vehicle streams.
4. Left-turning motor vehicles wait for vehicles queued in the opposite approach to clear and then accept a gap in that stream of combined motor vehicle and bicycle traffic.

These assumptions are based on personal observation and are necessary to the formulation of simpler simulation models. For example, the third assumption is based on the observation that bicyclists usually stay in a bicycle lane on the extreme right-hand side of the travel way rather than mix with motor vehicles.

On each of the four approaches to the signalized intersection, bicycle traffic moves to the right of the motor vehicle traffic. Only one side-street and one main-street approach are simulated in a standard model run. In the presentation of summary data on intersection operation, the delays experienced in the simulated approaches are considered to be representative of the respective opposite approaches.

Service Time

In this model, service time refers to the earliest time in a particular signal cycle at which a vehicle may proceed. The rules of operation of the model require turning vehicles to yield to through vehicles; thus, service time applies only to turning vehicles. The model calculates a queue length for opposing vehicle flows at the beginning of their green time based on the Poisson distribution, the specified flow rate, and a pseudorandom number. While the opposing queues are served, the turning vehicle is delayed. Once the queues are served, the turning vehicle is allowed to proceed when an acceptable gap in the opposing traffic is available. The gap acceptance criteria applied are identical to those described in the model for an unsignalized intersection.

Three assumptions are implicit in this procedure for generating service times for turning vehicles at a signal:

1. Opposing turning vehicles are treated as through traffic by the vehicle that intends to turn. The turning vehicle then yields to the opposing vehicle.
2. Vehicles that arrive during the time required to dissipate an opposing queue do not add significantly to the time required to dissipate that queue. This assumption least distorts the true situation when the time required to dissipate queues of opposing vehicles is short compared with the average arrival headway of vehicles that are moving into that queue.
3. Turning vehicles that arrive after their service time has passed are allowed to be served as through vehicles.

These assumptions seriously inhibit the ability of the model to predict operations when there is a high proportion of turning vehicles. The first of these assumptions tends to increase delay to a turning vehicle, and the other two assumptions decrease the delay. Model results should be interpreted cautiously whenever there is a high proportion of turning vehicles.

Motor Vehicle Delays

The simulation is performed from the viewpoint of the delayed motor vehicle. If there is a queue ahead when the vehicle arrives, the vehicle waits until the queue has been served. If it is a turning vehicle, it waits until the service time passes and then proceeds. Should the earliest time in the cycle at which the vehicle can leave exceed the cycle time, the vehicle is delayed until the next signal cycle.

The critical parameters in calculating motor vehicle delays are the signal settings, the demands of other motor vehicle traffic in the same approach, and the rate of service to motor vehicles. The first two parameters are inputs to the model, and the third is contained in the model structure. The service rate varies depending on the position of the motor vehicle in the queue. The first vehicle is served 2.7 s after the signal turns green, the second vehicle is served 2.5 s after the first, and the third and subsequent vehicles are served at 2-s headways.

The service rate is derived from data collected at a signalized intersection in Davis, where motor vehicles travel in a single-lane approach and bicycle traffic travels in a bicycle lane. This data set is compared with a previous study (5) for the middle lane of a three-lane approach to a signalized intersection in Santa Monica. The results from the two studies agree for the first and second vehicles in a queue. For the remaining vehicles, the values chosen for the model are compromises of the two studies.

Bicycle Delays

Bicycles are handled in much the same way as are motor vehicles. One difference is that, if a bicycle intends to turn right and the queue ahead of it numbers fewer than six bicycles, the bicycle is allowed to proceed around the corner without delay. If the queue is six bicycles or more, the path of the right-turning bicycle is deemed to be blocked and that bicycle must wait until the queue dissipates to proceed. Another difference is that turning bicycles that are waiting to be served do not inhibit the flow of other bicycles.

In the model, a headway of 0.67 s was used for through bicycles. This value was based on considerable research into bicycle operations on urban streets. The headway used corresponds to a saturation flow rate of 1.5 bicycles/s. This flow rate is typical of a 2.13-m (7-ft) wide bicycle lane.

