Level of Service on Finnish Two-Lane Highways

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ABSTRACT

Traffic flow data have been collected from 20 automatic traffic recorders on Finnish two-lane highways. Observations were aggregated in 15-minute time intervals plus an optional one-minute extension period using a doubly synchronous counting process. Refined passenger car flow rates were calculated using headways of passenger cars not in a platoon behind a heavy vehicle. In addition to linear speed-flow models, concave models were estimated, as suggested by the theory of Erlander. Speed decrease due to increasing flow rate was smaller on Finnish highways than estimated by the new *Highway Capacity Manual*. Capacity was, however, reached at lower densities so that the HCM 2000 capacity estimates appear plausible. The effects of directional distribution on average travel speed and capacity have been demonstrated and estimated.

1. THEORETICAL OVERVIEW

On ordinary two-lane highways passing vehicles must use the opposing lane. Passing demand is a consequence of speed differences between vehicles. Passing opportunity is supplied when there is a long enough headway in the *oncoming traffic* and a long enough *sight distance.*

If vehicles cannot pass slower vehicles without delay, platoons begin to form. Platooning increases the proportion of short headways and decreases mean speed. In front of slow vehicles there are empty zones, which cannot be used effectively. This reduces the capacity of two-lane highways.

Erlander (1967, 1969, 1971a, 1971b) has developed a model to estimate the average travel speed of traffic on a homogeneous, infinitely long two-lane highway. He applied the sight function of Gustavsson (1967). This model has some important limitations: opposing flow has exponential headways, platooning and passing in platoons are not considered properly, speed changes are instantaneous, and the highway segment considered is infinitely long. These limitations are more severe at high traffic densities. It is, however, assumed that the model can give some information about the effect of flow rates and no-passing zones on average travel speeds.

If there are no passing restrictions and no opposing traffic, the model assumes that vehicles travel at their desired speed and pass without slowing down. The average travel speed is thus equal to the average desired speed, irrespective of flow rate (Figure 1). It is evident that the result is not realistic, especially at high flow rates.

