TRAFFIC PERFORMANCE MODELING FOR INTERSECTIONS ON INTERURBAN AND TOWNSHIP ROADS

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Abstract: A comprehensive Highway Capacity Study (HCS) has been undertaken as a part of a national highway project including development of capacity guidelines for major intersections outside of urban areas in mainland East Asia. Field data collection of traffic flow and journey times was conducted in 5 signalized, 9 unsignalized intersections and 5 roundabouts. Furthermore studies of driver behavior and accepted gaps in conflicts between crossing traffic movements were performed in selected intersections. Delay-flow relationships were analyzed using multiple regression with power, exponential and linear models. Significant independent variables were traffic flow, split between major and minor road traffic, level of side friction and road width. The driver behavior studies showed that only 40% of the vehicles that had a choice between "gapping" or "pushing"actually waited for a gap in the major road flow. Gap acceptance models therefore could not be used to predict intersection performance for the studied unsignalized intersections and roundabouts. Critical gaps were nevertheless calculated and found to be in the range between 3.2 to 4 seconds for light and 5.3 to 7.8 seconds for heavy vehicles.

1 INTRODUCTION

The vehicle fleet on interurban and township roads in mainland East Asia includes a large proportion of low performing motor vehicles, slow-moving farm tractors, and man- or animal-powered vehicles. Passenger cars are still few although their number is expected to increase fast. Activities along the side of the road also create considerable "side friction" slowing down the traffic. In spite of high road standard and low traffic demand the level of traffic performance is generally low, making it difficult to apply capacity analysis methods from developed countries. A large-scale Highway Capacity Study (HCS) was therefore carried out in 1995-1998 with the purpose to develop draft capacity guidelines for motorways, interurban roads, township roads and major intersections outside of urban areas. HCS was part of Technical Assistance for which the World Bank had extended a loan.

The main part of the project dealt with interurban roads and motorways, from which results have been reported by Bang and Ronggui (1998). Although given a lower priority the HCS project also included major intersections on interurban and township roads. The purpose was to obtain rough estimates of intersection capacity as a basis for development of draft capacity guidelines. A second objective was to study driver behavior in different types of intersections as a basis for detailed future studies concerning intersection performance including simulation modeling. This paper describes results obtained for unsignalized four-arm intersections and roundabouts.

2 DATA COLLECTION

Two types of intersection field studies were carried out within HCS:

a) Traffic flow and travel time surveys

Surveys of traffic flow and travel time for all traffic movements in the intersection in order to obtain empirical relationship between delay, traffic flow and intersection characteristics (geometry, type of control, environmental conditions etc.). The following general data needs were identified:

- type of intersection and traffic control;
- geometric layout and design with specific focus on the approaches and exits in each road arm;
- traffic flow, composition, distribution on major/minor road, and distribution on turning movements;
- side friction events in the entries and the exits;
- actual travel time passing the intersection;
- ideal or reference journey time for unobstructed crossing of the intersection determined from actual speed in undisturbed sections upstream and downstream in each direction.

b) Driver behavior studies:

Surveys of driver behavior when crossing the intersection including:

- time headway at stop line passage;
- behavior in crossing conflicts as a function of right-of-way of the own movement (e.g. waiting for gaps, pushing etc);
- accepted and rejected time gap for determination of the critical gap in conflicts with a major traffic movement where the minor road movement yields.

2.1 Traffic Flow And Travel Time Surveys

The traffic flow and travel time field surveys (called QTS below) included 9 unsignalized intersections and 5 roundabouts. A summary of the characteristics of the surveyed intersections is shown in Table 1.