MODEL VALIDATION

The model outputs were validated by checking them against field data. Average travel times predicted by the model for vehicles moving through intersections were compared with average travel times measured in the field. Travel time was chosen for validation purposes because it could be more precisely measured in the field than delay (it is often difficult to define exactly when a vehicle begins to be delayed). Travel time was chosen over stopped time because stopped delay is only one portion of total delay. Considerable delay is experienced by bicycles that move slowly to avoid stopping.

In Figures 5 and 6, the mean travel time observed in the field is plotted as a function of mean travel time determined from the model for bicycle and motor vehicle traffic, respectively. The lines plotted in the graphs have a slope of one, which indicates equality between field observations and simulation outputs. A visual inspection would indicate generally good agreement between model results and field data. Linear regressions of the data give intercepts of 0.13 (±1.59) s and 5.71 (±3.91) s and slopes of 1.08 (±0.11) and 0.78 (±0.16). The intercepts are not statistically significantly different from zero, and the slopes are not statistically significantly different from one at the 5 percent level of significance. A regression that forces the fits to go through the origin of the axes yields slopes of 1.08 (±0.04) and

Figure 5. Comparison of field and model travel times for bicycles.

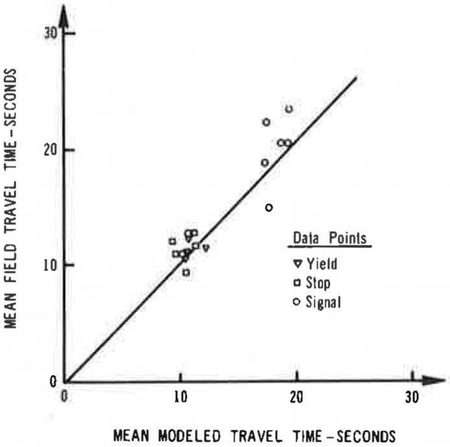


Figure 6. Comparison of field and model travel times for motor vehicles.

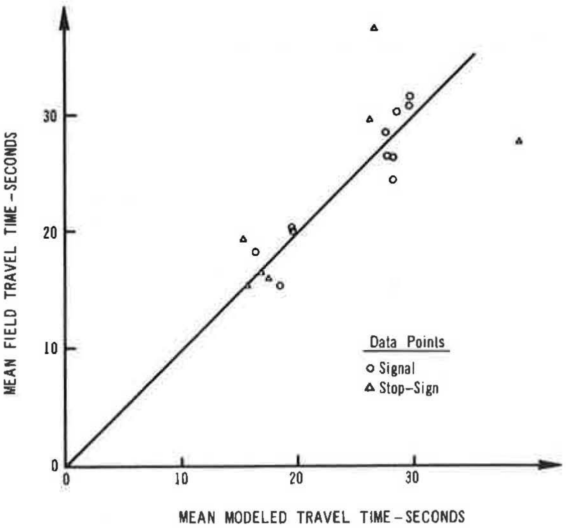


Figure 7. Mean delay at bicycle crossing controlled by yield sign (no motor vehicle control).

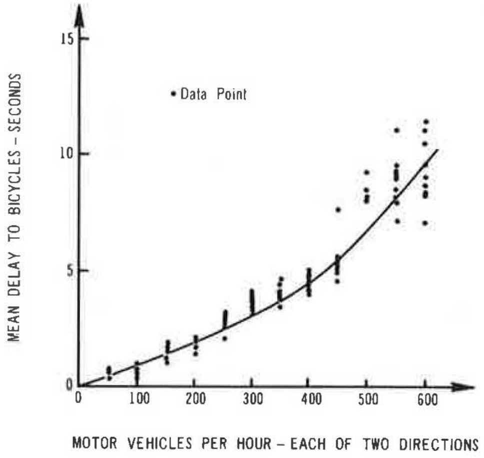


Figure 8. Mean delay to motor vehicles at bicycle crossing controlled by stop sign.

