Uncertainty in the Operational Analysis of Two-Lane Highways

R.Tapio Luttinen

TL Consulting Engineers,Ltd.
Svinhufvudinkatu 23 A, 15110 Lahti, Finland
Tel: 011.358.40.507.2523
Fax: 011.358.3.880.7420
tapio.luttinen@tloy.com

HCM2000 provides methods to estimate performance measures and the level of service for different types of traffic facilities. Because neither the input data nor the model parameters are totally accurate there is an element of uncertainty in the results. This paper presents an analytical method to estimate confidence intervals for service measures of two-lane highways. The input data and the model parameters are considered as random variables. The propagation of error through the arithmetic operations in the HCM2000 method is estimated. Finally the uncertainty in the average travel speed and percent time spent following is analyzed and four approaches are presented to deal with uncertainty in the level of service.

HCM2000 (*1*) provides methods for operational analysis, planning, and design of transportation facilities. With a set of input data of traffic and roadway conditions an analyst can obtain service measures and other measures of effectiveness (MOEs) as well as a level of service (LOS) describing the performance of a facility at given conditions.

Traffic flow is a stochastic process and the MOEs are statistical estimates based on this process. HCM2000 presents the results as point estimates, which describe averages over a number of locations. The manual does not give any indication about the confidence intervals of the estimates. This element of *uncertainty* has been recently under discussion (*2*).

HCM2000 has some discussion about the accuracy and precision of the methods. According to the manual "*accuracy* relates to achieving a correct answer, while *precision* relates to the size of the estimation range of the parameter in question" (italics added). The manual also suggests sensitivity analysis.

Limitations in the accuracy and precision cause uncertainty to analysts and decision makers. The purpose of this paper is to evaluate the sources of uncertainty in the HCM2000 procedures for two-lane highways. Sources of error due to the stochastic nature of traffic and roadway conditions, and the propagation of errors in the analysis are evaluated. Finally, the usefulness of the LOS concept in the light of uncertainty is discussed.

OPERATIONAL ANALYSIS OF TWO-LANE HIGHWAYS IN HCM2000

HCM2000 defines two classes of highways:

1. *Class I highways* are two-lane highways on which motorists expect to travel at relatively high speeds. These are highways that function as major intercity routes, primary arterials connecting major traffic generators, daily commuter routes, or as primary links in state and national highway networks.
2. *Class II highways* are two-lane highways on which motorists do not necessarily expect to travel at high speeds.

For Class I highways the level of service is defined by threshold values of both *percent time spent following* and *average travel speed*. For Class II highways the only service measure is percent time spent following.

The operational analysis procedure has six steps:

1. Estimation of free-flow speed (FFS)
2. Estimation of demand flow rate
3. Estimation of average travel speed (ATS)
4. Estimation of percent time spent following (PTSF)
5. Estimation of capacity
6. Estimation of level of service (LOS)

The uncertainty in each of these steps is analyzed below.

ERRORS IN THE OPERATIONAL ANALYSIS PROCEDURE

Sources of error

Inaccuracies in results can result from:

1. Errors in *input*
2. *Model* specification errors
3. Computational errors
4. *Human* errors

Errors in input may be due to measurement errors, sampling errors, temporary disturbances, or just bad judgment. HCM2000 suggests that the accuracy of input data is within the limits ±5 ...10 percent of the true value. If default values or predictions of future conditions are used, the expected error in input data will most likely be larger. Sensitivity analysis can be used to estimate the effects of inaccuracies in the input data.

Because mathematical models are, by necessity, simplifications of reality, the results cannot be considered "true values", even if the input data were exactly true. Many input variables, such as vehicle and terrain types, are only simplified descriptions of real conditions. In addition, the parameters of a model are statistical estimates having a limited accuracy. These issues cannot be managed with a simple sensitivity analysis.

The last two sources of error (computational and human errors) are not shortcomings of the method but problems in its application. Computational errors may occur, if the software does not exactly reproduce the mathematical method or uses algorithms with numerical instabilities. Human errors may occur, if the analyst does not totally understand the method or makes typing errors. The discussion below considers the effects of errors in input data and model specification.

Estimation of errors

An input value or a model parameter is considered as an estimate of a random variable X, which can be described as

$$X = \mathrm{E}[X] + \delta,$$

where E[X] is the expected value of X at current conditions, δ describes the randomness of X with mean E[δ]=0 and variance Var[δ]=Var[X]. The random process X can also be expressed as

$$X = \hat{X} + \eta + \delta,$$

where the *estimator* $\hat{X}$ is a function of one or more predictor variables, and $\eta = \mathrm{E}[X] - \hat{X}$ is the modeling error. The *residuals* $\varepsilon_i = x_i - \hat{X} = \eta_i + \delta_i$ of a good estimator have zero mean and a small variance. Many statistical modeling techniques assume that the residuals follow normal distribution.—In the terms of HCM2000, accuracy relates to E[ε]=E[η], and precision to Var[ε]. If the model is *unbiased*, E[ε]=0.

If the variate X is an input variable, δ describes the random variation among observations, such as vehicle counts. If X is a model parameter, such as the slope of the speed-flow curve, δ describes the unexplained variation among similar locations.

If the residuals of a model follow the normal distribution with mean zero and standard deviation σ, the interval $\hat{X} \pm 1.96\sigma$ covers 95 % of observations. This is called the 95 % *confidence interval*. The standard deviation of residuals is called *standard error*. The maximum residual within the 95 % confidence interval is called *maximum error* (ε_{95}). If the estimator is the mean of n observations, its 95 % confidence interval is $\bar{x}_n \pm 1.96\sigma(X)/\sqrt{n}$. For large n the standard error of the estimator is approximately normally distributed.

