Development of Speed-Flow Relationships for Indonesian Rural Roads Using Empirical Data and Simulation

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Highway capacity manuals from developed countries cannot be applied successfully in Indonesia because of large differences in driver behavior, traffic composition, and level of roadside activities. The Indonesian Highway Capacity Manual project was started in 1990 and has resulted in interim manuals for urban traffic facilities, interurban roads, and superhighways. Speed-flow relationships for interurban rural roads have been obtained from a combination of direct speed-flow measurements and simulation, using the VTI microscopic simulation model for two-lane, two-way undivided roads. The empirical data were used mainly for calibrating and validating the simulation model and for analyzing the effect on speed and capacity of cross-section and environmental conditions. The simulation model was used for determining speed-based light-vehicle units (used instead of passenger-car units and speed-flow relationships for flat, rolling, and hilly terrain. The results can be summarized as follows: (*a*) the light-vehicle free-flow speed for a flat two-lane, two-way road at ideal conditions is considerably lower in Indonesia than in developed countries; (*b*) free-flow speed is reduced by road width and side friction such as public transit stops, pedestrians, nonmotorized vehicles, and entries and exits from roadside properties and minor roads; (*c*) Indonesian drivers tend to overtake at short sight distances, which reduces the slope of the speed-flow curve; and (*d*) the capacity for two-lane, two-way roads is slightly higher in Indonesia than in developed countries.

Capacity values and speed-flow relationships used for planning, design, and operation of highways in Indonesia mainly have been based on manuals from Europe and the United States. Studies at the Institute of Technology in Bandung in the 1980s, however, showed that these sources might produce misleading results, possibly because of the high content of small utility vehicles and motorcycles on Indonesian roads and the side friction caused by roadside activities. The Indonesian Highway Capacity Manual (IHCM) project started in 1990 and so far has resulted in interim manuals for urban traffic facilities (*1*) and interurban roads and superhighways (*2*). The last phase of the IHCM project, including development of traffic engineering guidelines and computer software and implementation in national road management systems, will be completed in 1996.

Although the term "rural roads" is used in the title of the paper, it must be noted that the data base for the analysis also includes roads with considerable roadside development, residential and commercial. This development can be nearly continuous even far away from major urban areas because of the very high population density and difficult topography in many parts of Indonesia. Java, for instance, has a population of 115 million in an area smaller than Florida.

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DATA COLLECTION

Analysis Strategy

In determining speed-flow relationships from empirical speed-flow data for even a limited number of standard road classes, traffic, and environmental (roadside) conditions, it is necessary to conduct data collection at a very large number of sites. Another way is to use a simulation model calibrated for actual driver behavior and vehicle characteristics. A combination of these two methods was used in the IHCM project. The empirical data were used mainly for calibrating and validating the simulation model and for analyzing the effect on speed and capacity of cross-section and environmental conditions. The simulation model was used primarily for determining light-vehicle units (LVUs, instead of passenger-car units, as explained later) and speed-flow relationships at different horizontal and vertical alignments.

Vehicle Classes

The Indonesian Highway Administration distinguishes between 13 classes of vehicle for its routine classified counts. In the data collection for the IHCM project, the following seven vehicle classes and their average traffic compositions were distinguished:

- Light vehicles (LVs): passenger cars, jeeps, minibuses, pickups, microtrucks (58 percent).
- Medium heavy vehicles (MHVs): two-axle trucks with double wheels on the rear axle, buses shorter than 8 m (22 percent).
- Large trucks (LTs): three-axle trucks (2 percent).
- Truck combinations (TCs): truck plus full trailer, articulated vehicle (2 percent).
- Large buses (LBs): buses longer than 8 m (5 percent).
- Motorcycles (MCs): (11 percent).
- Unmotorized vehicles (UMs): mainly tricycles and bicycles (<1 percent).

The number of vehicle classes considered in IHCM was later reduced by including the truck combinations in the large-truck category and by considering unmotorized vehicles as elements of side friction rather than traffic flow.

Data Collection Methodology

Data were collected in the field during 1991–1993 at 150 sites, including 35 interurban road sections with continuous residential or commercial roadside development that were surveyed during the urban phase of the project. The basic survey equipment at each site included one or more short-base measurement stations equipped with pairs of pneumatic tubes (spacing of 3 m) connected to data loggers for recording vehicle axle passage times. By means of specialized software traffic flow and composition, space mean speed and headways were obtained automatically and cross-checked with the backup video recordings.

All side friction events were recorded manually, and all vehicles passing the short base were continuously video recorded. Through video data reduction (visual matching) of vehicles passing successive short-base stations, travel time and frequency of overtaking vehicles were also obtained for longer road sections in different terrain types.

