A Simulation Model of a Two-Lane Rural Road

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A simulation model has been developed to evaluate traffic flow and safety benefits arising from use of remedial devices which would aid passing maneuvers on two-lane rural roads. Inputs to the model are arbitrary and consist of road configuration data, vehicle data, traffic volumes, and passing probability data. The output statistics can be used to determine the relative benefits of alternative remedial aid systems in terms of safety and throughput.

Initially the effects of no-passing zone configurations due to road geometry and knowledge of oncoming car speed on tangents were investigated. The results show that no-passing zones cause a marked decrease in throughput, while oncoming car speed information appears to have a beneficial effect on safety. Additional runs will be made to study the effects of other passing rules on traffic flow and safety.

•THE Franklin Institute Research Laboratories (FIRL) has recently completed a study for the Bureau of Public Roads on the conceptualization of the overtaking and passing maneuver on 2-lane rural highways (1) and is presently developing functional specifications for remedial aids to assist drivers in solving discriminatory and judgmental problems associated with overtaking and passing. This study is in support of the Bureau of Public Roads program to minimize rear-end and head-on accidents and to increase the service volume on 2-lane rural highways.

The first study has shown that passing performance can be significantly improved if drivers are given additional information such as oncoming car speed or closing rate.

The present study is concerned with the development of functional specifications for cost effective remedial aids which would provide the driver with this additional information. This study uses the results of the completed program and other related research.

To evaluate the traffic flow and safety benefits of alternative remedial aids a computer simulation model has been developed. This model and some initial results are described in this paper.

TRAFFIC FLOW MODEL

General Description

The traffic flow model is the primary means for evaluating the effectiveness of alternative remedial aids in terms of both traffic flow and traffic safety. The model can simulate the movement of vehicle traffic on 2-lane rural roads with various road geometries and traffic volumes. During the simulation, which spans a specified interval of time, vehicles will, under certain conditions, attempt and execute passing maneuvers in order to attain and maintain their individual desired speeds. These conditions generally depend on the relative position and speed of each of the vehicles on the length of the road at a particular point in time. Although this road is assumed to be straight and

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level, the restrictions placed on the traffic flow by a more general configuration of road geometry are achieved in this model by specifying "no-passing" zones and sight distance restrictions for each direction of travel. Additionally, slow-down factors can be used for curves and grades if desired.

The elements of traffic, the vehicles in each lane, are introduced into the model from both ends of the road. Speed distributions and headway distributions are predetermined so that the traffic configuration will simulate some prescribed volume. The method is completely arbitrary to the extent that the time of entry and speeds of all introduced vehicles are at the discretion of the user. These data, together with other data associated with each of the vehicles entering the traffic pattern at any time (such as its desired speed, its actual speed, and its state of maneuvering), need only reflect plausible physical conditions, and are otherwise unrestricted.

The dynamic operation of the model consists of determining at any time the future picture of the traffic flow at some appropriately selected incremented time based on the present picture and on various estimates and decisions of the drivers of the vehicles. A maneuver by any vehicle to pass one or more (up to a maximum of 5) leading vehicles in its lane will be attempted, if certain conditions are satisfied. Some of the more important ones are as follows:

1. The vehicle is currently constrained to travel at a speed less than its desired speed, because of the speed of the leading vehicle (i.e., the vehicle immediately in front of it).
2. After overtaking 1 to 5 vehicles in a passing maneuver, there is a sufficiently large gap to allow a safe return to the traffic flow.
3. The vehicle is in a passing zone and will remain there until completion of the pass.
4. The probability of passing, as a function of the oncoming gap and lead car speed yields a number which is greater than the next random number.

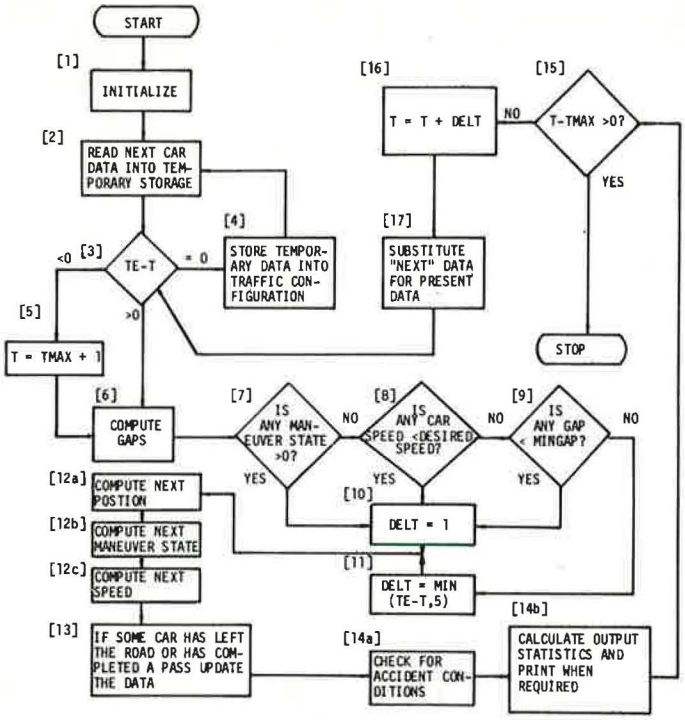
At any point in time during the simulation each vehicle on the roadway under observation will be in any one of four possible maneuver states indicating the following four different phases of maneuvering utilized in this model:

Maneuver State	Phase of Maneuvering
0	Traveling in its normal lane.
1	Decision to initiate a passing maneuver.
2	Traveling in the oncoming lane while passing one or more cars in its own lane.
3	Terminating the passing maneuver by re-entering its normal lane.

If, during maneuver state 2, a driver changes his mind about going through with the pass, because it becomes necessary to complete or abort the pass sooner than originally anticipated, certain latitudes of action are available by which the involved vehicle can accelerate or decelerate in the proper time to the speed required to re-enter its normal lane in order to avoid an accident. Only accelerative type passes are being considered in the model.

Programs

The traffic model (Fig. 1) can be most easily described in four sections:



*Classification of Symbols: T = Present time; DELT = Time increment; TMAX = Total Simulation time; TE = Time of entry of next vehicle.