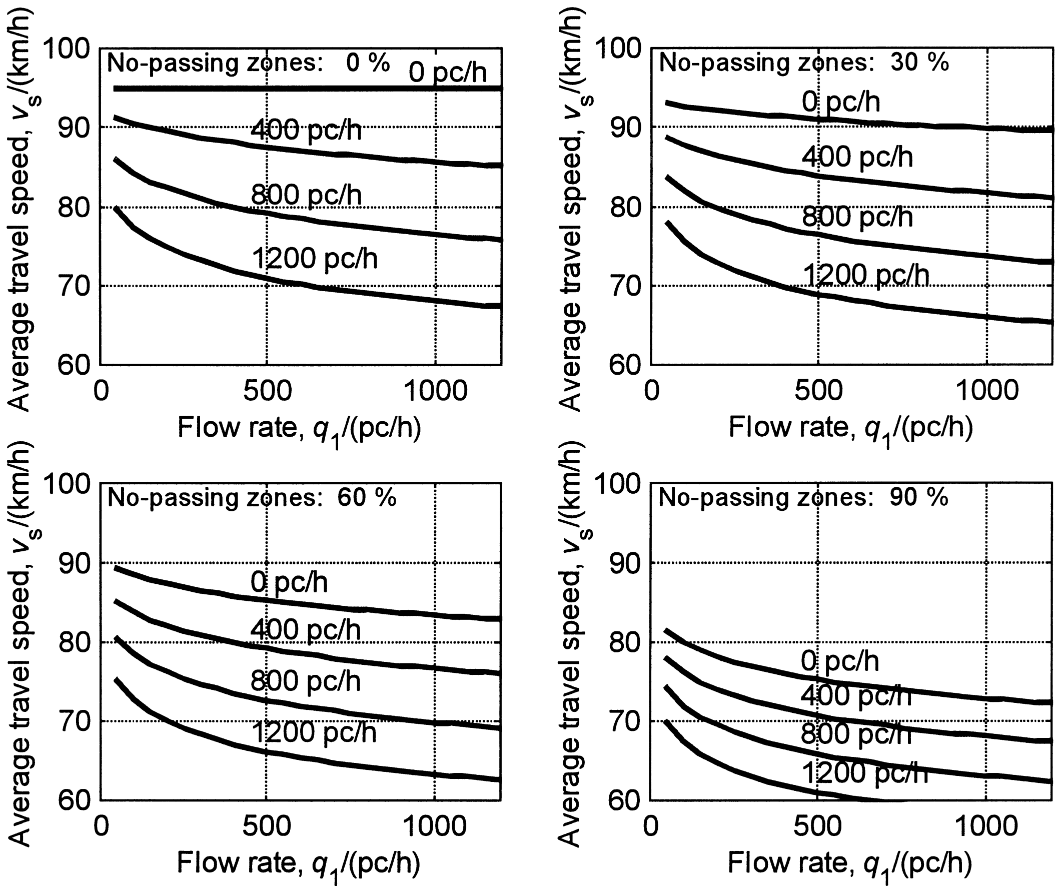

FIGURE 1 Speed-flow diagrams for different levels of opposing flow.

The model produces concave speed-flow curves. Speed decrease is steeper at low flow rates. When both opposing flow rate and percent no-passing zones are high, the initial drop in average travel speed is very steep. On highways with access points and finite travel distances the initial drop is not expected to be as dramatic.

Average travel speed decreases almost linearly as opposing flow rate increases (Figure 2). Average travel speeds decrease as the percentage of no-passing zones increases, but the effect of opposing flow rate decreases. This is intuitive: As one factor limits passing opportunities the effect of other factors diminishes.

2. DATA COLLECTION

2.1 Location of Traffic Counters

Data were collected by 20 automatic traffic recorders (ATRs). The counting periods covered rainless days during summers of 1997 and 1998. The geometric properties of the highway sections (Table 1) were retrieved from the Road Register of the Finnish National Road Administration (Finnra).

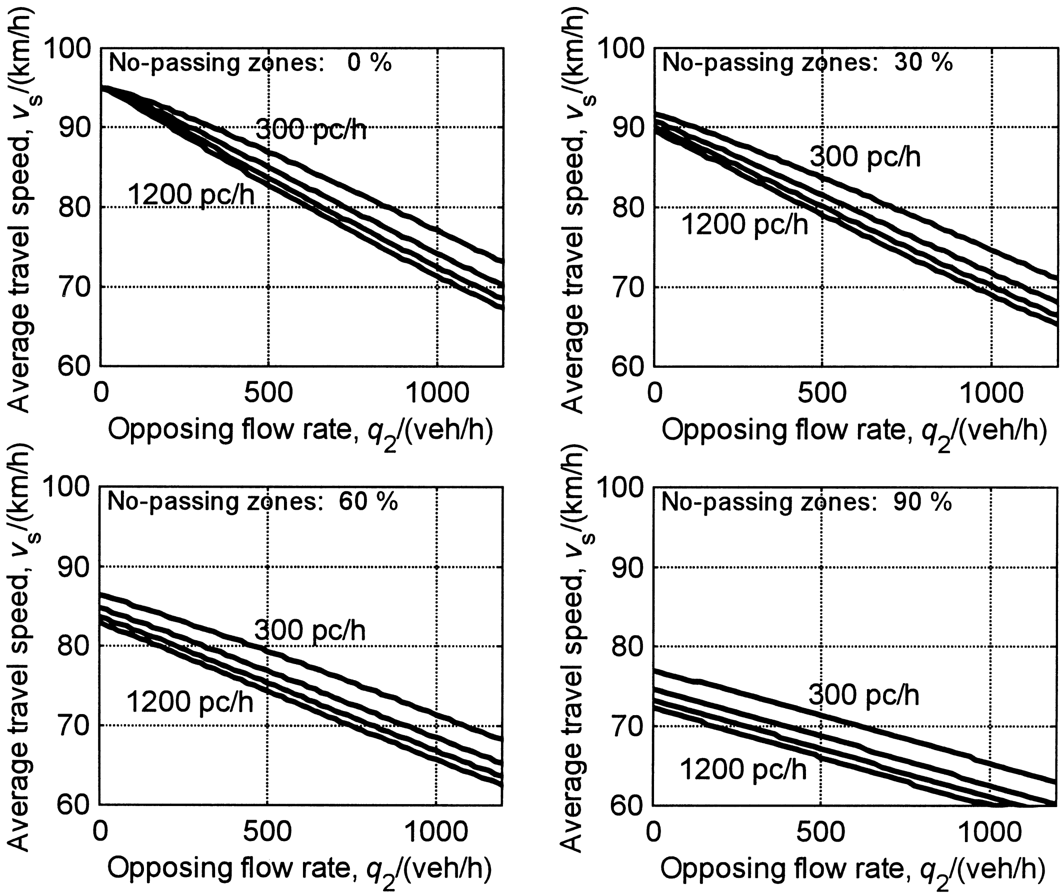

FIGURE 2 Speed-flow diagrams for different levels of flow in observed direction.