Nine overtaking surveys using continuous, stationary video recording of about 1-km segments of roads in combination with overtaking observations from a moving observer vehicle equipped with cameras pointing forward and backward were also made. Sight distances were measured with the help of roadside markers or existing electrical poles that were visible in the video recordings (Figure 1).

SIMULATION MODEL

Description of Model

The VTI Road Traffic Simulation Model System (*3*), developed by the Swedish Road and Traffic Research Institute, was used in the IHCM project. The VTI model is "event-controlled" and programmed in SIMULA. It describes traffic operation on a two-way, single-carriageway road at a microscopic level, in which the movements of individual vehicles are modeled as they "progress" along a defined road segment in the computer (Figure 2).

Each movement is determined from a set of stochastic attributes defining the driver behavior and the vehicle characteristics. The position and current speed of each vehicle is calculated on the basis of driver decisions, which in turn are related to external factors such as road alignment and interference with other vehicles in their own or the opposing stream.

FIGURE 1 Short-base measurement station along road section equipped with roadside markers for overtaking survey.

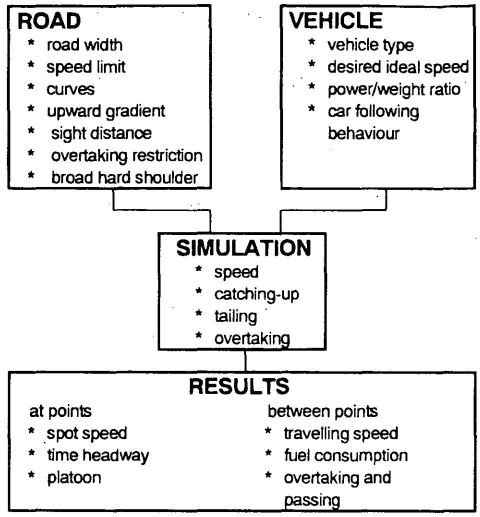

FIGURE 2 Overview of VTI simulation model for two-way roads.

Calibration of Model

The following calibrations of the VTI model for Indonesian conditions were performed on the basis of the field studies:

- Base free-flow speed for ideal road and environmental conditions;
- Free flow speed at different road cross sections, roadside land use, and side friction;
- Speed in horizontal curves;
- Variation of speed around the average value (median speed);
- Distribution of used driving power for each vehicle class (determines the ability to retain the speed of a vehicle in an upgrade);
- Mean time headway value between vehicles in a platoon (mean time headway for constrained vehicles); and
- Overtaking functions, on the basis of a function named the Gompertz model. The expression for this function is as follows:

$$\omega = \exp[-A \exp(-ks)] \qquad (1)$$

where

ω = overtaking probability (proportion of drivers accepting overtaking opportunity), A,
k = calibration constants, and
s = free sight distance (m).

The median value s_{50}, the sight distance that 50 percent of the drivers accept and the other 50 percent reject, is called the critical sight distance. It is described by the following equation:

$$S_{50} = \frac{\ln(A/\ln 2)}{k} = \frac{\ln A}{k} + \frac{\ln 1.443}{k} \qquad (2)$$

Table 1 presents the calibration constants and the calculated overtaking probabilities for accelerating or flying overtaking with a visible oncoming vehicle. Drivers performing flying overtakings accepted very short sight distances, and there was only a weak influence of the speed of the overtaken vehicle.

TABLE 1 Functions for Overtaking Behavior with Visible Oncoming Vehicles

Overtaken vehicle	Speed at overtaking	Type of over-taking	Calibr const Equation (1) A	Calibr const Equation (1) $k \cdot 10^3$	Critical sight distance (m) s_{50}
LV, LB	≥60	acc.	4.71	3.40	564
LV, LB	<60	acc.	6.20	7.25	302
MHV,LT	≥45	acc.	6.71	4.00	568
MHV,LT	<45	acc.	2.61	3.45	384
LV	>0	flying	3.38	21.0	75
LB	>0	flying	4.65	10.0	190
MHV	>0	flying	3.50	18.0	90
LT	>0	flying	3.55	11.9	137

Validation of Model

The calibrated model was validated using observed journey speed, overtaking ratio, and degree of bunching data from three specially designated long-base sites ranging from 3 to 7 km. The field data were compared with corresponding data from simulation runs with the same road and traffic characteristics. Few differences above 3 km/hr between observed and simulated speed occurred; the average difference was about 1 km/hr. Similarly good correspondence between observed and simulated data was obtained regarding overtaking ratios and degree of bunching (leading headway <5 sec). It was therefore concluded that the model could be used to simulate the traffic process on Indonesian two-lane, two-way undivided (2/2 UD) roads.