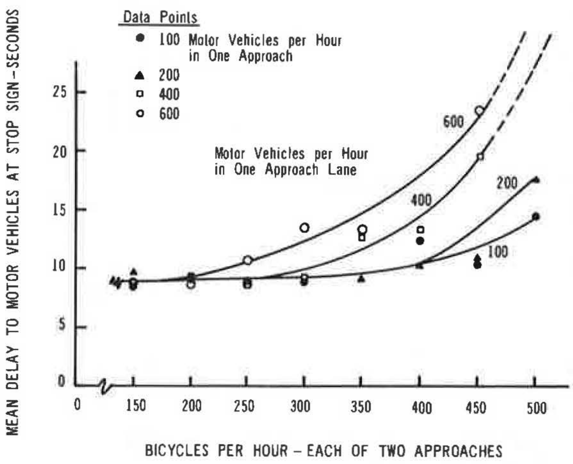
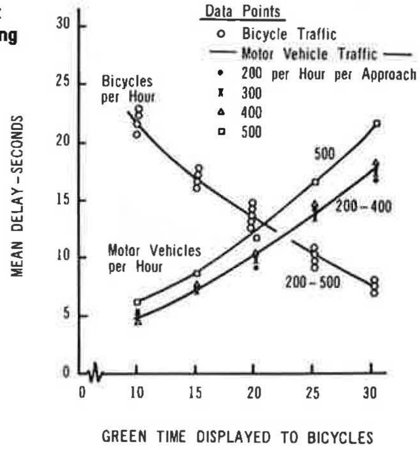


Figure 9. Mean delay at signalized bicycle crossing with 60-s cycle time.



1.00 (±0.04) for the data shown in Figures 5 and 6, respectively. These slopes indicate excellent agreement between the model results and the field data. On the basis of this evidence, one can conclude that the models are good representations of crossing and intersection situations for delays to both bicycles and motor vehicles.

Figure 10. Mean delay to motor vehicles at stop sign: no bicycles on main street.

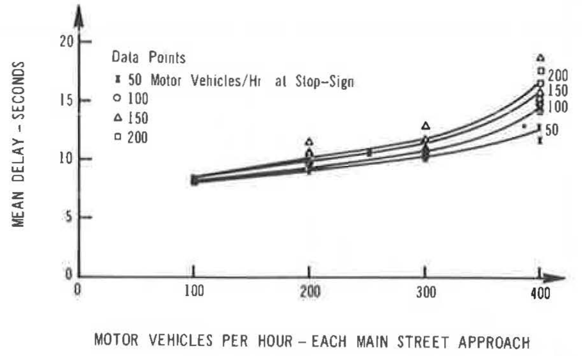


Figure 11. Mean delay to motor vehicles at stop sign: 100 bicycles/h/main-street approach.

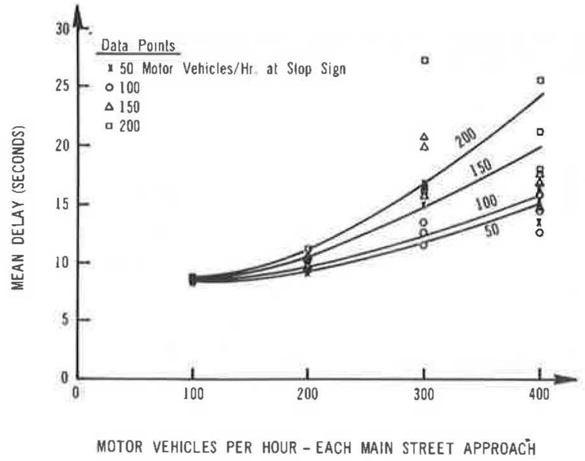
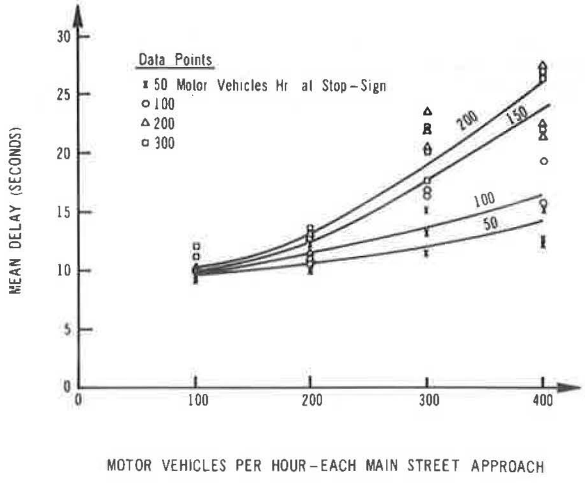


Figure 12. Mean delay to motor vehicles at stop sign: 200 bicycles/h/main-street approach.