2.2 Data Aggregation

In *Highway Capacity Manual* (TRB 1998) the capacities and service flow rates are based on 15-minute time intervals. The same interval length was used in Finland, but in order to minimize the probability of splitting a platoon, each interval was allowed to extend beyond 15 minutes by at most one minute. After 15 minutes the time interval was extended until a headway of at least eight seconds was found in both directions, or until the maximum extension (one minute) was reached. The extension period was limited to one minute in order to avoid significant deviations from the 15-minute base value.

Eight seconds has been found as the threshold value for the exponential tail of headway distributions (Luttinen 1996). Also, for headways greater than eight seconds there was no discernible speed adjustment due to the speed of the vehicle ahead.

TABLE 1 Characteristics of ATR Locations

ATR	Speed Limit (km/h)	Lane + Shoulder (m)	Hilliness (m/km)	Average Curvature (°/km)	No-passing Zones (%)
105	80	3.50+1.00	17	19	26
106	100	4.25+3.00	12	23	8
111	100	3.50+1.00	15	13	29
113	80	3.50+0.50	20	41	30
134	100	3.90+3.00	7	19	10
201	100	3.50+1.00	14	23	35
203	100	3.50+1.50	19	7	11
207	80	3.50+2.00	11	12	8
221	100	3.50+1.00	12	3	14
433	100	3.50+1.25	10	10	10
436	80	3.75+2.00	17	44	4
522	100	3.75+2.50	12	19	19
523	80	3.75+1.25	20	5	38
602	100	3.50+0.50	21	17	28
623	100	3.50+0.50	7	12	11
901	100	3.50+1.50	14	6	21
1023	80	3.50+1.50	8	22	8
1223	80	3.50+0.75	5	9	5
1226	100	3.75+2.25	3	17	0
9999	100	3.75+2.00	7	6	0

2.3 Flow Rate Estimation

Traffic flow in one direction passing an observation point can be described as a point process: Points along a time axis describe the passage times t_i of vehicles (Figure 3). The time headway between vehicles i and $i + 1$ is $h_{i+1} = t_{i+1} - t_i$. The number of arrivals in time interval $(0,a]$ is $N(a)$, and during $(a,b]$ the number of arrivals is $N(a,b) = N(b) - N(a)$.

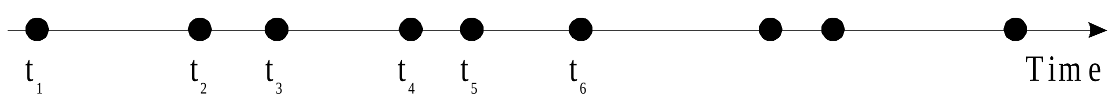

FIGURE 3 Traffic flow as a point process.

A *doubly synchronous counting* process was used, in which each counting period both begins and ends at the time of vehicle arrival (Figure 4). If counting period j has started at α_j, the period ends and the next period (j + 1) starts at the passage time of the last vehicle not later than $\alpha_j + \tau_j$, where τ_j includes the possible extension period. Flow rate q_j of counting period j is the reciprocal of the average time headway $\bar{h}_j$ in the same counting period:

$$q_j = \frac{N(\alpha_j, \alpha_{j+1})}{\tau_j} = \frac{N(\alpha_j, \alpha_{j+1})}{\sum_{i=N(\alpha_j)+1}^{N(\alpha_{j+1})} h_i} = \frac{1}{\dfrac{1}{N(\alpha_j, \alpha_{j+1})} \sum_{i=N(\alpha_j)+1}^{N(\alpha_{j+1})} h_i} = \frac{1}{\bar{h}_j} \tag{1}$$

This method enables the calculation of flow rate even for samples with some discarded observations. Even more importantly, the method enables the study of a subset, such as passenger cars, of a sample.