FREE-FLOW SPEED ANALYSIS

Base Free-Flow Speed

Free-flow speed was determined for unobstructed vehicles defined as vehicles with a headway to the nearest vehicle in front of more than 8 sec and no recent or immediate meeting with a vehicle in the opposing direction (±5 sec). To evaluate the effect on free-flow speed of different site conditions, regression analysis was performed with travel time (TT) as dependent variable with the following regression equation:

$$TT = 1/V_{LV} = \text{constant} + B * X + C * Y + D * Z \ldots \quad (3)$$

where

V_{LV} = speed of light vehicles (km/hr)
$X, Y, Z, \ldots$ = selected independent variables, and
$B, C, D, \ldots$ = regression coefficients.

When significant independent variables had been identified with stepwise multiple regression, the data base for 2/2 UD roads was normalized for a set of ideal conditions as follows:

- Carriageway 7 m wide,
- Shoulders 1.5 m wide and usable for parking but not driving,
- Undeveloped roadside land use,
- No side friction,
- No minor road access,
- Arterial road function, and
- Sight distance of 75 percent of the road section more than 300 m.

The free-flow speeds calculated for these conditions, called base free-flow speeds, were reviewed with simulation results and checked for consistency. The resulting base free-flow speeds used in IHCM are given in Table 2.

Terrain type describes the hilliness of the area through which a road passes and is defined by the total rise plus fall (in meters per kilometer) and the total horizontal curvature (in radians per kilometer) over the road segment (Table 3). (Values in parentheses were used to develop the graphs for standard terrain types in IHCM).

Free-Flow Speed for Actual Conditions

The regression analysis described in the previous section showed that free-flow speed was affected primarily by roadway width, side friction, and road functional class (arterial, collector, or local). Figure 3 illustrates empirical results of the influence of carriageway width.

In Indonesia often a great deal of activity occurs at the edge of the road, both on the roadway and on shoulders and sidewalks, which interacts with the flow of traffic, causing it to be more turbulent and hurting capacity and performance. The following side friction events were recorded manually in the IHCM field surveys:

- PED: number of pedestrians, whether walking or crossing,
- PSV: number of stops by small public transport vehicles (motorized as well as nonmotorized) plus the number of parking maneuvers,
- EEV: number of motor vehicle entries and exits into and out of roadside properties and side roads, and
- SMV: slow-moving vehicles (bicycles, trishaws, horsecarts, oxcarts, etc).

TABLE 2 Base Free-Flow Speed FV_0, 2/2 UD Road

	Base Free-Flow Speed FV0 (km/hr)				
Terrain Type	LV	LB	MHV	LT	MC
Flat	68	73	60	58	55
Rolling	61	62	52	49	53
Hilly	55	50	42	38	51

TABLE 3 Definition of General Terrain Types

Terrain Type	Vertical Curvature: Rise + Fall (m/km)	Horizontal Curvature (rad/km)
Flat	<10 (5)	<1.0 (0.25)
Rolling	10–30 (25)	1.0–2.5 (2.00)
Hilly	>30 (45)	>2.5 (3.50)

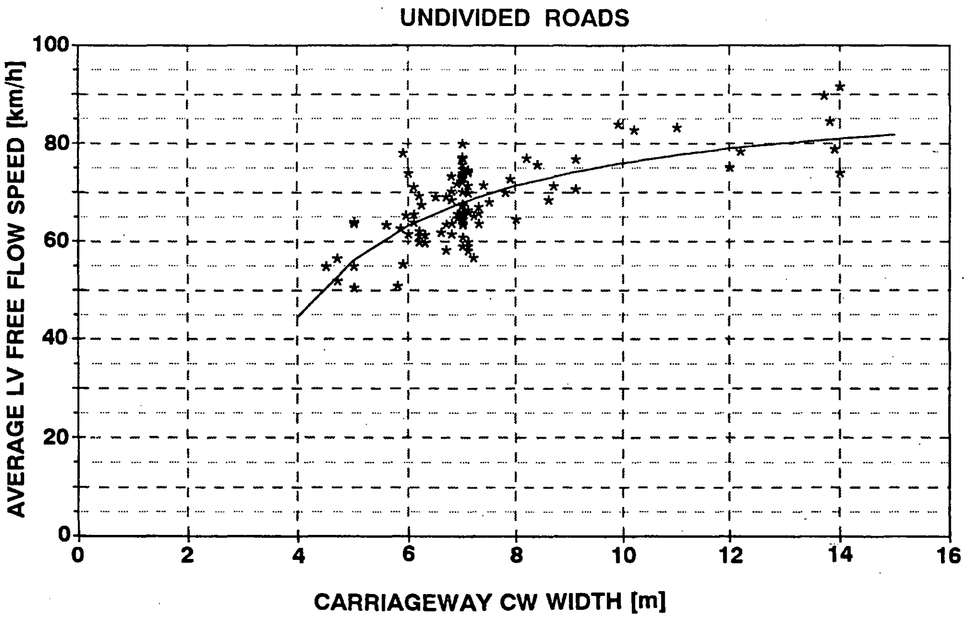

FIGURE 3 Relationship between carriageway width and free-flow speed for light vehicles.