Figure 1. Flow chart of the traffic model.

Main routine controls all input, updatings due to position changes, and printing of output statistics. This is steps 1-12a, 13, 14b-17 of the flow chart (Fig. 1).

Subroutine maneuver calculates the "next" maneuver state of each vehicle. This is step 12b.

Subroutine speed calculates the "next" speed of each vehicle. This is step 12c.

Subroutine accident investigates possible accident conditions and decides what type of correction can be made in the passing maneuver to avoid an accident. This is step 14a.

Main Routine—The most important function of the main routine is to calculate output statistics and to print results when necessary. Printing of results can occur in various ways, such as,

1. At every time increment;
2. At every time increment at which a vehicle is attempting to pass;
3. At every time increment at which a vehicle is actually passing;
4. Only when a possible accident condition occurs;
5. At equal time intervals;
6. At termination only.

The last two seem to be the preferred methods, since they yield enough output statistics and do not increase computer time to any great degree. Other functions of the main routine are as follows:

1. Computation of gaps;
2. Computation of positions;
3. Computation of the time increment;
4. Updating due to position changes (one vehicle passing another vehicle); and
5. Computation of speed changes.

Subroutine Maneuver—This is the heart of the model since it calculates exactly what each vehicle is going to do at every time increment. If the conditions mentioned earlier, along with several other conditions, are satisfied, then the final decision to pass is calculated as follows:

> As a result of observational studies on tangent sections of 2-lane public highways previously conducted by the Franklin Institute Research Laboratories for the Bureau of Public Roads (1) it was found that the decisions made by drivers whether to attempt to pass or not are based on many factors, but that the decisions, once made, closely resemble probability distribution curves with oncoming gap and lead car speed as independent variables. Because of this, it was decided to incorporate these probability curves into the model and to rely on them for the final decision to pass. These curves were derived for day-light conditions only.
>
> Given on oncoming gap and a lead car speed, the probability of passing is determined by linear interpolation of the probability curve in the appropriate region.

These calculations are done vehicle by vehicle, and are repeated whenever the conditions are such that a vehicle is in a potential passing situation. If a vehicle does not pass, then it remains in maneuver state 0 until the next opportunity. If a vehicle does attempt to pass, a check is made at each time increment to decide if the pass will be completed safely or if other action must be taken.

Subroutine Speed—Subroutine speed merely calculates a vehicle's next speed as a function of its present and next maneuver state.

Subroutine Accident—Subroutine accident checks each passing maneuver to decide if corrective action such as acceleration or deceleration is needed to complete the pass sooner or abort it. This is done by projecting what the oncoming gap will be when the pass is completed and then testing the effects of increasing the speed to complete the pass in less time or decelerating and returning to the normal lane. No vehicle other than the passing vehicle is altered. Projected accidents where no avoidance procedures can be taken in the model to deter a possible accident are also identified.

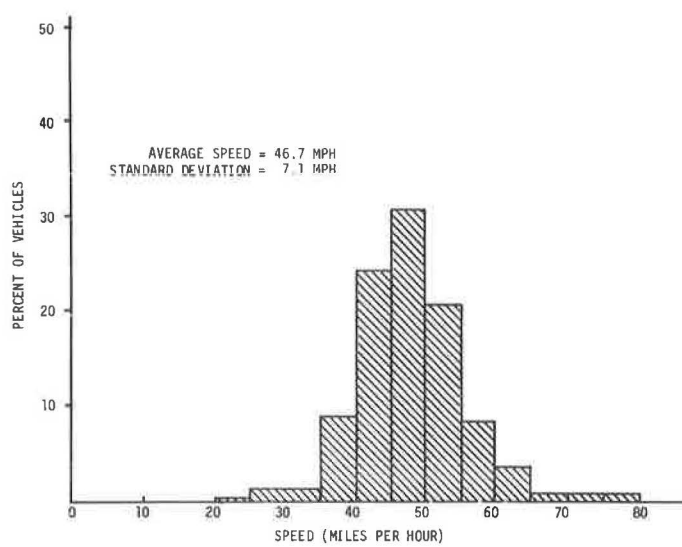


Figure 2. Speed distribution.

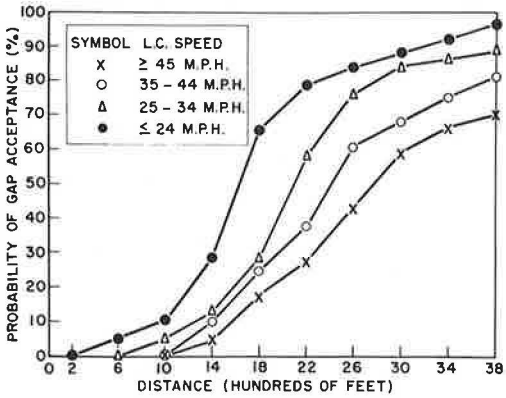


Figure 3. Gap acceptance without knowledge of oncoming car speed.

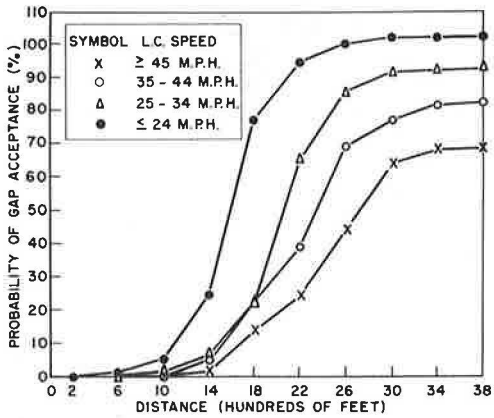


Figure 4. Gap acceptance with knowledge of oncoming car speed.

Input Data

The inputs to the model consist of road configuration data, vehicle data, and passing probability data.

Road Data—The road data consist of road length, no-passing zone configurations, sight distance restrictions, and the maximum simulation time to be used. These numbers are all read into the program and do not change during a given simulation.

They may be varied in order to obtain various roadway geometries with arbitrary lengths in order to simulate the effect of remedial aids on traffic flow and safety under different conditions.