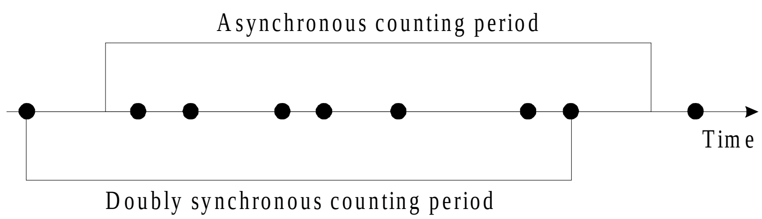

FIGURE 4 Asynchronous and doubly synchronous counting methods.

2.4 Refined Passenger Car Flow Rate

The direct effect of heavy vehicles was eliminated by analyzing only passenger cars not in platoons following heavy vehicles. All heavy vehicles were excluded, as well as all vehicles following heavy vehicles in a platoon, until a headway larger than eight seconds was found. The opposing flow was, however, the total flow rate (including heavy vehicles) of oncoming vehicles.

A subset S includes vehicles that are neither heavy vehicles nor vehicles in a platoon behind a heavy vehicle. The *refined passenger car flow rate*, $q_{S,j}$, for counting period j is calculated using time headways:

$$q_{S,j} = \frac{N_S(\alpha_j, \alpha_{j+1})}{\sum_{i=N(\alpha_j)+1}^{N(\alpha_{j+1})} h_i \mu_S(i)} = \frac{\sum_{i=N(\alpha_j)+1}^{N(\alpha_{j+1})} \mu_S(i)}{\sum_{i=N(\alpha_j)+1}^{N(\alpha_{j+1})} h_i \mu_S(i)} = \frac{1}{\bar{h}_{S,j}} \tag{2}$$

where $\mu_S(i)$ is a membership function defined as

$$\mu_S(i) = \begin{cases} 0, & \text{if vehicle } i \text{ is not a member of subset } S, \\ 1, & \text{if vehicle } i \text{ is a member of subset } S. \end{cases} \tag{3}$$

Analysis of a subsample of vehicles would have been problematic if the size of the subsample N_S (α_j , α_{j+1}) had been only a small proportion of the expected sample size. Consequently, a subsample was accepted only if it was larger than 3/4 of the expected sample size for flow rate $q_{S,j}$; i.e., N_S (α_j , α_{j+1}) > 0.75 $q_{S,j}\tau_j$.

This procedure eliminated the direct effect of heavy vehicles: All passenger cars that could move freely because of a heavy vehicle ahead were eliminated from the analysis. There was, however, a possibility of an indirect effect: Drivers may have adjusted their speeds to the overall conditions caused by heavy vehicles, even though they were not under the direct influence of any single heavy vehicle. In addition, the method has some difficulties in obtaining data under very high volume conditions.

2.5 Directional Analysis of Traffic Flows

In early capacity manuals (Bureau of Public Roads 1950, Highway Research Board 1965) directional split was not considered to have any effect on the operating conditions on two-lane highways. The third edition of the HCM (TRB 1985) introduced adjustment for directional distribution in the calculation of percent time delay (PTD). The adjustment is the same at all flow levels indicating that the proportion of traffic in opposing direction is considered more meaningful than the opposing flow rate. HCM 2000 is expected to make a combined adjustment for directional distribution, two-way flow rate, and percent no-passing zones in the calculation of percent time spent following (PTSF). There will be, however, no adjustment for directional distribution in the estimation of average travel speed.

It is argued that directional distribution should be considered in the estimation of travel speed, and that it is even better to analyze the properties of traffic flow separately for both directions. There are three main reasons for this:

1. Flow rate and platooning in the observed direction increase passing demand, while in the opposing direction flow rate restricts and platooning increases passing opportunities. These twofold effects are hidden, if only total flow is analyzed.
2. Two-way density is not a meaningful measure on two-lane highways with a skew directional distribution, because the major flow cannot effectively use the free space on the opposing lane. Let us consider an extreme example: If the directional split is 99/1 and traffic in one direction is highly congested, the total density is about half of the density of the congested lane. At this density traffic should flow rather smoothly. Directional analysis avoids the averaging of the characteristics of traffic flow.
3. Previous studies (McLean 1989) have indicated that opposing flow rate does not have as large an effect on average travel speeds as the flow rate in the observed direction. These results are confirmed here.

The analysis below is based on a directional analysis of traffic flow. Opposing flow rate has been used as an additional parameter in the models.