To reduce the number of variables in the speed-flow analysis, a single measure of side friction (FRIC) was determined empirically equal to the sum of the weighted impacts of each of the four frictional items just described.

$$FRIC = 0.6 \times PED + 0.8 \times PSV + 1.0 \times EEV + 0.4 \times SMV$$

Five side friction classes relating to the value of FRIC were also predetermined:

Class	*Value of FRIC*
Very low	<50
Low	50–149
Medium	150–249
High	250–350
Very High	>350

The impact of side friction was shown to be related to shoulder width, with a 16-km/hr speed reduction for very high side friction at shoulder widths below 1.0 m, a 12-km/hr speed reduction at 1.5-m shoulder widths, and a 5-km/hr speed reduction at shoulders wider than 2 m. If there was no side friction, shoulder widths (range 0.5–3.0 m) had no significant impact on free-flow speed.

Road function class and land use had a speed reduction range from 0 km/hr for arterial and 0 percent land use to 11 km/hr for local and 100 percent land use (roadside development).

The actual free-flow speed for each vehicle type can be calculated in IHCM as follows:

$$FV = (FV_0 + FFV_W) \times FFV_{SF} \times FFV_{RC} \qquad (4)$$

where

FV = free-flow speed for actual conditions (km/hr),
FV_0 = base free-flow speed for predetermined standard (ideal) conditions,
FFV_W = adjustment for effective carriageway width,
FFV_{SF} = adjustment for side friction, and
FFV_{RC} = adjustment for road functional class and land use.

DETERMINATION OF LIGHT-VEHICLE UNITS

In determining general speed-flow relationships for mixed traffic flows, it is necessary to convert the different vehicle types into a uniform unit. This is very important in a developing country because of the large variations in traffic compositions. Light-vehicle units, or LVU, were determined for each category instead of passenger-car units (PCU) because of the low frequency of passenger cars outside major cities in Indonesia. Free-flow speed for a passenger car is typically 5 to 10 km/hr higher than for an average light vehicle.

The primary methodology used for determining LVU was by means of simulation using the Swedish VTI model. Additional analysis using 5-min speed-flow data from selected sites in flat terrain was performed. The criterion of equivalency for speed-based LVU was the effect of different vehicle types on the speed of light vehicles, with LVU for light vehicles = 1.0.

Analysis was also performed using a capacity equivalency criterion for determining capacity-based LVU as described in the following.

Speed-Based LVUs

Determination of LVU by Simulation

The simulation model was used to determine LVU for different general terrain types for roads with 7.0-m roadway width and medium side friction. The journey time for light vehicles (TT_{LV}) was observed as the dependent variable and calculated for each subsection of the roads and for their total length. The LVU value for each vehicle type was calculated according to following formula:

1. Define the journey-time-flow constant for LV at 100 percent LV in the traffic flow as

$$\Delta T_{LV} = \left(\frac{1}{V_{1,200}} - \frac{1}{V_{600}}\right) \cdot 3{,}600/600 \quad (5)$$

where V_{600} and $V_{1,200}$ are the space mean speeds (km/hr) for LV at traffic flow 600 and 1,200 veh/hr with 100 percent LV. The flow levels represent a normal traffic flow range for interurban roads. The calculation is done in journey time since the speed-based LVU is determined regarding the effect of different traffic compositions on space mean speed.

2. Define in the same way the journey-time-flow constant for LV at the proportion p of LV and the proportion $1 - p$ of Type X as

$$\Delta T_{p,X} = \left(\frac{1}{V_{1,200}} - \frac{1}{V_{600}}\right) \cdot 3{,}600/600 \quad (6)$$

where V_{600} and $V_{1,200}$ now are the space mean speeds (km/hr) for LV at traffic flows with the proportion p of LV.

3. The LVU for vehicle type X can now be calculated as

$$p\Delta T_{LV} + (1 - p)\,\alpha\Delta T_{LV} = \Delta T_{p,X} \quad (7)$$

where α is the LVU value.

In this way LVU values for three terrain types were obtained, as shown in Table 4. Since the simulation model did not include motorcycle traffic, the LVU for MC could not be determined using this method.