The MOE estimates are variates obtained as functions, sums, products and quotients of random variables and constants. The error analysis should be able to estimate the effect of these mathematical operations on the probability distribution of the resulting new variate, especially its expectation and variance. The basic properties of expectation and variance applied in the error analysis are now briefly presented:

1. *Linear transformation of a random variable.* Let a and b be constants. The expectation and variance are E[a+bX] = a+bE[X], and Var[a+bX] = b^2 Var[X], respectively.

2. *Function of a random variable.* The PTSF estimate for two-way flows in HCM2000 uses the transformation $Y = e^X$,where X is the passenger-car equivalent flow rate estimate scaled by a constant *(*-0 .000879 *)*. If X follows normal distribution $N(\mu,\sigma)$, then Y is a log-normal variate with $E[Y] = \exp(\mu+\sigma^2/2)$ and $\mathrm{Var}[Y] = \exp(2\mu+\sigma^2)\,[\exp(\sigma^2)-1]$.
3. *Sum and difference of two random variables.* The expectation and variance are $E[X\pm Y] = E[X]\pm E[Y]$ and $\mathrm{Var}[X\pm Y] = \mathrm{Var}[X]+\mathrm{Var}[Y]2\pm\mathrm{Cov}[X,Y] = \mathrm{Var}[X]+\mathrm{Var}[Y]\pm2\rho_{X,Y}\sigma_X\sigma_Y$, where $\mathrm{Cov}[X,Y]$ and $\rho_{X,Y}$ are the covariance and correlation coefficient of variates X and Y, respectively (*3*). The sum of normal variates follows normal distribution.
4. *Product of two random variables.* The expectation follows directly from the definition of covariance: $E[XY] = E[X]E[Y]+\mathrm{Cov}[X,Y] = E[X]E[Y]+\rho_{X,Y}\sigma_X\sigma_Y$. The exact equation for variance (*3*) was considered too complicated, and the following approximation (*4*) is used: $\mathrm{Var}[XY] = \{(E[X])^2\ \mathrm{Var}[Y]+(E[Y])^2\ \mathrm{Var}[X]+\mathrm{Var}[X]\ \mathrm{Var}[Y]\}(1+\rho^2_{X,Y})$. The pdf of $Z=XY$ is not normal, even if X and Y are normal variates.
5. *Quotient of two random variables.* Expectation and variance can be approximated as follows (*3*):

$$\mathrm{E}[X/Y] = \frac{\mathrm{E}[X]}{\mathrm{E}[Y]} - \frac{\mathrm{Cov}[X,Y]}{(\mathrm{E}[Y])^2} + \frac{\mathrm{E}[X]\mathrm{Var}[Y]}{(\mathrm{E}[Y])^3}$$

$$= \frac{\mathrm{E}[X]}{\mathrm{E}[Y]} - \frac{\rho_{X,Y}\sigma_X\sigma_Y}{(\mathrm{E}[Y])^2} + \frac{\mathrm{E}[X]Var[Y]}{(\mathrm{E}[Y])^3}$$

$$\mathrm{Var}[X/Y] = \left(\frac{\mathrm{E}[X]}{\mathrm{E}[Y]}\right)^2 \left(\frac{\mathrm{Var}[X]}{(\mathrm{E}[X])^2} + \frac{\mathrm{Var}[Y]}{(\mathrm{E}[Y])^2} - \frac{2\mathrm{Cov}[X,Y]}{\mathrm{E}[X]\mathrm{E}[Y]}\right)$$

$$= \left(\frac{\mathrm{E}[X]}{\mathrm{E}[Y]}\right)^2 \left(\frac{\mathrm{Var}[X]}{(\mathrm{E}[X])^2} + \frac{\mathrm{Var}[Y]}{(\mathrm{E}[Y])^2} - \frac{2\rho_{X,Y}\sigma_X\sigma_Y}{\mathrm{E}[X]\mathrm{E}[Y]}\right)$$

The quotient of two independent standard normal variates follows the Cauchy distribution (*3*).
If X and Y are independent, the covariance and the correlation coefficient are zero.

UNCERTAINTY IN FREE-FLOW SPEEDS

Standard deviation of free-flow speeds

At very low flow conditions there is very little interaction between vehicles, and they can travel almost all the time at the speed desired by the drivers. Such traffic conditions can be characterized as free-flow conditions and the speeds are called *desired speeds*. The average travel speed at free-flow conditions is called *free-flow speed*.
Even under similar roadway conditions all vehicles do not travel at the same speed. Drivers and vehicles have different characteristics. There are also some inaccuracies in the perception of speed and control of the vehicle, which cause additional variation in the speeds. As the design speed or posted speed increases, the proportion of "slow drivers" is likely to increase. Accordingly, it can be expected that the standard deviation increases as the average free-flow speed increases. A higher standard deviation at higher free-flow speeds indicates larger errors in the estimation.

FFS estimation based on speed measurements

HCM2000 presents two methods for the estimation of free-flow speeds: (*i*) field measurements and (*ii*) estimation with guidelines based on the characteristics of the road section. The primary field measurement procedure estimates FFS using speed data under *low-volume conditions*. Total two-way flow should not exceed 200 pc/h. The sample size (n) should be at least 100 speed measurements. The FFS estimator $\sigma(\hat{v}_0)$ is the arithmetic mean of the sample. No adjustments are made.
Assuming that speed data from flow rates not higher than 200 pc/h properly describe free-flow conditions, the standard error of the FFS estimator is

$$\sigma(\hat{v}_0) = \frac{\sigma(v)}{\sqrt{n}}$$

where $\sigma(v)$ is the standard deviation of measured speeds. McLean (*5*) has estimated that the coefficient of variation of desired speeds is 0.11–0.14. If the estimated FFS is 100 km/h and sample size is 100, the standard error can be approximated as 1.25 km/h. The 95 % confidence interval is approximately 97.5–102.5 km/h.