3. SPEED-FLOW MODELS

The 1985 HCM (TRB 1985) describes speed decrease as a function of two-way volume. The shape of the curve is concave: the decrease is steeper at low volumes, but more level at higher traffic volumes. HCM 2000 is expected to assume a linear relationship between speed and flow rate:

$$\bar{v}_s = v(0) - 0.0125 q_{\mathrm{pc}} - f_{\mathrm{np}}, \tag{4}$$

where $v(0)$ is free-flow speed, q_{pc} is passenger-car equivalent flow rate (pc/h), and f_{np} is adjustment for percentage of no-passing zones.

Speed-flow curves were estimated using refined passenger car flow rates. In order to avoid indirect effects of heavy vehicles, only measuring periods having less than 10% heavy vehicles were accepted. Both directions were analyzed separately. Samples with an absolute residual higher than three times the residual standard deviation were considered outliers and were excluded from the analysis. Both a linear and a concave model was estimated. More weight was given to high-volume observations, because variance of average speeds was lower at high traffic volumes.

The linear model was

$$\hat{v}_{\mathrm{s}} = b_0 + b_1 q_{\mathrm{d}} + b_2 q_{\mathrm{o}}, \tag{5}$$

where

$\hat{v}_{\mathrm{s}}$ = estimated space mean speed of passenger cars (km/h)

q_{d} = refined passenger car flow rate (pc/h) in observed direction

q_{o} = total opposing flow rate (veh/h)

b_0, b_1, b_2 = parameters of the model, estimated by linear regression analysis.

For each ATR data set the regression was statistically significant.

The slope of the speed-flow curve was not as steep as in HCM 2000, but similar to the results of earlier Finnish studies. The slope was steeper on highways with high free-flow speeds. Figure 5 displays the effect of directional split on speed decrease per 1000 veh/h increase in two-way flow rate. Speed decrease was steeper when free-flow speed was high and directional split was uneven. Maximum speeds were reached when directional split was even.

Concave speed-flow curves were estimated using the square root function as proposed by Brilon and Weiser (1998). The effect of opposing flow was estimated by a third parameter:

$$\hat{v}_{\mathrm{s}} = b_0 + b_1 \sqrt{q_{\mathrm{d}}} + b_2 q_{\mathrm{o}} \tag{6}$$

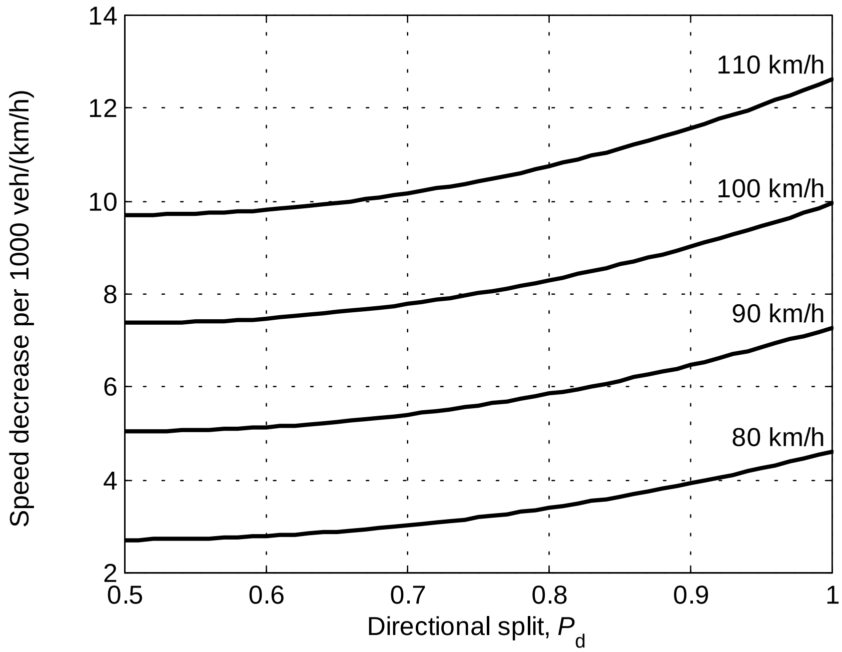

FIGURE 5 Speed decrease per 1000 veh/h increase in total flow rate with free-flow speeds 80–110 km/h.

The concave shape and linear effect of opposing flow was suggested by the Erlander model. Average values for parameters were: $b_0 = 101.7$, $b_1 = -0.2899$, and $b_2 = -0.0045$ on highways with 100 km/h posted speed; and $b_0 = 87.7$, $b_1 = -0.2335$, and $b_2 = -0.0017$ on 80 km/h highways. In this model also, the effect of opposing flow was considerably smaller than the effect of flow rate in the observed direction.