Determination of LVU from Empirical Speed-Flow Data

The assumptions underlying this regression analysis were that the speed-flow relationship is linear and that LVU therefore could be determined from least-square fits of speed-flow samples with different traffic composition:

$$V_{LV} = A - K_{LV} \cdot Q_{LV} - K_{MHV} \cdot Q_{MHV} - \ldots - K_{MC} \cdot Q_{MC}$$

where

V_{LV} = speed (km/hr),
A = constant representing free-flow speed,
Q = traffic flow for each vehicle type (veh/5 min), and
K = speed reduction effect caused by specific vehicle type.

The LVU were obtained as the ratio between the K-coefficient for a specific vehicle type and for light vehicles: for example,

$$LVU_{MHV} = K_{MHV}/K_{LV}$$

For flat roads, MHV = 1.5, LB = 1.2, LT = 2.7, and MC = 0.8. The LVUs for MHV, LB and LT were thus very similar with the results obtained with simulation.

Capacity-Based LVUs

At levels of high traffic flow, most vehicles are traveling in platoons. Speed-based LVUs do not represent the relative impact of different vehicle types at such conditions, leading to a need for a second set of LVUs based on a capacity equivalency criterion.

TABLE 4 Speed-Based LVU Determined by Means of Simulation

Terrain Type	Vehicle Class MHV	LB	LT
Flat	1.5	1.4	2.7
Rolling	2.0	1.6	4.5
Hilly	4.5	1.8	12.5

Capacity-based LVU can be determined by analyzing time headways of a single stream of vehicles during congested conditions (*4*). According to this method, the headway for a particular vehicle type (e.g., MHV) can be determined as follows:

$$LVU_{MHV} = H_{MHV}/H_{LV}$$

where H_{MHV} is the mean headway between an MHV following an MHV during the passage of the stop line or conflict point, and H_{LV} is the mean headway between an LV following an LV during the passage of the stop line or conflict point.

Since the Indonesian surveys covered only a few cases of single-stream flow at capacity level on rural roads, headway data for bunching conditions (headway < 5 sec) on such roads were analyzed. Significant LVU results were obtained only for MHV in flat terrain (LVU = 1.2). The other values were obtained in combination with engineering judgment (Table 5). Transition from speed-based to capacity-based LVU in IHCM is based on the actual traffic flow (in vehicles per hour) in a number of predefined flow classes for different road types. Capacity-based LVU are used for determining the degree of bunching.

Synthesis of LVU Results

The simulation results were compared with LVU results obtained from regression analysis of the speed-flow data. The resulting recommended speed-based LVU are presented in Table 5. The table also gives the capacity-based LVU obtained as described earlier.

SPEED-FLOW RELATIONSHIPS

Speed-Flow Modeling Using Simulation

The VTI simulation model was used to produce speed-flow relationships for two-lane, two-way roads in different terrain types. For

TABLE 5 Synthesis of LVU Results for 2/2 UD Roads

Terrain Type	Criterion for Equivalency	LVU LV	MHV	LB	LT	MC
Flat	Speed	1.0	1.5	1.2	2.7	0.8
	Capacity	1.0	1.2	1.5	2.0	0.25
Rolling	Speed	1.0	2.0	1.3	4.0	0.6
	Capacity	1.0	1.3	1.7	2.5	0.25
Hilly	Speed	1.0	3.5	1.5	5.5	0.4
	Capacity	1.0	1.5	2.0	3.0	0.25

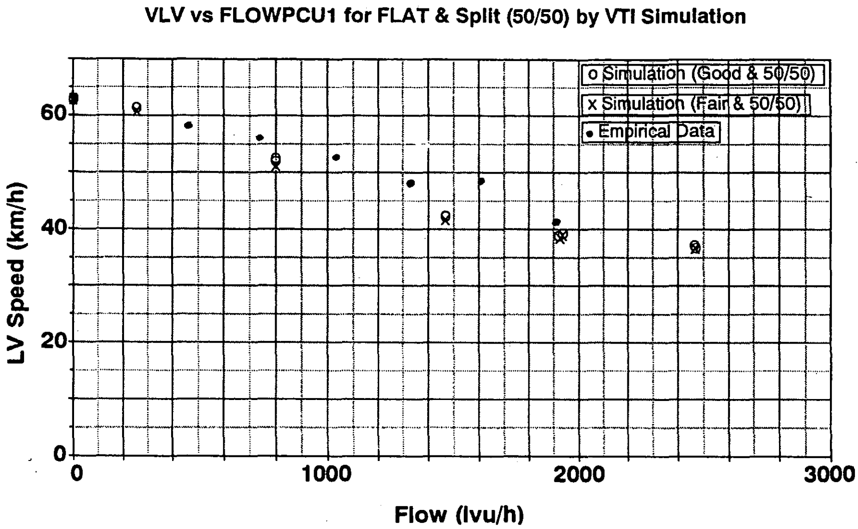

FIGURE 4 LV speed (km/hr) as function of flow (lvu/hr) for flat roads.

flat roads the simulations were performed with two sight conditions, one with 75 percent sight distance above 300 m ("good"), and one with 40 percent sight distance above 300 m ("fair").