SIMULATION RESULTS

Traffic Delays at Bicycle Crossings

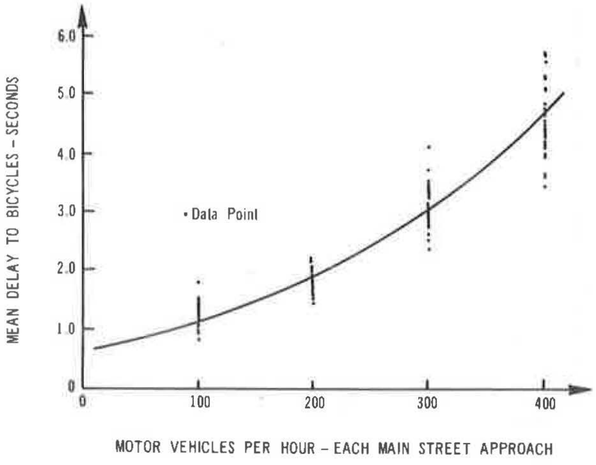
An exclusive bicycle path is considered by many to be the best type of bicycle facility whenever it can be conveniently and effectively located. But, because grade-separated crossings are expensive, bicycle traffic and motor vehicle traffic must occasionally cross or mix. Bicycle crossings may be uncontrolled or controlled for bicycles only, for motor vehicles only, or for both types of vehicles. Clearly, selection of the method of control depends on traffic volumes. As traffic volume increases, the crossing becomes less safe and delay becomes longer.

Figure 7 shows average delay to bicycles that are controlled by yield signs when there is no control for motor vehicles. This situation also approximates the situation of no control. The average delay to bicycles is shown as a function of the volume of motor vehicles. The result shows that average bicycle delay increases linearly with an increasing volume of motor vehicles up to about 300 vehicles/h/direction. Beyond this level of vehicle flow, the mean delay to bicycles increases rapidly with increasing motor vehicle volume. There is no motor vehicle delay in the situation studies because it is assumed that bicycles always yield to motor vehicles. Furthermore, it is assumed that bicycles delayed at the same approach do not interfere with each other. So the average delay to bicycles is not dependent on bicycle volume. Field studies indicate that this assumption is valid up to a flow of 600 bicycles/h/direction.

An alternative method of control is to control motor vehicles with stop signs and give the right-of-way to bicycles. Average delay to motor vehicles as a function of bicycle volume and motor vehicle volume is shown in Figure 8. Mean delay to low volumes of motor vehicles does not vary much when there is a bicycle flow of less than about 400 bicycles/h/direction. As the flows of motor vehicles and bicycles increase, however, the average delay to motor vehicles increases rapidly.

Mean delay to bicycles and motor vehicles when both are controlled by a traffic signal with a cycle time of 60 s is shown in Figure 9. Mean delay is shown as a function of the green time (in seconds) allocated to bicycles. The case of zero green time is identical to that in which the bicycle crossing is controlled by a stop sign (Figure 8). Clearly, a reduction in the delay to bicycles is at

Figure 13. Mean delay to bicycles at stop sign.



the expense of delay to motor vehicles and vice versa. In comparison with the previous cases in which only one type of vehicle is controlled by a stop or yield sign, the average delay to controlled vehicles is generally less under the signal control. Vehicles that previously were not controlled by stop signs, of course, suffer increased delay under signal control. Signal control is, therefore, more appropriate for high volumes of traffic and for safety considerations.

Bicycles at Urban Intersections

Bicycles on urban streets are separated from the motor vehicle travel way when they are assigned bicycle lanes striped near the curbs of the roadway. This situation is quite different from the case of multiple-lane motor-vehicle-only traffic in that bicycles and motor vehicles conflict only on turning movements. Existing information for intersections with motor vehicle traffic only is, therefore, not suitable for evaluating the performance of an intersection where there are high volumes of bicycles.

Two control strategies for combined traffic are analyzed. The first is a stop-sign control for which all vehicles on the side-street approaches are required to stop. Bicycles are modeled so that only a fraction of them will stop if there is no conflicting main- or side-street motor vehicle traffic. The second control alternative is the traffic signal. Only the case of a fixed-time operation on a 60-s cycle is presented. Delay encountered by bicycles at a signalized intersection is predominantly caused by waiting for the green light. Traffic conflicts add only marginally to the total delay when there are few turning movements. The simulation results reported here are for a case in which there are 30 percent turning vehicles on the side street and 10 percent on the main street. The proportions of left- and right-turning vehicles are assumed to be equal.