Speed decreased steeper if free-flow speed (b_0) was high or lane width (w_1) was small:

$$\hat{b}_1 = -0.166 - 0.00906 b_0 + 0.213 w_1 \qquad (7)$$

In order to give more weight to samples with a large range of flow rates, each sample was weighted with the square root of flow rate range. The squared multiple correlation coefficient was not high ($R^2 = 0.33$), but regression was statistically significant ($P = 0.001$).

The effect of opposing flow was correlated with free-flow speed:

$$\hat{b}_2 = 0.0150 - 0.000191 b_0 \qquad (8)$$

The square root of opposing flow rate range was used as a weighting factor. The regression was significant ($P < 0.0005$) with $R^2 = 0.35$. The effect of no-passing zones was not statistically significant.

The concave speed-flow model gave a slightly better fit to the data than the linear model. Especially at low volumes the empirical speed-flow data appeared to be concave. The concave shape also has a theoretical foundation, as shown above.

4. CAPACITY

In the 1985 HCM (TRB 1985) the capacity estimate for two-lane highways in ideal geometric and traffic conditions was 2800 pc/h. If directional split was 100/0, the capacity estimate was 2000 pc/h.

HCM 2000 will decrease the capacity for each direction of travel to 1700 pc/h, but the total two-way capacity will increase to 3200 pc/h. As traffic flow in minor direction increases from 1500 pc/h to 1600 pc/h, the capacity of major direction decreases from 1700 pc/h to 1600 pc/h.

As traffic flow reaches capacity, platoon percentage approaches 100%, and there are practically no passenger cars unaffected by heavy vehicles. Consequently, the discussion below is based on total vehicle flow rates. It was, however, difficult to find congested conditions on two-lane highways.

The highest flow rate (1597 veh/h) was observed at ATR 436 (Figure 6). Corresponding average travel speed was 72 km/h, which indicated an optimal density of 22 veh/km. The proportion of heavy vehicles was 10%, and opposing flow rate was 919 veh/h. Posted speed was 80 km/h.

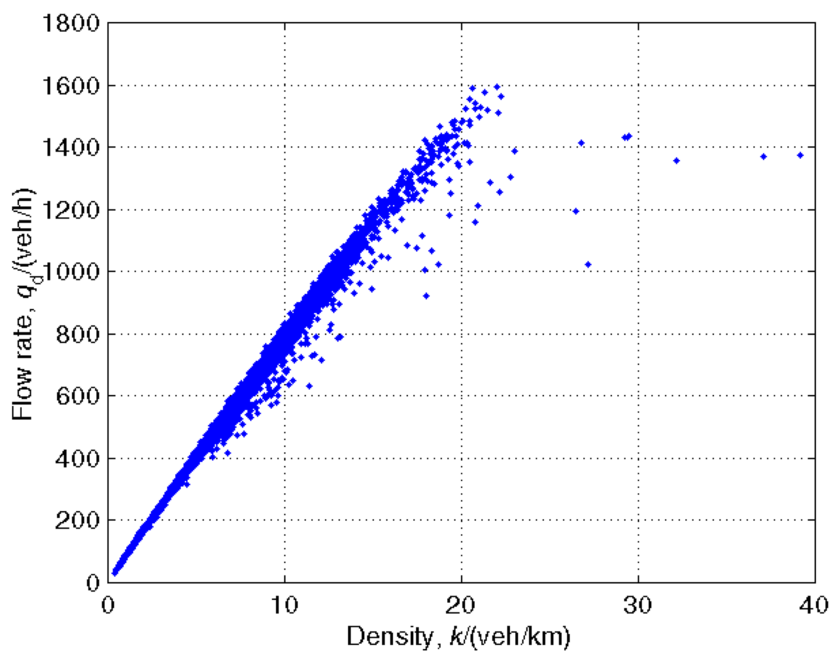

FIGURE 6 Flow-density diagram of ATR 436.

Maximum observed directional flow rate at ATR 9999 was 1548 veh/h. It was reached at density 18 veh/(lane km) and average speed 86 km/h. Proportion of heavy vehicles was 6%, opposing flow rate was 516 veh/h, and posted speed was 100 km/h.