Simulations were performed for five traffic flows: 250, 600, 1,200, 1,800, and 2,200 veh/hr. At every flow level a traffic composition of 63 percent LV, 25 percent MHV, 8 percent LB, and 4 percent LT was used, which represented average conditions for the studied roads. Motorcycle traffic was not included in the simulation. Simulations were also made with different directional splits in the traffic flow: 50/50, 60/40, and 70/30. For each case of flow and directional split, two simulations were made to decrease the random effects in the simulation. The results were plotted as speed-flow diagrams, with the flow presented in speed-based LVUs per hour.

Figure 4 presents the speed for light vehicles as a function of the flow for the flat road with 50/50 directional split. The speed-flow curve is almost linear up to 1,700 LVU/hr, at which level there appears to be a knee in the curve. The free-flow speed is 63 km/hr, and the speed at 2,800 LVU/hr is 37 km/hr. The difference between good and fair sight distance conditions is noticeable only in the middle flow range, which may be due to the tendency of Indonesians to overtake with very small accepted sight distances. Empirical speed-flow observations for other roads with the same general characteristics are also shown in the figure; they appear to indicate a more linear relationship.

Simulations of the flat road with different directional splits showed that this variable had very little impact on average speed, maybe because that speed decrease in the direction with more traffic is compensated by a speed increase in the other direction.

Figure 5 presents the speed-flow curve for a road in rolling terrain at different directional splits. The free-flow speed is 54 km/hr. The

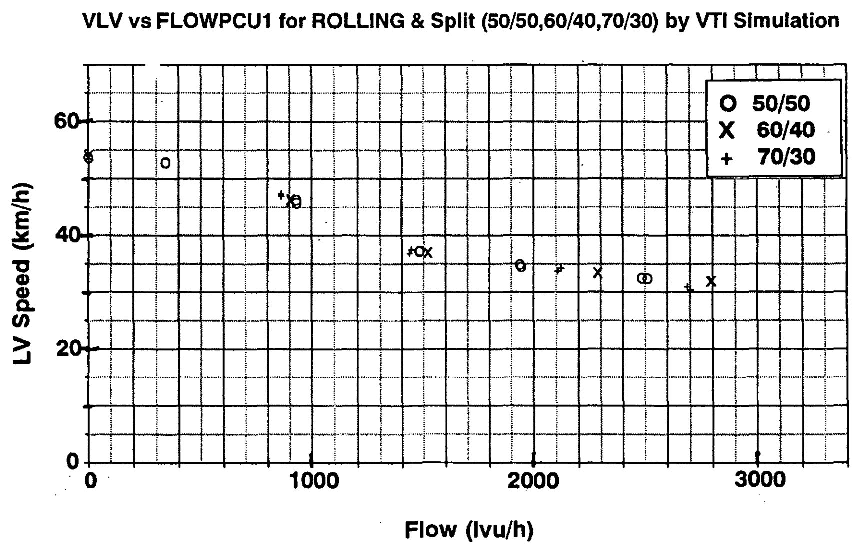

FIGURE 5 LV speed for road in rolling terrain with different directional splits.

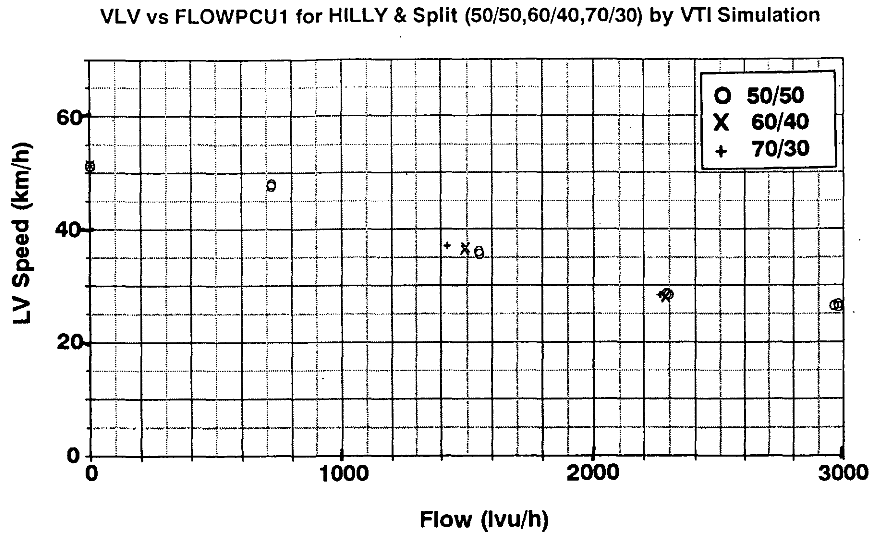

FIGURE 6 LV speed for road in hilly terrain as function of directional split.