Vehicle Data—The vehicle data consist of desired speed (which equals actual speeds upon entering), maximum speeds, headway time gaps (which determine a vehicle's time of entry), and maneuver state (which is 0 upon entering). Each vehicle's desired and maximum speed do not change throughout the simulation, but this could be done if desired. An acceleration rate of 5 ft/sec^2, and a maximum emergency deceleration rate of 20 ft/sec^2 are used—these are average vehicle data from the Traffic Engineering Handbook (2). These also do not change throughout the simulation. The speed distributions used in the model were determined from observational studies completed previously (1) and are typical free speeds on 2-lane rural roads in southern New Jersey, and from the literature. The speed distribution in Figure 2 is approximately normally distributed with a mean of 46.7 mph and a standard deviation of 7.1 mph. The headway distributions have been taken directly from the Highway Capacity Manual (3) and are in the form of a modified Poisson distribution. Ranges from 100 to 800 vph have been used successfully in the model. Other headway and speed distributions can be used in the model as desired.

The desired speeds and headway time gaps are randomly assigned to the vehicles by a separate data preparation program before each simulation begins.

Passing Probability Data—The passing probability data (Fig. 3) consist of four probability curves obtained from the observational studies on public highways mentioned previously. The curves show the percent of passing opportunities accepted as a function of lead car speed and oncoming gap, and are based on passing behavior without giving drivers information on oncoming car speed.

Any remedial aid would change the passing behavior of the drivers, hence also changing the probability distribution curves which are now being used in the model. Several experimental studies have been conducted on closed roads as part of the previous program to determine the effect on passing behavior of providing drivers with information such as oncoming car speed or closing rate as compared to no knowledge conditions. These controlled road tests yield new probability distributions describing passing behavior if drivers were given information on oncoming car speed or closing rate.

Additional experimental studies can be run if it is desired to test the effect of giving drivers other information such as distance to an oncoming car or to the end of a passing zone. These distributions have been corrected so that they would simulate actual passing behavior of drivers using a remedial aid providing oncoming car speed (OCS). This was accomplished by noting that in the controlled tests, providing drivers with OCS caused a 50 percent reduction in the variance of passing gap acceptance without changing the mean passing time. The real curves were then adjusted so as to reflect this 50 percent reduction in variance. The new curves (Fig. 4) are merely the original set (Fig. 3) with a 50 percent reduction in variance. The means of both sets are the same based on results of the experimental studies on closed roads.

Output Statistics

The output statistics, which can be used to determine the relative benefits in terms of safety and throughput, consist of the following:

Volume;
Average speed and standard deviation;
Number of attempted and completed passes and aborts;
Number of vehicles passed and percent of multiple passes;
Amount of delay (seconds) suffered by the vehicles which leave the road;
Number of possible accident conditions termed emergency indicators, when some type of evasive (i.e., acceleration or deceleration) action must be taken, during a passing maneuver;
Number of projected accidents, when no evasive action can be taken in the model to deter a possible accident;
Average safety margin (average time to meeting of oncoming car after completion of a pass); and,
Number of speed change cycles.

An increase in the output volume in an equal time interval would indicate an increase in throughput.

An increase in average speed by use of a remedial aid would cause an increase in throughput on the road. If the standard deviation decreased it would signify that traffic is flowing more evenly.

An increase in the number of passes and number of vehicles passed taking place under identical traffic conditions would signify a better use of passing opportunities and hence should increase throughput.

A reduction in the amount of delay caused to a given group of vehicles would show that the remedial device has a beneficial effect on throughput, since vehicles would be traveling at speeds which differ less from their desired speeds.

An increase in the average safety margin and decrease in the number of emergency indicators would signify safer passing conditions on the road.

A reduction in the number of speed change cycles would signify a smoother flow of traffic.

The output statistics can be used to determine the relative benefits of alternative remedial aid systems in terms of safety and throughput. The prime benefit measures for each remedial aid are effect on road user costs including motor vehicle running costs, time costs, and accident costs. Changes in speeds, delay and other output statistics can be converted to dollars to develop estimates of annual savings associated with a given type of remedial aid system for all 2-lane rural roads or some roads which have more than a given ADT. By use of cost-benefit analysis techniques, optimal solutions for remedial aid systems can then be developed.

The program is written in FORTRAN IV and is presently being run on a UNIVAC 1107 at the Franklin Institute.

USES OF THE TRAFFIC FLOW MODEL

The primary use of the traffic flow model is to evaluate the effects of remedial aids for passing maneuvers on traffic flow and safety. Two basic applications have been considered:

1. Use of existing no-passing zones for passing maneuvers by providing drivers with information describing the opposing traffic (e.g., positions and speeds of oncoming cars).
2. Providing drivers with oncoming car speed (OCS) or closing rate on tangents.

A series of simulations was run for each of these applications.

No-Passing Zones

Each of the following series included four simulations: 0, 25, 50, and 70 percent no-passing zones. Each simulation was accomplished using a 30,000-ft road, a 50-50 traffic directional distribution, 10-15 percent heavy trucks, and the no-knowledge passing rule mentioned previously. Passing was allowed only on tangent sections.

Series Number	Volume (vph)	Speed (mph)
1	100	46.7
2	200	41.7
3	200	46.7
4	200	51.7
5	400	41.7
6	400	46.7
7	400	51.7
8	600	46.7

Knowledge of Oncoming Car Speed

The same eight series were re-run using the passing rule derived when knowledge of oncoming car speed was provided to the drivers. For both applications, other directional distributions and road lengths were also simulated to test the sensitivity of the model. The results of some of these simulations are described in the following sections.

RESULTS OF THE TRAFFIC FLOW MODEL

Effect of No-Passing Zones

The first use of the model was to study the effects on traffic flow of various geometric configurations on 2-lane rural roads. Representative roads were studied in flat (southern New Jersey), rolling (foothills of Virginia), and mountainous (Vermont, New Hampshire, Maine, and Virginia's Skyline Drive) terrain to collect data describing various road configurations which were used to generate typical configurations for the model. It was determined from these data that 25, 50, and 70 percent no-passing zones approximated the configurations found on these three types of roads, respectively. A method developed by Stanley R. Byington of the Bureau of Public Roads was then used to derive the arrangement and spacing of the no-passing zones.