The results for the side-street stop-sign case are shown in Figures 10-13. Figures 10, 11, and 12 show mean motor vehicle delays as a function of motor vehicle and bicycle flows on the main street. It can be seen that the presence of bicycles on the main street causes a significant increase to side-street motor vehicle delay. Further increases in bicycles on the main street, however, add less to the average delays to side-street motor vehicles. The results also show that bicycle flow on the main street has a pronounced effect on the sensitivity of side-street motor vehicle delay to the increases of main-street motor vehicle flow.

Bicycles at a stop sign are delayed considerably less than are motor vehicles for several reasons. Most bicyclists do not stop unless there are motor vehicles in or near the intersection. In addition, bicycles do not queue as do motor vehicles, so several bicycles can be served by a single gap in the main-street traffic stream. The mean delay to bicycles is shown in Figure 13. This delay is not sensitive to main-street bicycle traffic since a basic assumption of the simulation model is that bicycle delay caused by conflicting bicycle movements is negligible. The data presented in Figure 13 show widely varying delays for one given set of traffic conditions. Bicycle delay is generally sensitive to the volume of main-street motor vehicle traffic. However, bicycle delay is so low (less than 5 s/bicycle at 400 motor vehicles/h on each main-street approach) that delay to bicycles at a stop sign is rarely excessive when it is compared with delay for another type of traffic control.

Main-street traffic is given priority by the placement of the stop sign on the side street. The only delay imposed on main-street traffic is caused by conflicts encountered during a turning movement. Because turning movements were held in the simulation to 5 percent of the main-street volume, delay to main-street traffic was low. In addition, the sample sizes of turning vehicles were too small to show relations between delay and other intersection or traffic characteristics.

A total of 118 h of simulation was done on the signalized-intersection model to generate the data shown in Figures 14 and 15. These two figures show mean delay at a traffic signal for motor vehicles and bicycles, respectively. Mean delay is plotted versus the green time displayed to the traffic in question. The combinations of traffic volumes simulated range from 50 to 400 motor vehicles/h/approach and from 0 to 200 bicycles/h/approach. Under signal control, it is not necessary to distinguish between main- and side-street traffic.

Many factors affect the performance of a signalized intersection. It is difficult to enumerate and analyze all of these factors individually. One is signal splits. In the simulation results presented here, green time was apportioned between the intersecting approaches to obtain an equal degree of saturation. This commonly used method of setting signal splits is explained by Webster (6).

The data were analyzed to determine the effect of bicycles on delay at a signalized intersection when bicycle flow varies. No conclusions could be drawn. Under the low turning percentages investigated in the simulation, which is typical of most intersections, the presence of bicycles does not significantly increase delay. However, because of the large number of factors that affect the operation of a signalized intersection, a

Figure 14. Mean delay to motor vehicles at traffic signal.

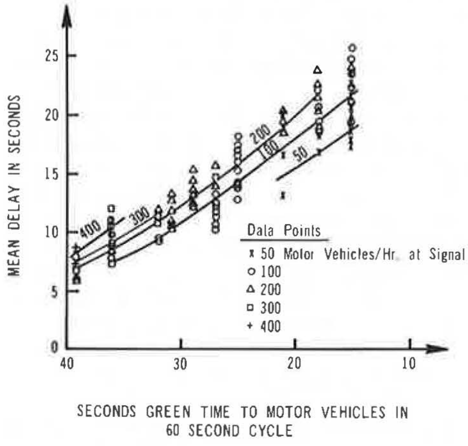
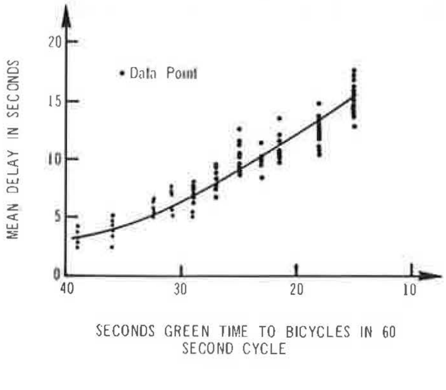


Figure 15. Mean delay to bicycles at traffic signal.



more extensive investigation may be required to explore the extent of the influence of bicycles on motor vehicle delay.