shape of the curve is essentially the same as for the flat road, but there is a more clear S-shape, with the steepest drop in speed between 800 and 1,600 LVU/hr. At 2,800 LVU/hr the speed is about 31 km/hr.

The result for the hilly road is presented in Figure 6. The free-flow speed is 51 km/hr. The curve looks very much the same for the rolling road. The steepest drop in speed is between 800 and 1,800 LVU/hr. At a flow of 3,000 LVU/hr, the speed is 27 km/hr.

Speed-Flow Modeling Using Empirical Data

Aggregated short-base 5-min speed-flow data were used to test different speed-flow and speed-density models for flat conditions. Each sample in this data base represents the average speed and flow value for all observed 5-min periods falling in predetermined flow classes for each site. The data base covered 123 sites with a total of 546 sets of flow class average observations.

The impact of site conditions (road width, side friction, land use, road function class, sight distance class) were analyzed with multiple regression. The samples in the data base were then normalized for site conditions deviating from the predetermined ideal conditions for each road class as described earlier.

Speed-density and speed-flow regressions were then made for each road class (e.g., 2/2 UD road 6.5 to 7.5 m wide) with the following models: linear speed-flow model, single-regime, Underwood, May. The linear speed-flow model ($R^2 > 0.6$) was selected for 2/2 UD roads (Figure 7). There was no apparent knee in the relationship as obtained with the simulation. Similar linear

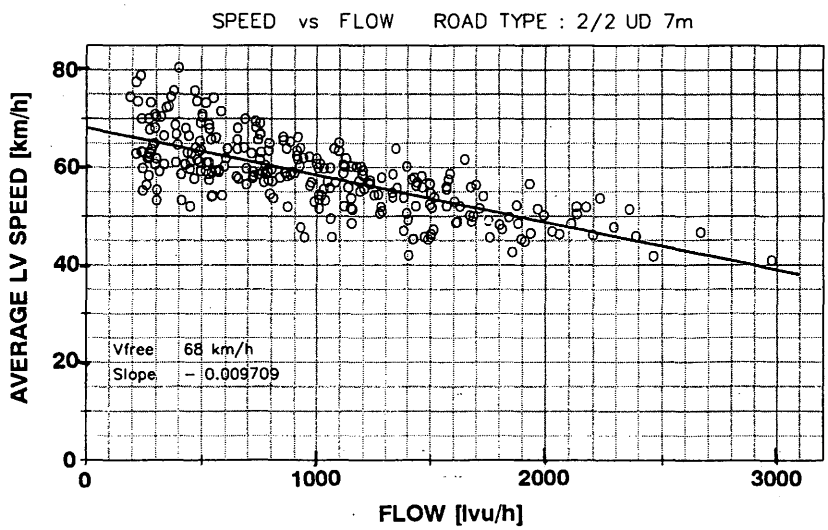

FIGURE 7 Speed-flow relationship for LV, undivided 7-m-wide flat terrain.

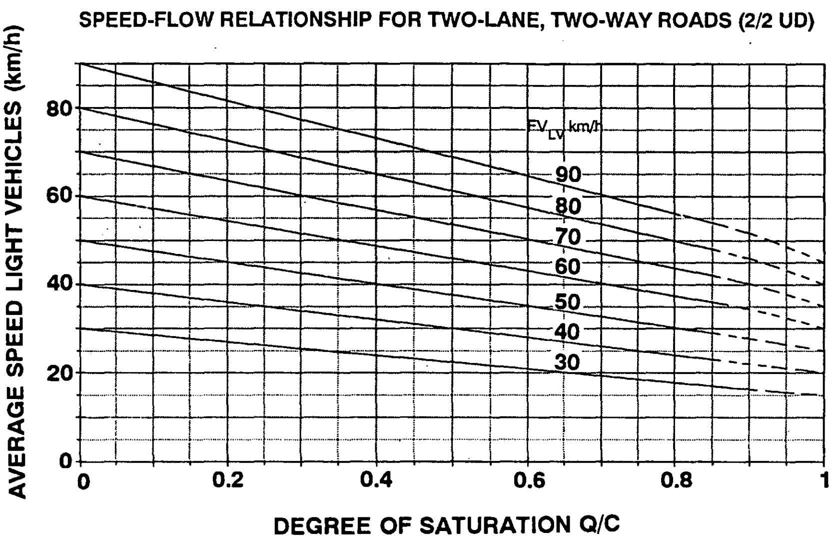

FIGURE 8 Diagram for determination of speed as function of free-flow speed and degree of saturation (*Q/C*).