This estimation method assumes that traffic volumes not exceeding 200 pc/h can be used to approximate free-flow conditions. According to HCM2000 the average travel speed decreases 1.25 km/h for every increase of 100 pc/h in the flow rate under base conditions. There is some evidence that at low flow rates the speed decrease may be steeper than at high flow rates (*6–8*). There are also indications that flow rates should be very low, about 100 veh/h or lower, for the flow to be considered random (*9*). At flow rate 200 km/h there is a negative bias of approximately 2.5 km/h in the FFS estimate. This shifts the confidence interval estimated above slightly upwards. Accordingly, if a free-flow speed estimate of 100 km/h is based on 100 speed observations representing a flow rate of 200 km/h, with a 5 % risk of error the true free-flow speed is approximately in the range 100–105 km/h.

It is suggested that flow rate correction is made for all FFS estimates. Considering that the proportion of heavy vehicles is usually highest at low-flow conditions, heavy vehicles and vehicles in platoons following heavy vehicles should be excluded (*7*). Also care should be taken that the location of measurement is representative of the road segment analyzed. With these enhancements the error in the estimated FFS can be considered to be below five percent.

If low-volume data are not available, FFS can be estimated from *higher-volume data* using the speed-flow relationship

$$\hat{v}_0 = \bar{v}(q) + 0.0125\frac{q}{f_{\mathrm{HV}}},$$

where $\bar{v}(q)$ is the mean speed measured at flow rate q, and f_{HV} is the heavy-vehicle adjustment factor. The sample should include at least 100 observations.

As flow rate increases the variance of travel speeds decreases (*8,10*), and the required sample size is lower than at free-flow conditions. With a minimum sample size of 100 and 95 % confidence level the error in $\bar{v}(q)$ does not exceed approximately ±2 km/h. The adjustments, however, present another source of error, as demonstrated in the following example.

Example: Travel speeds were measured on a two-lane highway having rolling terrain with 40 % no-passing zones. The mean speed at two-way flow rate 500 veh/h with 10 % trucks was 90 km/h. The heavy vehicle adjustment factor is 0.87, which gives a FFS estimate of 97.2 km/h. Using this FFS estimate as an input value the HCM2000 gives 83 km/h as the ATS estimate for 500 veh/h. There is a difference of 7 km/h between the measured mean speed and the estimated ATS, which is due to the FFS estimation method. This bias can be avoided if the grade adjustment is also used in the estimation of FFS.

In the error analysis below the HCM2000 procedure is assumed without the suggested modification. As a working hypothesis, the maximum error in the FFS estimate is assumed to be ±10 %.

FFS estimation based on roadway characteristics

If field data are not available, FFS can be estimated using the following equation:

$$v_0 = v_{\mathrm{B}} - f_{\mathrm{LS}} - f_{\mathrm{A}},$$

where v_{B} is the base free-flow speed (BFFS), f_{LS} is the adjustment for lane width and shoulder width, and f_{A} is the adjustment for access point density. According to HCM2000 the BFFS ranges between 70 to 110 km/h, but no guidance on its estimation is given. The estimation of access point density has necessarily a subjective element.

This method is very subjective. The accuracy of the FFS estimate depends entirely on the expertise of the analyst. FFS estimation based on roadway characteristics is basically an educated guess, and as such very error prone.

UNCERTAINTY IN GRADE ADJUSTMENT

The MOEs are estimated for given passenger-car flow rates at base conditions. Grade and heavy vehicle adjustment factors are used to express the prevailing roadway conditions and vehicle mix as equivalent passenger-car flows at base conditions.

HCM2000 defines two *terrain types*: level and rolling. Mountainous road segments are analyzed as specific upgrades or downgrades. The terrain type information is applied in the estimation of the grade adjustment factors and the passenger-car equivalencies (PCEs).

The HCM2000 *Grade adjustment factors* (f_G) were estimated using simulations with 42 types of terrains (level, rolling, and 40 combinations of specific percentages and lengths of grade) and three flow rates (400, 800, and 1,600 pc/h) for both directions of travel combined (*11*). All vehicles were passenger cars, and directional distribution was 50/50. Five replicate simulation runs were made. In order to get monotonically increasing or decreasing values, selected simulation runs were discarded and replaced by interpolated values.

Grade adjustment factors are defined for three categories of two-way flow rates:0–600, 601–1,200, and above 1,200 pc/h. For level terrain f_G=1.00. The difference in f_G for ATS at rolling terrain between flow rates 0–600 and 601–1,200 pc/h is 0.22. This indicates that at these traffic and roadway conditions an error of 0.11 is tolerated.

At flow rates not exceeding 600 pc/h the difference in the adjustment factor for ATS between the terrain types is 0.29, which indicates that an error of at least 0.15 is tolerated by the method at low flow rates. At flow rates 601–1,200 pc/h the difference is 0.07 and at flow rates exceeding 1,200 pc/h the difference is 0.01, which indicate minimum errors of 0.04 and 0.01 at the boundary between level and rolling terrain. In PTSF analysis the minimum errors are lower: 0.12, 0.03, and 0.01, respectively.

As a working hypothesis it is assumed that the true value at the boundary of two flow rate categories is the average of adjustment factors for both categories. Within 200 pc/h from the boundary flow rate the modeling error returns to zero. The standard deviation is assumed to be a quarter of the difference between the adjustment factors at the boundaries. At flow rates 600 and 1,200 pc/h the adjustment factors between consecutive flow rate classes were compared. The factors between the two terrain types were compared at simulated flow rates: 400, 800, and 1,600 veh/h. It should be emphasized that these assumptions are based on the obvious inaccuracies in the HCM2000 method. The resulting confidence interval (Fig. 1) should be considered as the minimum conceivable confidence interval.