Table 1 gives the output of the 16 runs. The most significant overall results on traffic flow with increasing traffic volume were the following:

1. A decrease in average speed and its standard deviation.
2. An increase in delay.
3. An increase in the number of passes and aborts.
4. An increase in the number of vehicles passed.
5. An increase in the number of possible accident conditions (emergency indicators).
6. A decrease in the average safety margin.
7. An increase in the number of speed change cycles.

The following comparisons were made with Normann's data (4, 5, 6) for 0 percent no-passing zones: (a) total number of passes per hour per mile, and (b) number of passes per vehicle per hour per mile. The results are shown in Figure 5.

TABLE 1

EFFECT OF NO-PASSING ZONES WITHOUT KNOWLEDGE OF ONCOMING CAR SPEED

Operation	Run Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Input:																
Volume, vph	100	100	100	100	200	200	200	200	400	400	400	400	600	600	600	600
Speed, ft/sec	68.5	63.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5
Standard deviation, ft/sec	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
% No-passing zones	0	25	50	70	0	25	50	70	0	25	50	70	0	25	50	70
Output:																
Volume, vph	113	113	113	113	237	237	237	237	371	371	371	371	546	543	541	539
Speed, ft/sec	67.6	65.9	65.4	63.8	67.3	66.0	63.9	62.0	66.4	64.1	61.8	57.1	63.6	61.4	59.0	54.8
Standard deviation, ft/sec	9.5	8.8	8.2	9.6	8.0	7.0	7.3	7.6	7.9	7.1	7.4	9.8	6.7	6.4	6.4	8.6
Delay/hour/mile, sec	25	106	296	621	196	501	1177	1828	784	1826	3051	6348	2643	4232	6195	10646
Delay/vehicle/mile, sec	0.2	0.9	2.6	5.5	0.8	2.1	5.0	7.7	2.1	4.9	8.2	17.1	4.8	7.8	11.5	19.8
No. attempted pass/hour/mile	11	9	7	3	39	27	19	8	88	59	35	18	151	99	58	29
No. passes/hour/mile	11	9	7	3	38	26	18	7	85	56	32	16	138	87	51	23
No. pass/vehicle/hour/mile	0.10	0.08	0.06	0.03	0.16	0.11	0.08	0.03	0.23	0.15	0.09	0.04	0.25	0.16	0.09	0.04
No. aborts/hour/mile	0	0	0	0	1	1	1	1	3	3	3	2	13	12	7	6
No vehicles passed/hour/mile	12	10	7	5	40	28	22	9	93	69	41	24	162	103	65	32
Multiple passes, %	5	14	5	37	6	7	22	21	10	23	29	49	16	18	26	39
No. em. ind/hour/mile	1	1	1	0	6	5	3	2	20	16	6	2	53	29	13	5
Average safety margin, sec	33.8	35.9	38.6	31.9	15.7	14.4	14.9	13.7	13.3	12.0	12.8	19.0	8.3	9.0	11.0	14.0
No. speed ch/hour/mile	22	20	17	12	83	69	70	51	213	188	158	150	433	399	296	274
No. speed ch/vehicle/hour/mile	0.2	0.2	0.2	0.1	0.4	0.3	0.3	0.2	0.6	0.5	0.4	0.4	0.8	0.7	0.5	0.5

TABLE 2

EFFECT OF NO-PASSING ZONES WITH KNOWLEDGE OF ONCOMING CAR SPEED

Operation	Run Number															
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Input:																
Volume, vph	100	100	100	100	200	200	200	200	400	400	400	400	600	600	600	600
Speed, ft/sec	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5	68.5
Standard deviation, ft/sec	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
% No passing zones	0	25	50	70	0	25	50	70	0	25	50	70	0	25	50	70
Output:																
Volume, vph	113	113	113	113	237	237	237	237	371	371	371	371	544	542	540	539
Speed, ft/sec	67.6	66.6	65.0	63.0	67.1	65.7	63.4	61.3	65.9	63.2	60.6	55.6	62.9	60.5	58.1	54.1
Standard Deviation, ft/sec	9.5	8.6	8.3	9.8	7.9	7.1	7.4	8.3	7.9	7.6	8.1	11.1	7.0	6.7	7.1	8.6
Delay/hour/mile, sec	29	138	359	751	233	600	1348	2140	1013	2347	3820	7853	3218	5025	7046	11242
Delay/vehicle/mile, sec	0.3	1.2	3.2	6.6	1.0	2.5	5.7	9.0	2.7	6.3	10.3	21.2	5.9	9.3	13.0	20.9
No. attempted pass/hour/mile	11	8	5	1	37	24	15	6	82	50	26	16	133	84	42	17
No. passes/hour/mile	11	8	5	1	37	24	15	6	80	46	24	14	124	77	39	14
No. pass/vehicle/hour/mile	0.10	0.07	0.04	0.01	0.16	0.10	0.06	0.03	0.22	0.12	0.06	0.04	0.23	0.14	0.07	0.03
No. aborts/hour/mile	0	0	0	0	0	0	0	0	2	4	2	2	9	7	3	3
No. vehicles passed/hour/mile	11	9	6	2	39	27	16	7	91	55	29	21	151	99	49	36
Multiple passes, %	5	14	13	38	7	10	10	35	13	19	21	48	21	28	26	(>75)
No. em. ind/hour/mile	1	1	0	0	4	5	2	1	14	7	4	2	37	19	5	4
Average safety margin, sec	36.8	39.1	48.6	24.0	17.2	15.1	17.8	22.2	14.4	13.9	15.8	19.1	10.3	10.7	18.0	18.3
No. speed ch/hour/mile	21	18	16	11	79	63	61	47	205	173	143	131	414	385	248	247
No. speed ch/vehicle/hour/mile	0.2	0.2	0.1	0.1	0.3	0.3	0.3	0.2	0.6	0.5	0.4	0.4	0.8	0.7	0.5	0.5

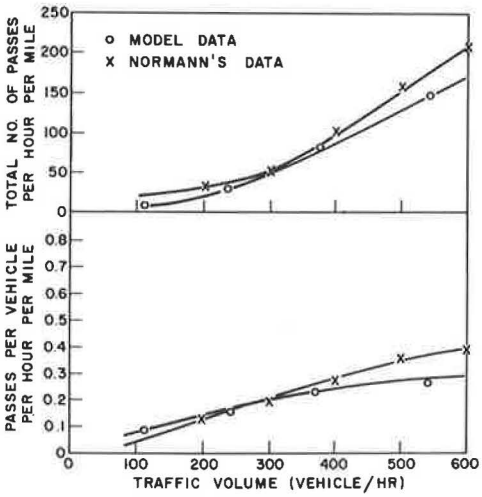


Figure 5. Comparison of model data with Normann's data.