relationships were obtained for each vehicle type, with the lines converging at a speed of 35 to 40 km/hr at a flow level of 2,900.

Estimation of Capacity

The capacity of 2/2 UD roads was estimated in the following ways:

1. Direct observation of speed and flow rate averages per 5 min. Because of the lack of road sections where the observed maximum flow could be clearly identified as representing the capacity of the road section itself and not of an adjacent bottleneck, only a few observations had been made, of which the highest ranged from 2,800 to 3,000 LVU/hr (Figure 7).
2. Observation of flow rates during short periods of simultaneous bunching conditions in both directions (headways < 5 sec). These observations indicated a capacity ranging from 2,800 to 3,100 LVU/hr.
3. Theoretical estimation from speed-flow-density modeling, showing capacity of about 3,000 LVU/hr occurring at a density of 81 LVU/km.

The conclusion at this stage of the IHCM project was that the base capacity of a 2/2 UD, straight, 7-m-wide road with no side fric-

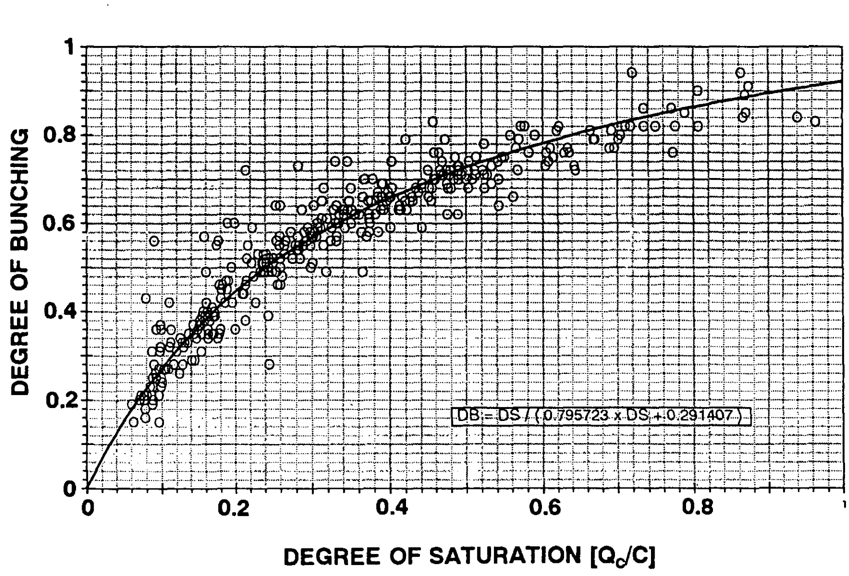

FIGURE 9 Diagram for determination of degree of bunching for 2/2 UD roads.

tion and shoulders of more than 1 m is 2,900 LVU/hr. Capacity is calculated in IHCM as a function of road width (5 to 10 m: adjustment factor 0.81–1.21), side friction/shoulder width [very high (< 0.5 m) to very low (>2 m)]: adjustment factor 0.74–1.03, and directional split (50/50 to 70/30: 1.0–0.88).

SYNTHESIS

The results from the simulation and empirical analysis of speed-flow data taken with the capacity estimations showed that the actual average speed for a particular vehicle type in a mixed flow could be predicted from information of free-flow speed and flow/capacity equals degree of saturation. A diagram for this purpose, which is used in the interim IHCM (*2*), is shown in Figure 8, using a linear speed-flow curve. The method has some similarity to the approach used in the 1992 revision of the HCM (*5*) and in the HDM-Q model (*6*). Similar diagrams based on single-regime speed-flow curves (*7*) have been proposed for multilane roads.

The degree of bunching can also be predicted in IHCM from information on *Q/C* as shown in Figure 9.

The speed-flow relationships and parameter values reported in this paper are the results from the interim IHCM for interurban roads. They are being reviewed and may be revised in the final version, to be published in 1996. The speed-flow relationship may therefore be revised in the shape of a two-part linear model with a breakpoint at a degree of saturation of 0.85. The proposal to use both speed- and capacity-based LVU is also subject to further study.

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Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.