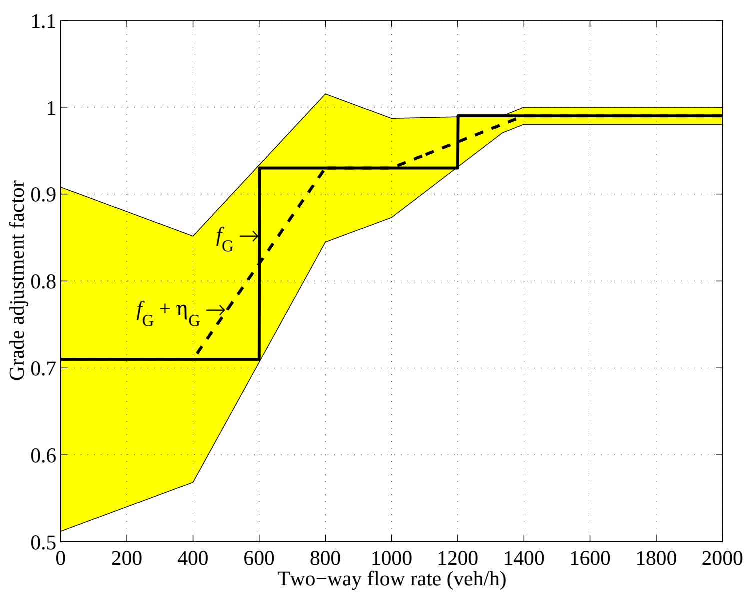

Figure 1: 95% confidence interval for ATS grade adjustment factor at rolling terrain

In HCM2000 the grade adjustment factor is calculated before the adjustment for heavy vehicles, although the flow rate categories are expressed in passenger cars per hour. The procedure is applied here so that the flow rate categories for grade adjustment are expressed as veh/h.

UNCERTAINTY IN THE ADJUSTMENT FOR HEAVY VEHICLES

Adjustment method

Since HCM1965 (*12*) the impact of heavy vehicles has been described in terms of *passenger-car equivalencies*, which indicate the number of passenger cars that have the same operational effect on traffic flow as a single heavy vehicle of a given category. A measured or estimated demand flow rate *(q)* is transformed into an equivalent passenger-car flow rate (q_p) using equation

$$q_{\mathrm{p}} = \frac{q}{f_{\mathrm{G}} f_{\mathrm{HV}}}.$$

The heavy vehicle adjustment factor is:

$$f_{\mathrm{HV}} = \frac{1}{1 + P_{\mathrm{T}}(E_{\mathrm{T}} - 1) + P_{\mathrm{R}}(E_{\mathrm{R}} - 1)},$$

where P_T and P_R are the proportions of trucks and RVs, and E_T and E_R are the PCEs for trucks and RVs, respectively. The precision of passenger-car equivalent flow rates depends on the precision the estimates for heavy-vehicle proportions, PCEs and demand flow rates. To simplify things, only trucks are considered below.

Uncertainty in the truck proportion

If a sample of N vehicles includes n trucks, the estimated proportion of trucks is $\hat{P}_{\mathrm{T}} = n / N$, and the 95 % confidence interval is

$$P_{95} = \hat{P}_{\mathrm{T}} \pm 1.96 \sqrt{\frac{\hat{P}_{\mathrm{T}}(1 - \hat{P}_{\mathrm{T}})}{N}}.$$

For short counting periods, such as 15 minutes, the main source of error is random variation. If counting period is longer than the analysis period, the effect of systematic errors increases.
It is assumed that there is an absolute error of 5 % in the truck proportion. At low flow rates and high truck proportions the error may be very large, but the effect of truck proportion on the PCE flow rate and MOE estimates diminishes at low flow rates.

Uncertainty in passenger-car equivalencies

The second source of uncertainty in the adjustment for heavy vehicles is the *PCE value*. The estimates are based on five replicate simulation runs and have two sources of error: (*i*) the inaccuracy in the statistical estimate of the PCE and (*ii*) the inaccuracies in the simulation model. The differences in PCE values between consecutive categories can be as high as 0.6, which indicates that errors of the magnitude 0.3 are tolerated in the model. The confidence intervals were approximated using the same approach as with the grade adjustment factor.

The accuracy of passenger-car equivalent demand flow rates

Let us assume that the distribution of vehicle counts follows the Poisson distribution. The variance of the distribution is then equal to the mean. Because the Poisson model is likely to underestimate the variation of traffic flows it should be taken as an indicator of a lower limit of real maximum errors. If input flow rates are based on predictions, the errors in estimates are considerably larger.
The passenger-car equivalent flow rate is

$$q_{\mathrm{p}} = q\frac{1+P_{\mathrm{T}}(E_{\mathrm{T}}-1)}{f_{\mathrm{G}}} = q\frac{g_{\mathrm{T}}}{f_{\mathrm{G}}},$$

where g_T=1 +P_T(E_T-1). The confidence limits of q_p are estimated assuming that all parameters are random variables. The expectation and variance of the truck adjustment are

$$\mathrm{E}[g_{\mathrm{T}}] = 1 + \mathrm{E}[P_{\mathrm{T}}D_{\mathrm{T}}]$$

$$\mathrm{Var}[g_{\mathrm{T}}] = \mathrm{Var}[P_{\mathrm{T}}D_{\mathrm{T}}]$$

where D_T=E_T-1. The expectation of D_T is E[D_T]=E[E_T]-1 and variance Var[D_T] =Var[E_T]. The combined adjustment for grade and trucks is the quotient f_p=g_T/f_G. Finally, the passenger-car equivalent flow rate is the product q_p=qf_p. The expectation and variance of q_p can be estimated by using the tools for algebraic operations of stochastic variables presented above.