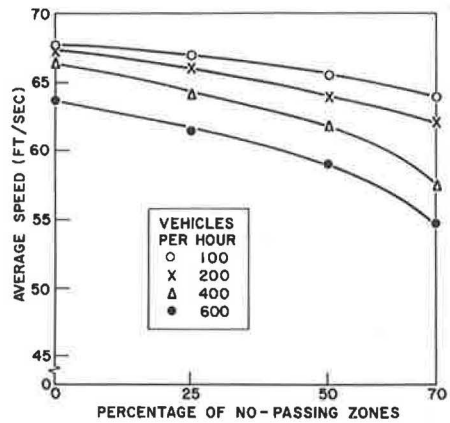


Figure 6. Effect of no-passing zones on average speed.

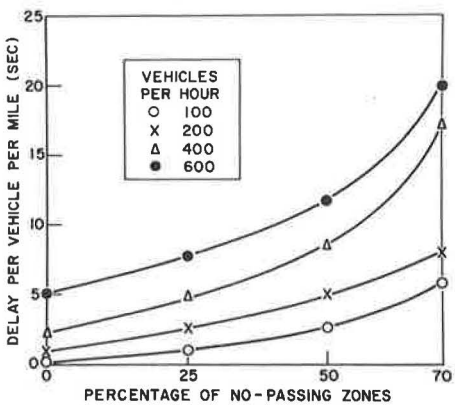


Figure 7. Effect of no-passing zones on time delay.

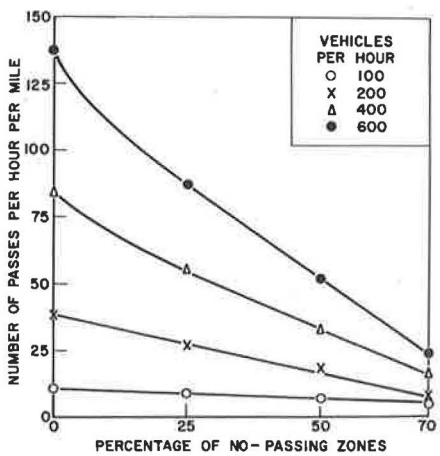


Figure 8. Effect of no-passing zones on passing maneuvers.

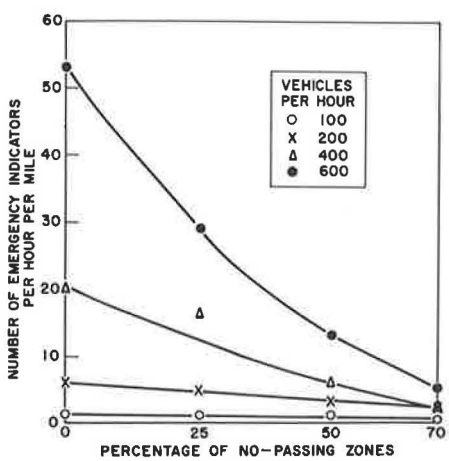


Figure 9. Effect of no-passing zones on emergency indicators.

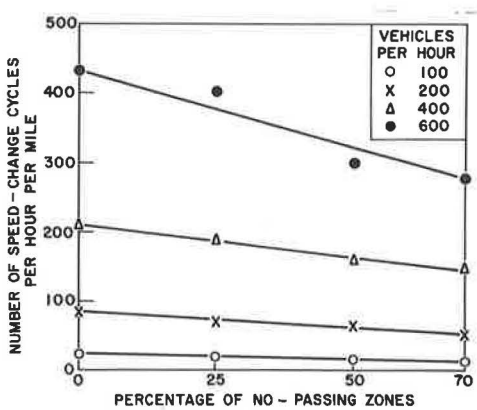


Figure 10. Effect of no-passing zones on speed change cycles.

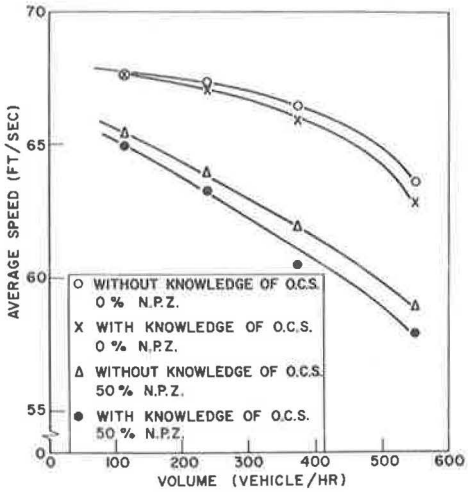


Figure 11. Effect of knowledge of OCS on average speed.

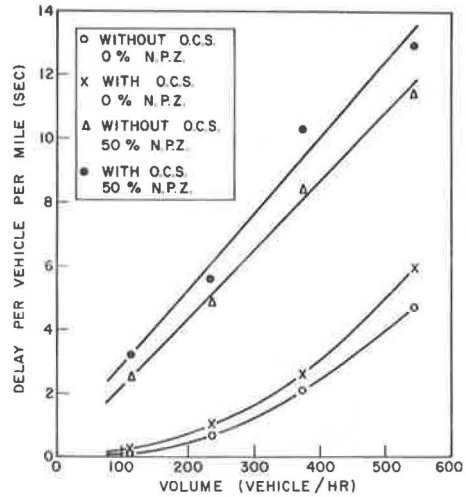


Figure 12. Effect of OCS on time delay.