Figures 7 and 8 display comparisons of speed-flow and flow-density curves between the concave model and the HCM 2000 model. In the HCM 2000 model no passing sight restrictions are assumed.

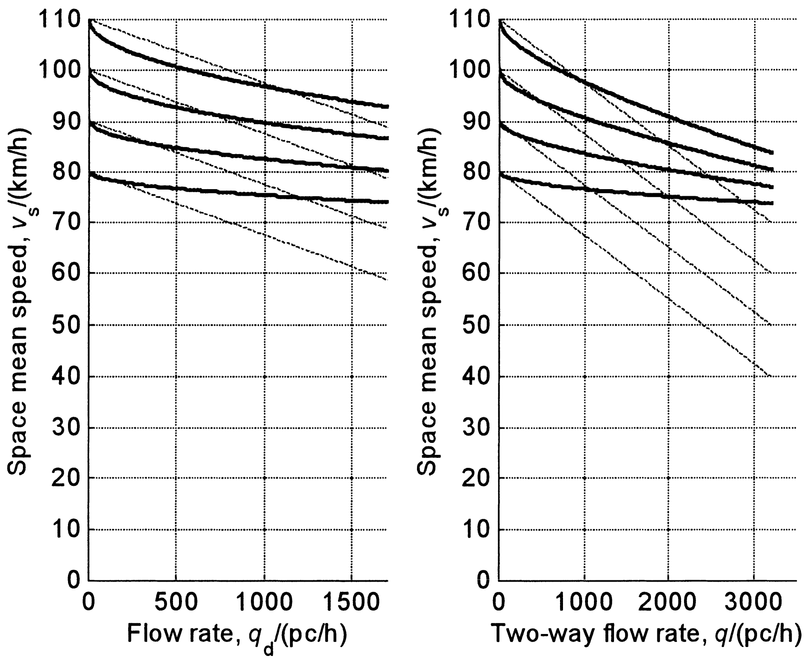

FIGURE 7 Concave speed-flow curves compared to HCM 2000 curves (dashed) with traffic in one direction of travel only (left) and evenly distributed between both directions (right).

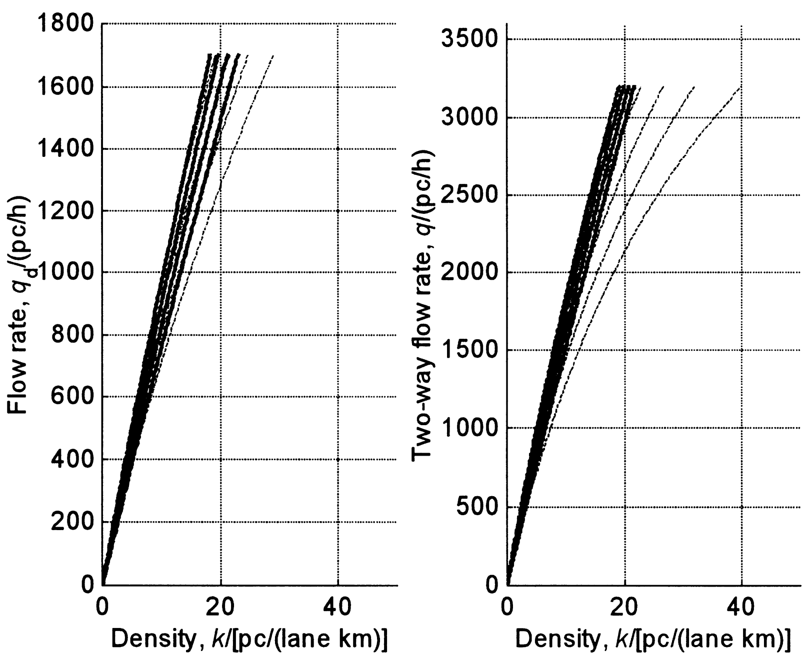

FIGURE 8 Flow-density curves of concave speed-flow models compared to HCM 2000 curves (dashed) with traffic in one direction of travel only (left) and evenly distributed between both directions (right).

Assuming the capacity estimates of HCM 2000, optimal densities are about 19–22 veh/km. These values are similar to the observed results. Similar results have also been observed earlier in Finland (Tie- ja liikennelaboratorio 1980).