Figures 2 and 3 display the 95 % confidence intervals of PCE flow rates at rolling terrain. The traffic counting period is 15 minutes and the proportion of trucks is 15 %. The confidence interval is widest, when the counting period is short and the proportion of heavy vehicles is high. The uncertainties are largest at moderate flow rates and in the analysis of ATS. The black curve also displays the boundaries at 600 and 1,200 veh/h, where a small increase in flow rate may result in a considerable decrease in the passenger-car equivalent flow rate. The normality assumption is a major simplification, but figures 2 and 3 can be used to illustrate the magnitude of uncertainty.

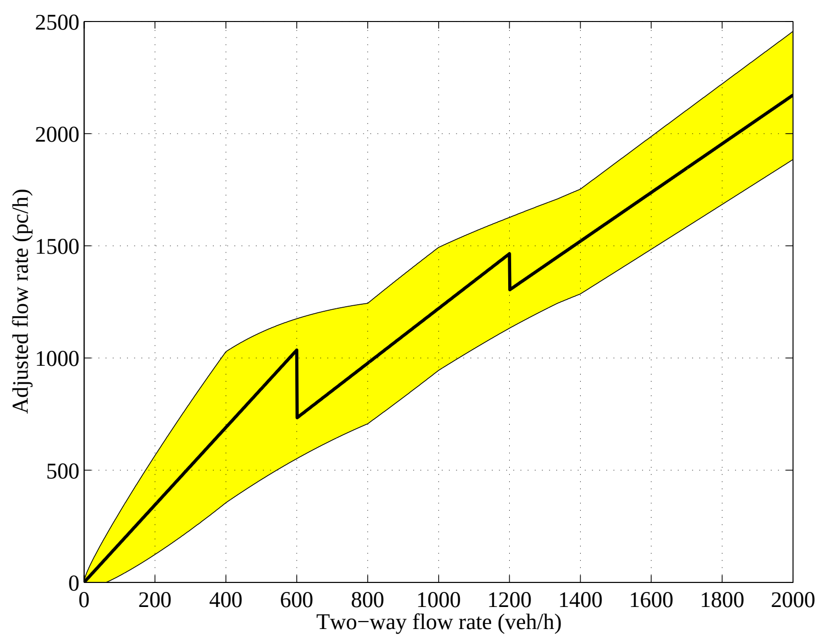

Figure 2: Passenger-car equivalent flow rate and its 95% confidence interval for the HCM2000 ATS procedure at rolling terrain with 15% trucks and one 15-minute counting period

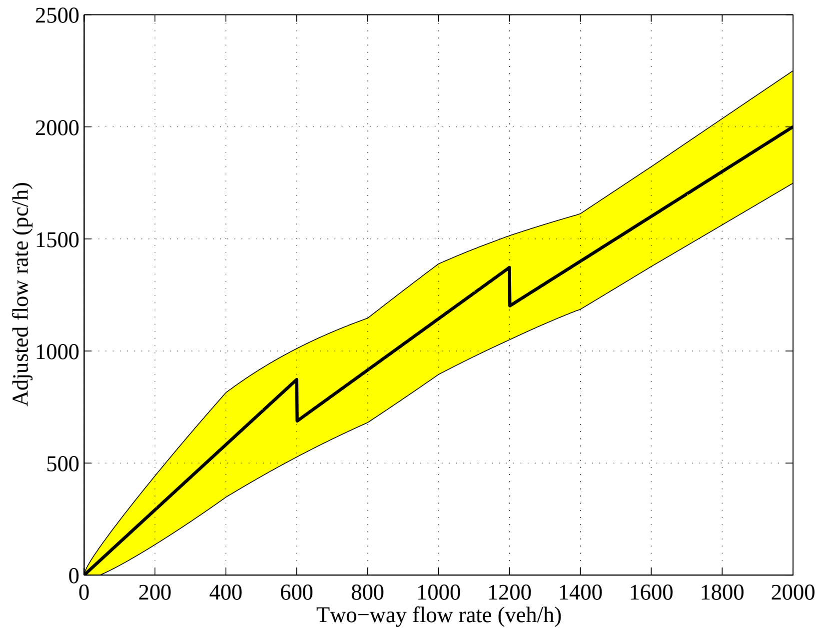

Figure 3: Passenger-car equivalent flow rate and its 95% confidence interval for the HCM2000 PTSF procedure at rolling terrain with 15% trucks and one 15-minute counting period

UNCERTAINTY IN AVERAGE TRAVEL SPEEDS

The average travel speed is

$$\bar{v} = v_0 - 0.0125 q_{\mathrm{p}} - f_{\mathrm{np}},$$

where f_{np} is the adjustment for no-passing zones. The ATS can be considered a sum (or difference) of three random variables, the last of which has not been discussed yet.

The adjustment for no-passing zones in HCM2000 is the difference between the average result of five simulation runs for the specified percentage of no-passing zones and the average of five otherwise identical simulation runs for no no-passing zones (*11*). No indications about the precision of the adjustment have been given. Considering that the percentage no-passing zones is an average measure which does not describe how the no-passing zones are distributed along the roadway, it is assumed that the coefficient of variation of f_{np} is 0.1—the precision suggested for input data in HCM2000.