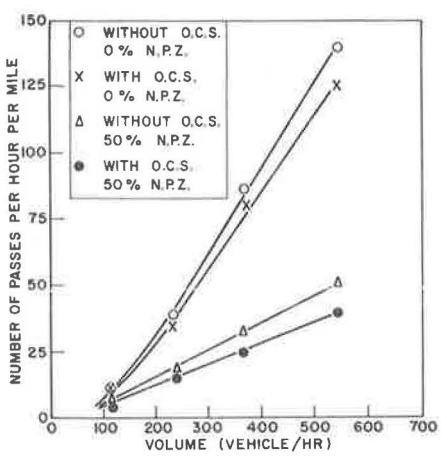


Figure 13. Effect of knowledge of OCS on passing maneuvers.

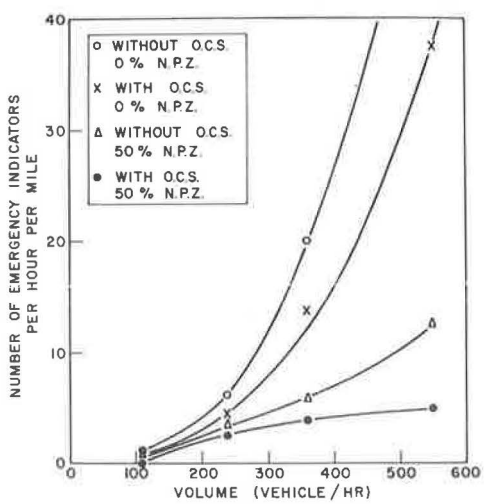


Figure 14. Effect of knowledge of OCS on emergency indicators.

In both instances there seems to be good agreement, at least between the traffic volumes of 100 to 600 vph. Any differences in results could be attributed to the fact that we used a 50-50 directional distribution while in Normann's data a $^2/_3$-$^1/_3$ is used. All of the preceding help to verify the reliability of the model to describe actual road conditions at different traffic volumes.

The following effects were due to no-passing zone configurations.

1. A decrease in average speed as the percentage of no-passing zones increased (Fig. 6).
2. An increase in delay as percentage of no-passing zones increased (Fig. 7).
3. A decrease in the number of passes and number of vehicles passed but an increase in the percentage of multiple passes as the percentage of no-passing zones in-

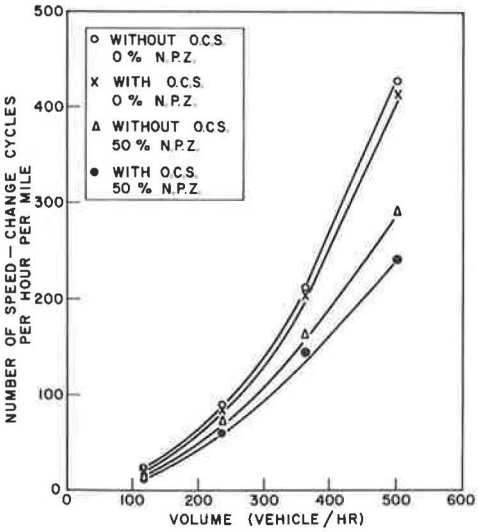


Figure 15. Effect of knowledge of OCS on speed change cycles.

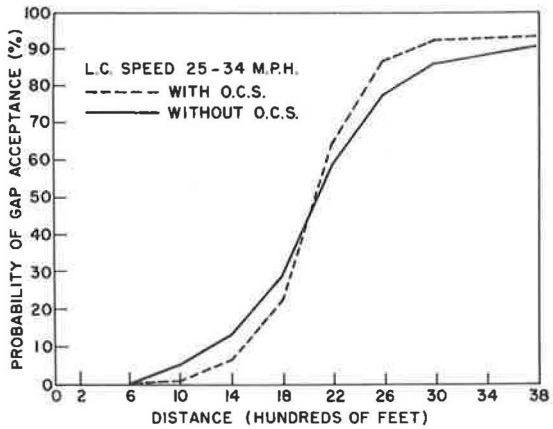


Figure 16. Comparison of passing probabilities with and without knowledge of oncoming car speed.

creased. Figure 8 shows the number of passes per hour per mile as a function of volume and the percentage of no-passing zones.

4. A decrease in the number of possible accident conditions (emergency indicators) as the percentage of no-passing zones increased (Fig. 9).

5. A decrease in the number of speed change cycles as the percentage of no-passing zones increased (Fig. 10).

There was little difference in results when a longer road, or different directional distributions were used while input speed was inversely related to the number of passes.

Effect of Knowledge of Oncoming Car Speed

The traffic flow model was run under the conditions mentioned previously to disclose the effects of providing drivers with knowledge of oncoming car speed. The results of the 16 simulations are given in Table 2.

The effects of providing drivers with knowledge of oncoming car speed as compared to no-knowledge (the previous 16 simulations) were the following:

1. A decrease in the average speed (Fig. 11).
2. An increase in delay (Fig. 12).
3. A decrease in the number of passes (Fig. 13), number of aborts, and number of vehicles passed.
4. A decrease in the number of possible accident conditions. Figure 14 shows the number of emergency indicators with and without knowledge of oncoming car speed for different traffic volumes with 0 and 50 percent no-passing.
5. An increase in safety margin ranging from 9 percent at 100 vph to 24 percent at 600 vph for 0 percent no-passing.
6. A decrease in the number of speed change cycles (Fig. 15).

These results can be partly explained by Figure 16. This is merely one of the curves of Figure 3 and the same curve, with a 50 percent reduction in variance, as shown in Figure 4. The lower part of the curve has been depressed, whereas the upper part has been elevated by the 50 percent reduction in variance.

These changes indicate the following:

1. Unsafe passes or passes with small oncoming gaps have a much lower probability of acceptance, hence occur less often.

2. Large gaps, though accepted now with greater probability, are not as significantly changed as are small gap acceptance probabilities, i.e., they had a high probability of occurrence before and after.

From item 1, a reduction in unsafe conditions, passes and aborts has been caused, hence also a reduction in throughput, since drivers are forced to wait for larger gaps. This would also increase the average safety margin. Also since the probability of accepting gaps ≥ 2,500 feet is so high already, the slight increase in performance at the upper end of the curve does not offset the loss in throughput suffered by depressing the lower end. This seems to verify the results which were calculated in the simulation model for the 16 runs.

The reduction in the number of speed change cycles is a consequence of both a lower standard deviation from the mean speed, and the decrease in the number of passes.