Although the data were not adequate for direct analysis of capacity, the following indications can be observed:

1. The highest observed directional flow rate was about 1600 km/h at ATR 436. At ATR 9999 a flow rate of about 1550 veh/h was reached. Traffic and roadway conditions at both locations were good, but not ideal.
2. These observations (Figure 6) as well as earlier research support the lane-capacity estimate of 1700 pc/h in HCM 2000.
3. One-way capacity estimate 1700 pc/h indicates that optimum densities are slightly above 20 pc/km (Figure 8), which is similar to observed values.

When traffic flow is evenly distributed between both directions, the flow-density relationships indicate that optimum densities are reached at flow rate near 3200 pc/h, which is also the capacity estimate of HCM 2000.

Based on these observations, the HCM 2000 capacity estimates can be applied in Finland. The capacity is, however reached at higher speeds and lower densities than estimated in the HCM 2000.

Flow rates 1700 pc/h/lane with directional distribution 100/0, and 1600 pc/h/lane with evenly distributed traffic are reached with approximately equal traffic densities. This suggests a linear relationship between directional capacity and opposing flow rate, which gives two-way capacity

$$C = \frac{1700}{\frac{1}{16}(15P_\mathrm{d}+1)} = \frac{27200}{15P_\mathrm{d}+1} \text{ (pc/h)} \tag{9}$$

where P_d is the proportion of traffic flow in the major direction. Figure 9 displays C and the capacity curve of HCM 2000

$$C_\mathrm{HCM} = \min\left\{\frac{1700}{P_\mathrm{d}},\ 3200\right\} \text{ (pc/h)} \tag{10}$$

5. CONCLUSIONS

The results presented are based on a directional analysis of traffic flow. Data were aggregated in 15-minute time intervals with an optional one-minute extension period using a *doubly synchronous counting process*. The effect of heavy vehicles was eliminated by using *refined passenger car flow rates*. These methods can be suggested for future studies.

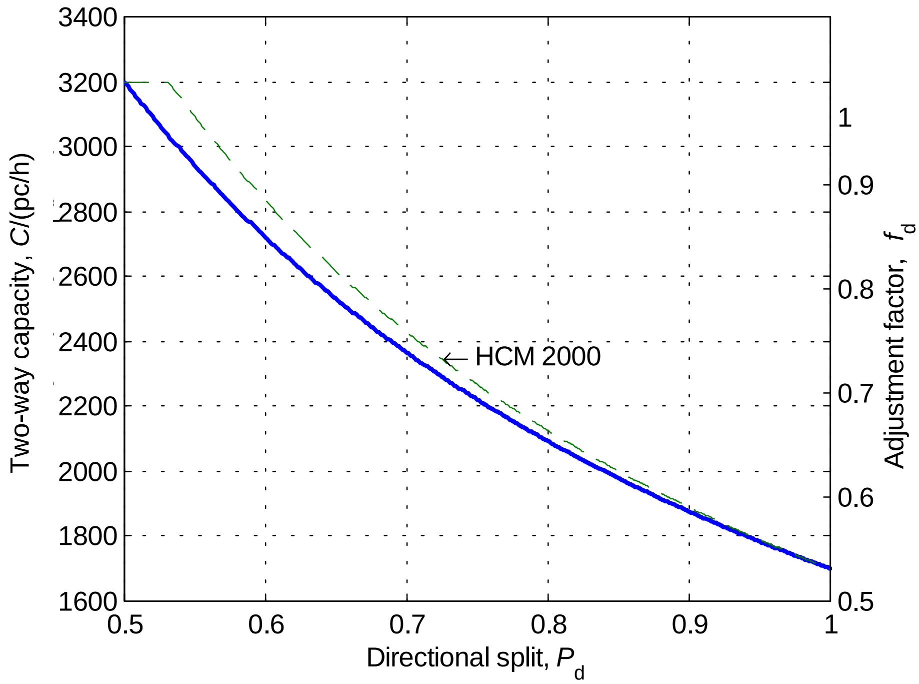

FIGURE 9 The effect of directional distribution on two-way capacity.

Both linear and concave speed-flow models were estimated. Speed decrease due to increasing flow rate was smaller on Finnish highways than estimated in the HCM 2000. Capacity was, however, reached at lower densities so that HCM 2000 capacity estimates appear plausible. The results, however, indicate a linear relationship between directional capacity and opposing flow rate.

The effect of opposing flow on average travel speeds was lower than the effect of the flow rate in the observed direction. This suggests that directional distribution should be considered in the estimation of average travel speeds.

ACKNOWLEDGMENTS

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