Regression analysis for ATS was performed both for two-way data and directional data (*11*). When the regression lines were forced to have a y-intercept equal to the free-flow speed, the slopes ranged from -0.0081 to -0.0117 with R^2=0.77...0.87. An analysis to obtain an overall common slope provided a model with slope -0.0097. Slope -0 .0125 in both directions in directional analysis provided R^2 = 0.588. This slope was accepted also as the slope for two-way analysis rather than the slope -0.0097.

It can be assumed that the range of possible slopes should include -0.0097. This indicates that the maximum error cannot be smaller than 0.0028. Accordingly the expected slope factor is assumed to be -0.0125 with standard deviation 0.0015.

Figures 4 and 5 display the 95% confidence intervals for ATS with different truck percentages and counting periods. The estimated free-flow speed is 95 km/h, and the percent no-passing zones is 40. The normality assumption is open to criticism, but given the uncertainties in the precision of the parameters, this approach can be justified.

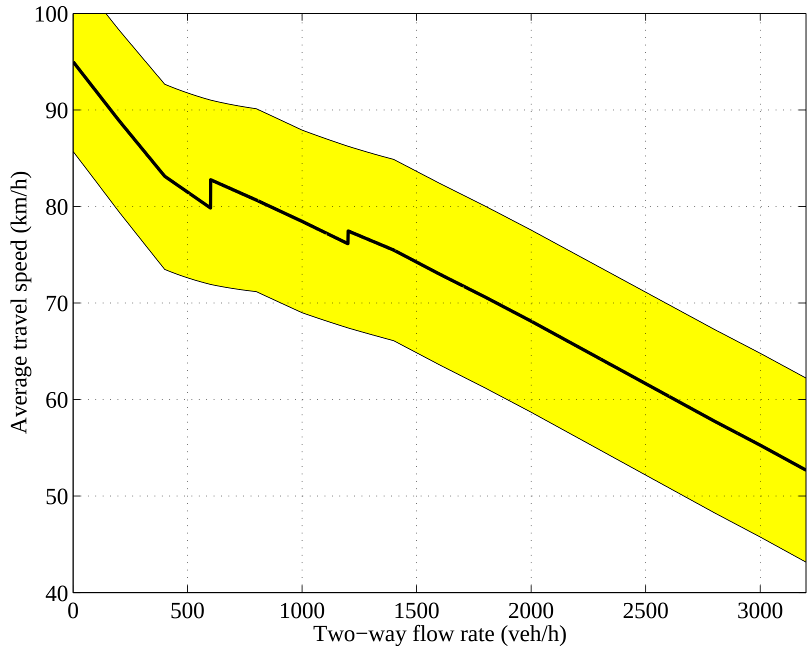

Figure 4: ATS and its 95% confidence interval at rolling terrain with 5% trucks, four 15-minute traffic counting periods, and no uncertainty in the slope factor

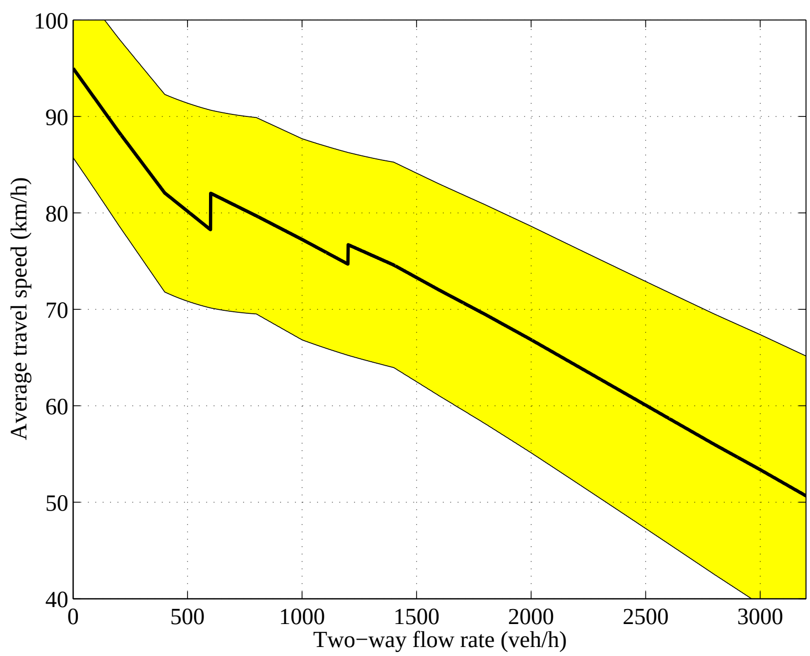

Figure 5: ATS and its 95% confidence interval at rolling terrain with 15% trucks, 15-minute traffic counting period, and uncertainty in the slope factor

In figure 4 the slope factor is assumed to be “true”. Figure 5 shows the impact that the uncertainty in the slope factor has on the confidence interval. The large uncertainty in the FFS partly hides the effect of other factors.

In figure 5 the LOS, as estimated by HCM2000, drops to C (70–80 km/h) at flow rate 500 veh/h, increases back to B (80–90 km/h) at 600 veh/h, and drops to C again at 750 veh/h. At flow rates exceeding 500 veh/h the confidence interval is approximately 20–30 km/h. In figure 4, where the proportion of trucks is lower and the traffic counting interval longer, the confidence interval does not exceed 20 km/h. Uncertainty in the slope factor increases the confidence interval especially at high flow rates.

UNCERTAINTY IN PERCENT TIME SPENT FOLLOWING

In the two-way model PTSF is calculated as

$$\hat{P}_{\mathrm{F}} = 100\left(1 - e^{-0.000879 q_{\mathrm{p}}}\right) + f_{\mathrm{d,np}},$$

where $f_{\mathrm{d,np}}$ is the adjustment for directional distribution and no-passing zones. The uncertainty in the passenger-car equivalent flow rate q_{p} has been discussed above. The precision of two parameters must still be estimated: the slope parameter (-0.000879) and the adjustment $f_{\mathrm{d,np}}$.