Similar results were also obtained with a 60,000-foot road, input speeds of 42 and 52 mph, or a 60-40 directional distribution.

SUMMARY AND CONCLUSIONS

From the results in the two previous sections the following conclusions can be drawn:

1. When drivers are given knowledge of oncoming car speed on tangents, there appears to be an increase in safety, as shown by the reduction in the number of emergency indicators and increase in safety margin, but the average speed is reduced so that a significant loss in time occurs.
2. As the percentage of no-passing zones increases, there is a marked decrease in throughput as indicated by average speed, time delay, and number of passing maneuvers. The safety on the road, as determined by the emergency indicators, seems to increase slightly (even though the average safety margin oscillates).

These results apply only to the situation where no-passing zones can be removed by road reconstruction or remarking. However, the costs involved to reconstruct roads from, say, 70 percent no-passing to 50 or 25 percent no-passing, is high. Alternately, passing rules arising out of use of remedial aids, which provide drivers with information on oncoming car speed and distance or time headway, could be used to permit passing in no-passing zones. Such remedial aids may provide substantial benefits in throughput and safety at considerably less cost than road reconstruction.

Additional sets of simulations using different passing rules will be run to further investigate the possible use of no-passing zones for passing maneuvers.

The time required for a simulation is directly related to both the traffic volume, road length, and percentage of no-passing zones. At 100 vph using a 30,000-ft road and 0 percent no-passing zones, 1 min of computer time is required for 1 hr of simulation; but at 600 vph using 25 percent no-passing zones and a 60,000-ft road, 30 min of computer time was required for 1 hr of simulation.

ACKNOWLEDGMENTS

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The authors are indebted to the many individuals, organizations and state highway departments who contributed information for use in this study. Particular thanks are due to Stanley R. Byington for his many helpful suggestions and contributions.

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Discussion

STANLEY R. BYINGTON, U. S. Bureau of Public Roads—To recognize the value of the value of the simulation model (SIMMOD) developed by Cassel and Janoff, one must consider that simulation is an intermediate step between mathematical analysis and experimental testing and normally an essential step in the design of a large-scale system. This consideration should include seeking answers to the following questions: (a) what large-scale system design is dependent on SIMMOD; (b) what mathematical analysis has been performed, what experimental testing is contemplated, and how does such analysis and testing relate to SIMMOD; and (c) what are the limitations of SIMMOD?

Following is an examination of the first two questions as they pertain to the Bureau of Public Roads Research and Development program to minimize rear-end and head-on accidents and to increase service volume on two-lane rural highways. Questions pertaining to other possible applications of SIMMOD are then raised, the answers to which are left to Cassel and Janoff. Such answers should give some indication as to the limitations of SIMMOD and where minor modifications can be made to the model to make it more applicable.

SIMMOD and Large-Scale System Design

Can SIMMOD be employed in the design of a large-scale system? This can best be answered by studying the role of SIMMOD in the development of a real world system; namely, a passing aid system called PAS. PAS is an electronic system which will inform motorists of oncoming vehicles beyond their line of sight and judgment capability, as along tangents, and will provide the motorists with information on the adequacy of available passing distance as derived from vehicle closing velocities and existing headways.

The development of PAS is part of an overall program to develop systems and/or procedures for aiding drivers in solving discrimination, judgment, information and vehicle control problems on 2-lane rural highways so as to raise their present level of service. The procedure being followed in developing the aforementioned systems and procedures, including PAS, consists of (a) studying the driver's task to uncover those limiting factors in driver performance (judgmental and operational) that are amenable to improvement; (b) identifying possible remedial aids and screening them through cost effectiveness analysis, experimental study of driver acceptance and use, and review of pertinent existing legal statutes and regulations; (c) developing functional specifications for the most promising remedial devices, procedures or systems; (d) designing and testing a "bread board" prototype of the functionally defined remediation devices; and (e) building and analyzing a field hardened version of the remediation devices.

The role of SIMMOD in developing PAS utilizing the aforementioned procedures is best studied by reviewing the history of PAS. In some cases, past studies and experience have already defined a limiting factor in driver performance (3). For example, the problem of driving on high-volume and/or winding 2-lane rural highways is well known by all those who drive on such roadways. Restricted sight distances, oncoming traffic and adverse environmental conditions make it difficult or impossible to pass slower moving vehicles and, as a result, motorists realize markedly increased travel times and inconvenience. Geometrically restricted opportunities to pass also encourage unsafe passing attempts (7) and may encourage unsafe following conditions, such as tailgating.

In the example, the limiting factor or problem is an insufficient number of passing zones for the frequency of passing maneuvers required by drivers to maintain desired speeds. Remediation for this problem can take two forms: removing the need for adequate passing sight distance or passing zones, and/or providing adequate passing sight distance to establish additional passing zones. Remediations of the first type consist of providing additional traffic lanes at selected locations, such as climbing lanes on grades, or along the entire length of an existing 2-lane rural road through conversion to a 4-lane facility. Another option, but far less desirable, is the exercising of control over the entry of traffic to a roadway and/or the speed at which vehicles are permitted to operate. Either control results in less maneuver freedom for drivers which is really the problem attempting to be solved. Remediation to provide adequate passing sight distance consists of realigning segments of a highway or providing the required sight distance electronically through a system such as PAS.

Screening of the proposed PAS remediation measure initially consisted of mathematically analyzing the costs and benefits of a PAS production model making certain assumptions as to how such a system would eventually be designed and how and where it would operate. Although estimates of costs and benefits used in the analysis were crude, they did serve to point out that implementation of PAS was not outside the realm of economic feasibility. This preliminary benefit-cost analysis, together with subsequent experimental study on possible system use by drivers and examination of the system's legal aspects, indicated that further development of PAS was warranted. Still, a more detailed economic evaluation of PAS was needed to answer questions like the following:

- Under what traffic volume conditions should PAS be operated?
- How do geometric conditions, such as intersections and ratio of passing to no-passing zone mileage, affect the possible benefits of PAS?
- How are PAS benefits affected by the accuracy with which information is transmitted to drivers? (A wider spacing of sensors to detect the presence, direction and velocity of vehicles will result in lower system cost but will reduce system benefits through the need for larger safety factors.)
- How does the percentage of drivers who use the system affect the economic feasibility of PAS?