Bicycles are delayed considerably less by a traffic signal than are motor vehicles. There are two reasons for this lower delay. First, the saturation flow rate for bicycles is so high (5400 bicycles/h/approach) that there is no observable increase in delays as bicycle demand goes from 0 to 200 bicycles/h/approach. The second factor that makes bicycle delay relatively low is that the bicyclist is more aggressive than the motorist. The bicyclist will proceed on the amber phase more often than the motorist will, and the right-turning bicyclist will often proceed without first stopping when the signal is red. The simulation model reflects these characteristics by extending the effective green time and allowing bicyclists to turn right on red without delay.

In the model, individual left-turning bicycles were occasionally predicted to be delayed more than 60 s at the traffic signal. In reality, however, left-turning bicyclists are rarely willing to accept such a long delay and will use unusual maneuvers to make a quick left turn. Most of the maneuvers observed were extremely unsafe.

DISCUSSION OF RESULTS

The simulation models developed in this study give a fairly good representation of delays at intersections and crossings. The simplicity of the model structure allows the use of simulation to extrapolate limited observations of bicyclist behavior in traffic to many situations of intersection and crossing controls. In the development of the models, emphasis was placed on representing traffic characteristics observed in the field, and simplifications and idealizations were made in the mechanical aspects of the simulation process. This trade-off has resulted in efficient programming and computer operations and little sacrifice in validity in the results.

These models are useful in the study of delay to bicycles and motor vehicles at intersections under various methods of traffic control. Establishing appropriate criteria and warrants, however, is beyond the scope of this paper and the simulation models. Values and other subjective bases play an essential role in determining the trade-off between bicycle delays and motor vehicle delays and between safety and efficiency. The data obtained from the simulation are helpful in providing a quantitative basis for exploring standards. For example, stop-sign control of bicycle traffic may be the most efficient control for a bicycle crossing in relation to delay. But this type of control may make it impossible or unsafe for bicyclists to cross a busy motor vehicle traffic stream. On the other extreme, a traffic signal would positively separate the flows at a bicycle crossing and offer safer and more convenient conditions for bicycles. This solution is costly, however, and may lead to larger aggregate delays, especially for motorists.

The results of the simulations offer some quantitative indications on the level of delays involved for various combinations of traffic flow. A discussion on how the simulation data may be used to select proper traffic control at bicycle crossings has been presented by Ferrara (7). Accident records and operational experiences for significant bicycle flows have not yet been extensively documented. As bicycles become a more important mode of transportation, better understanding will be forthcoming to guide the decisions. In the meantime, the simulation results discussed here provide some information that can be useful in resolving the difficult and often controversial problem of traffic conflicts between bicycles and motor vehicles.

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REFERENCES

1. T. C. Ferrara. Establishing Warrants for Control of a Bicycle Crossing Through Simulation. TRB, Transportation Research Record 570, 1976, pp. 20-23.
2. H. A. Groth. Untersuchungen uber den Raduerkehr. Division of Highways, Federal Department of Transportation, Bonn, Germany, Traffic Engineering and Highway Design Rept. 9, 1960.
3. H. H. Saitz. Zeitluckenuntersuchungen fur den Fahrraduerkehr an ungesteuerten Strassenknoten. Die Strass, Vol. 8, No. 3, March 1968.
4. D. F. Lott and R. Sommer. Bicycle Lanes in Davis, California: First Year Report. Department of Psychology, Univ. of California, Davis, July 7, 1969.
5. C. J. Ancker, Jr., A. V. Gafarian, and R. K. Shay. The Oversaturated Signal Intersection: Some Statistics. Transportation Science, Vol. 2, No. 4, 1968, pp. 340-361.
6. F. V. Webster and B. M. Cobbe; British Road Research Laboratory. Traffic Signals. Her Majesty's Stationery Office, London, Road Research Technical Paper 56, 1966.
7. T. C. Ferrara. Planning Safe and Efficient Bicycle Crossings. Journal of Urban Planning and Development Division, ASCE, Vol. 104, No. UP1, 1978, pp. 73-86.

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