One source of uncertainty in the PTSF analysis is the discrepancy between the results of directional analysis and two-way analysis (*13*). The PTSF is lower in the two-way model. This also indicates some uncertainty in the slope parameter. The comparison of directional and two-way PTSF curves (*13*) indicates that the standard deviation of the slope parameter most likely exceeds 0.0001, which is the value assumed here.

In the directional model the adjustment for no-passing zones does not depend on the flow rate in the observed direction. PTSF estimates can be as high as 130 percent (*13*), when flow rate in the observed direction is 1,700 pc/h and 200 pc/h in the opposing direction, free-flow speed is 70 km/h, and percent no-passing zones is 100. The adjustment $f_{\mathrm{d,np}}$ is 45.2 % (Exhibit 20-20). This indicates that the relative error in the adjustment can be as high as 66 %. The error can also be high at the lower end of directional flow rates. The adjustment is applied even at free-flow conditions, where PTSF can, by definition, be assumed to approach zero. In the analysis below it is assumed that the standard relative error in $f_{\mathrm{d,np}}$ is 35 %.

Figures 6 and 7 display the 95% confidence intervals for PTSF with different truck percentages and counting periods. The percent no-passing zones is 40 and the directional distribution is assumed even. For the assumption of normality, the same observations apply as above.

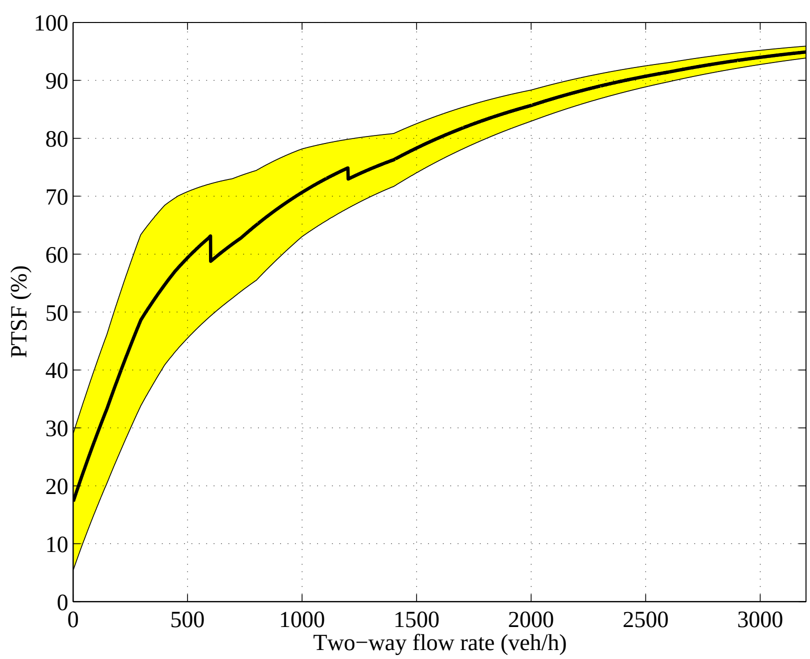

Figure 6: PTSF and its 95% confidence interval at rolling terrain with 5% trucks, four 15-minute counting periods, and no uncertainty in the slope factor

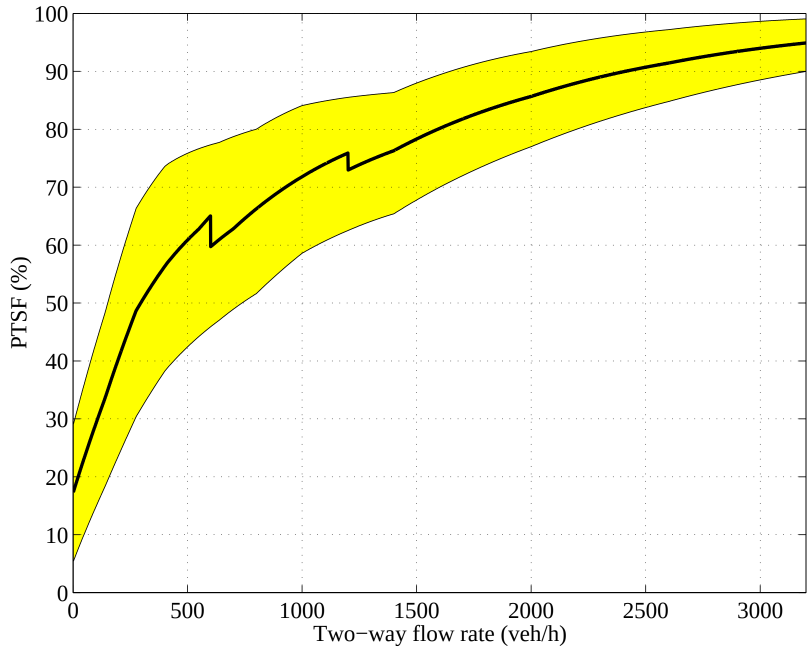

Figure 7: PTSF and its 95% confidence interval at rolling terrain with 15% trucks, one15-minute counting period, and uncertainty in the slope factor

If the scale factor is assumed "true" the confidence interval at high flow rates is very thin. Uncertainty in the slope factor increases the confidence interval substantially. Here the effect of slope factor is more pronounced than in the ATS estimates, where the uncertainty in the FFS was dominating.