All of these questions can be initially studied using SIMMOD. Eventually, however, a system like PAS must be experimentally analyzed on a real highway with respect to its reliability, accuracy, maintainability and economic feasibility. Thus, it is planned that PAS will be installed on 50 miles of rural highway and analyzed under normal driving conditions, proceeding from the highly controlled situation using test subjects to the standard uncontrolled situation with normal traffic. In the meantime, though, a simulation model like SIMMOD can be effectively employed in determining the potential usefulness of such a system and in the actual design of the system.

Limitations of SIMMOD

The preceding discussion certainly lends evidence as to the possible usefulness of SIMMOD, but what are its limitations? Answers to the questions below should, in part, answer the primary question just stated.

1. Can the model handle the overtaking maneuver?
2. How is passing performance measured?
3. What kinds of remedial-aid devices can be evaluated using SIMMOD?
4. How would slow-down factors be introduced into the model?
5. How is SIMMOD different from other (ITTE model and Shumate and Dirkson's model) 2-lane road simulation models?
6. Can the model handle both types of passes, accelerative and flying?
7. What constitutes a speed change within the model?
8. Of what value is the measure of number of accidents within SIMMOD? (Accidents are such a rare event that even lengthy runs of the model would produce no accidents.)

Treatment of at least some of the above questions by Cassel and Janoff, in their closing statement, should serve to benefit those who are interested in making use of SIMMOD, or a modification thereof, for their own purpose.

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F. G. LEHMAN, Newark College of Engineering—This paper represents a good application of the digital simulation technique to a specific type of highway traffic problem. Whenever a suitable model is found, simulation is an efficient tool for determining the effects of parameter changes such as the authors have done for number of no-passing zones, traffic volumes, etc.

The objectives of the study are well conceived and very clearly stated. The authors should be commended on the carrying out of their objectives in a very direct manner. It is apparent that the work has been done in close relation with people in highway practice.

The heart of this study is the model of the passing maneuver, knowledge of which must come from human factors data. In this work, a simple, logical model is based primarily on a set of probability functions for gap acceptance and changes in these functions with the passing driver's knowledge of oncoming car speed. Data for these functions have been supplied from a recent study referenced in the paper. Because of the importance of these data for the present study, the validity of this previous study is crucial. Some background information establishing this previous work as authoritative would increase confidence in the validity of the model.

Because simulation studies are often suspected to be academic exercises, it is necessary to build up a strong case for validity. This the authors have attempted to do by carefully analyzing their results in the light of experience, reason, and real data. A case in point where a more acceptable check is desired is the comparison with Normann's data in Figure 5. On the basis of curve shape, the comparison is good, but the difference in values between model data and real data is rather significant. The authors explain this difference by attributing it "to the fact that we used a 50-50 directional distribution while in Normann's data a $\frac{2}{3}$-$\frac{1}{3}$ is used." Why did not the authors program for a set of runs using the same directional distribution? However, only initial results have been presented. It is expected that other model tests against real data are being planned to further demonstrate the reliability of the simulation results.

Before applying the results of a simulation study, it is necessary to observe the caution that such results can show the feasibility of certain types of remedies but do not prove that they will be effective. The importance of the human factors in the situation should receive strong recognition.

ARNO CASSEL and MICHAEL S. JANOFF, Closure—The authors would like to thank Mr. Byington and Dr. Lehman for their remarks concerning this paper. However, a few additional comments are warranted based on the questions raised.

In reply to Byington's questions:

1. Any overtaking maneuver which is not converted immediately to a potential passing maneuver is instead converted to a following condition at some safe distance.

2. Passing performance is measured directly both by the number of attempted passes, actual passes, aborts and emergency indicators, and indirectly by average speed and

delay. An increase in passing performance would be indicated by an increase in both the number of passes and the average speed and a decrease in aborts, emergency indicators, and delay.

3. The model can test any type of remedial aid that would input a rule (or set of rules) by which a pass-no-pass decision could be made as in the following two examples:

Example 1: Pass if the oncoming gap is greater than or equal to a fixed number of seconds (fixed number of feet); no-pass if less than this value.

Example 2: Passing rules determined by the probability curves presently used in the model.

4. Slow down factors are presently being used for trucks on uphill grades and could be extended to other vehicles. A uniform deceleration is used on the uphill grades with a uniform acceleration on the downhill. A crawl speed of 20 ft/sec is presently being used in the model.

5. Our model differs from other simulations in that the main feature, the passing maneuver, is treated superficially in other models. We can employ various passing rules which simulate specific types of remedial aids and then measure the benefits; other models have no more than one passing rule.

6. The model presently converts all possible passing situations into accelerative passes but with minor logistical changes flying and accelerative passes could be treated distinctly by deleting the condition mentioned earlier that vehicles must be traveling at a speed less than desired speed to enter a potential passing situation.

7. A speed change cycle, as calculated in the model, is a change in operating speed from and back to a given speed. These occur mainly when slowing down due to congestion or when performing passing maneuvers.

8. The calculation of the number of projected accidents is not used in any economic analysis but is merely a check on the validity of the model. To date, less than 6 projected accidents have appeared during the simulation runs.

In reply to Lehman's questions:

The reliability of the original empirical data which were used to derive the probability curves presently being used has been discussed in the final report of our first contract. But, basically these data were the result of 2000 passing observations made on a 2-lane rural road in southern New Jersey. It would be desirable to repeat these tests in different geographical areas and under different road configurations as verification but this has not yet been accomplished. Also, the median of the accepted distances (i.e., the accepted oncoming gaps) was theoretically appropriate for the given oncoming car speed distribution encountered.

The second question of basing the differences on a difference in directional distributions has been partially answered by additional simulations.

After running the model at a 60-40 distribution and noticing little difference in output, further simulations at other input speeds were accomplished. At higher operating speeds, typical of lower traffic volumes, a decrease in the number of passes per vehicle was obtained, while at lower operating speeds, coinciding with greater traffic volumes, an increase in the number of passes per vehicle was obtained. These changes caused a better fit of the model data to Normann's data in Figure 5.