UNCERTAINTY IN CAPACITY

The capacity in major direction is 1,700 pc/h until traffic flow in the minor direction reaches 1,500 veh/h. After that the maximum two-way capacity of 3,200 pc/h is the determining factor. The capacity is assumed to be unaffected by free-flow speed (*11*). The consideration of other factors, such as highway geometry and the impact of heavy vehicles, has not been reported.

Although the capacity is presented in passenger cars per hour, the manual does not present any capacity adjustment factors. The capacity is checked against the passenger-car equivalent flow rates obtained from both ATS and PTSF analysis. Because the adjustment factors for grade and heavy vehicles at high flow rates are unity in PTSF analysis, it can be assumed that the ATS adjustment factors should be used to convert veh/h to pc/h in the capacity analysis.

The capacity estimate is based on observations of maximum flow rates on a few two-lane highways (*11*). These data indicate that the capacity for a two-lane highway must be *at least* 3,200 pc/h.

As a working hypothesis the capacity estimates are assumed to be within the limits ±5 **. . .** 10 percent of the true value, which is the range assumed for input data in HCM2000. There may be a slight negative bias in the two-way capacity estimate.

UNCERTAINTY IN THE LEVELS OF SERVICE

The six levels of service (A–F) used since HCM1965 (*12*) are assigned to given performance measures based on expert judgement. The discussion on accuracy and precision is relevant from two points of view:

1. How certain is it that the true value of a service measure is within the bounds of a level of service?
2. How closely the levels of service indicate true user perceptions?

The first question is very important, if the performance measures are close to the critical values. Figure 5 indicates that the ATS confidence interval typically covers three levels of service. At flow rate 1,750 veh/h the confidence interval, however, covers levels of service B to E. The confidence interval for PTSF in figure 7 also covers three levels of service at low to medium flow rates.

The question of user perceptions is an important issue in current discussion on the HCM methodology (*14-16*). If the levels of service do not reflect the users' perceptions, the LOS classification should not be given any important role. The analysis of accuracy and precision in the LOS assignment would then be irrelevant. This discussion is, however, beyond the scope of this paper.

One aspect of user perception is, however, relevant to our discussion: The LOS grades are qualitative measures of performance. Near a critical value a small change, well within the limits of the precision of the method, may change the LOS. It is, however, most likely that the users do not find any abrupt change in the quality of service within this small change in the performance measure.

The LOS classification emphasizes the importance of the estimation of accuracy and precision, especially near the critical values. At the same time the discussion above on the accuracy and precision as well as user perception makes the current LOS classification questionable. Some possible ways to circumvent these problems would be (*17*)

1. *Sublevels.* Subdivide the current levels of service {A, B, C, D, E, F} to {A+, A, A-, B+, B, B-, C+,…}.
2. *Continuous scale*. Map the performance measures to a continuous scale 0–10, where values 10–9 would indicate LOS A, 6–5 would be LOS E, and 5–0 would describe congested conditions. The precision of the results could be indicated by confidence intervals.
3. *Statistical approach*. Present the probabilities $F_i(x)$ that the value x of a performance measure indicates level of service i.
4. *Fuzzy approach*. Use fuzzy definitions (*18*) for LOS. The input and performance measures could be fuzzified also.

The purpose would be to give decision makers some information about the level of certainty behind the designation of a LOS, and to lower or smooth out the LOS steps at critical values.

CONCLUSIONS AND DISCUSSION

The confidence intervals for input, model parameters as well as the service measures of two-lane highways have been estimated by assuming the traffic flow as well as the HCM2000 method to be stochastic processes. The strength of the analytical approach, as compared to Monte Carlo methods or sensitivity analyses, is its clarity. The propagation of error in terms of mean and variance can be easily traced. However, if the simplifying assumption of Gaussian residual errors cannot be accepted then the method becomes laborious, and the Monte Carlo method should most likely be preferred.

In the estimation of ATS most uncertainty is due to the estimation of FFS. If the accuracy and precision of FFS estimates can be improved the confidence interval at high flow rates depends mostly on the uncertainties in the slope parameter. Uncertainties in other factors are highest at low flow rates, but also the effect of uncertainties is lowest there assuming that the structure of the HCM2000 model is correct. Uncertainties in flow rates and percentages of heavy vehicles increase the confidence interval at medium flow rates, especially near 600 veh/h.

In the PTSF analysis the impact of uncertainties in flow rates and percentages of heavy vehicles are highest at medium flow rates, as in the case of ATS. The questions of accuracy and precision in the slope factor and in the adjustment for no-passing zones are raised by the differences in the results between directional and two-way models as well as the possibility of directional PTSF estimates exceeding 100 percent. On two-way analysis with a 50/50 directional split the effect of uncertainties in the slope factor are highest at high flow rates and the effect of no-passing zone adjustment highest at low flow rates. As the directional distribution becomes more skew the effect of uncertainties at high flow rates due to the no-passing zone adjustment increases.

The estimated confidence intervals presented above can be assumed to be the minimum intervals according to the current knowledge. With the current state of knowledge, there are, however, considerable uncertainties in the estimates of uncertainty.

Empirical research based on field measurement should be performed to improve the estimation procedure for the free-flow speed and resolve the conflict between directional and two-way models of PTSF. Further research could also improve the accuracy and precision of the slope factor of ATS and the no-passing zone adjustment for the PTSF.

Many issues deserve further research: (*i*) The estimation of uncertainty in the capacity estimates faces the same problems as the capacity studies themselves; namely lack of data. The estimation of the effects of highway geometry and traffic composition on capacity would probably require international effort. (*ii*) HCM2000 does not consider interaction between road segments. On one of similar road segments passing rates may be lower and platooning heavier, if drivers are waiting for a three-lane segment ahead. (*iii*) The development of new methods should include the estimates of accuracy and precision, and the analyst should be able to assess the importance of uncertainty in the results.

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