Table 1 Summary of Characteristics of Surveyed Intersections

Variable	Unsignalized intersections (three- and four-arm)	Roundabouts
Major road width: range; average (m)	9.0 – 17.0 11.8	9.0 – 21.0 14.2
Minor road width range; average (m)	9.0 – 15.0 10.8	9.0 – 16.0 12.8
Traffic flow major road range; average (pcu/h)	285 – 987 629	600 – 2400 1351
Traffic flow minor road range: average (pch/u)	256 – 493 356	560 – 900 705
Flow ratio minor/total range; average	0.21 – 0.60 0.38	0.20 – 0.48 0.37

The basic data collection method was to register vehicle identity (license plate number), vehicle type and passage time in both directions of travel on all intersection arms in sections sufficiently far away from the intersection to be undisturbed. This was achieved by using a survey station in each intersection arm equipped with detectors for automatic recording of vehicle passage time, vehicle type, direction of travel and spot-speed. The stations were also equipped with video camcorders for recording of the license plate number of each passing vehicle. The data for all intersection arms and directions was then processed to obtain the actual travel time between the upstream and the downstream survey station for each traffic movement (straight-through as well as turning movements).

Each intersection area was also observed using continuous video recording during each survey. The quality obtained from those recordings was however generally poor due to lack of high camera positions, but sufficient to review the discharge process and to exclude data when the intersections was blocked due to accidents and other abnormal events.

The main purpose of the QTS surveys was to measure **delay** defined as the difference between **actual travel time** and the **reference (ideal) travel time** between the in- and out-stations for each direction in the intersection implying that geometric delay (DG) as well as traffic delay (DT is included. Geometric delay is caused by the intersection geometry and traffic control and occurs even if the vehicle is alone when crossing the intersection. Traffic delay is caused by interaction with other vehicles in the intersection resulting in queues or slow movements in conflict areas. These two components could not be estimated separately from the available data, and the distinction was also irrelevant for the main purpose of this study.

The main problem with calculating delay was to estimate the reference travel time, which is hypothetical and cannot be measured. Two alternative methods to define reference travel time were used in the study based on data from the in- and out survey stations which were located sufficiently far away from the intersection to permit observation of undisturbed speed on the road links.

a) The **individual reference travel time method** used the observed individual speed in the in- and out-station to calculate an individual reference travel time for each vehicle, TT_{is}:

$$TT_{is} = L_{in} / V'_{in} + L_{out} / V'_{out} \qquad [1]$$

where

V'_{in}, V'_{out}	measured spot speeds from short-base stations for actual vehicle in- and out-station
L'_{in}, L'_{out}	distances from in- and out-station to intersection center point

The vehicle spot delay D_{is} is then calculated as:

$$D_{is} = TT_i - TT_{is} \qquad [2]$$

where

TT_i: observed travel time for the vehicle

TT_{is}: individual reference travel time

b) The **vehicle class average reference travel time method** used the observed average vehicle class speed in the actual time period in the in- and out-station to calculate a vehicle class reference travel time for each vehicle class and direction in the time period. This method provided more stable results at low traffic flows.

2.2 Driver Behavior Studies

In order to better understand the traffic interaction process in intersections a number of micro-studies were performed. These studies were also intended to be useful for future development and implementation of simulation models for intersections.

a) Traffic behavior for crossing conflicts for vehicles from a minor road

Driver behavior in conflict points between crossing vehicle movements in unsignalized intersections was studied using video recording from an elevated position. The following types of behavior were observed visually from the video recordings:

1) no conflict (the vehicle is "alone" in the conflict area);
2) gapping (the vehicle stops and waits for acceptable gap in major road traffic);
3) pushing (the vehicle does not stop and wait for a gap but continues forward thus forcing the major road traffic to slow down or stop);
4) following (following after a lead vehicle of type 2 or 3).

Classification was made by vehicle type (1: Light Vehicles: including cars, jeeps, mini vehicles; 2: Heavy Vehicles: including buses, trucks, truck combinations).

b) Accepted and rejected gaps for gapping straight-through vehicles from a minor road crossing a major road traffic flow.

Rejected and accepted gaps for straight through minor road vehicles crossing a major road flow were registered from video recordings of the traffic process in the conflict area in unsignalized intersections.

3 DELAY - FLOW RELATIONSHIPS

3.1 General

A stratified sample of 15-minute intervals at each site was selected for license plate identification, resulting in 50-150 observations for the delay analysis from each interval. The intervals were selected to represent a range of conditions regarding the total traffic and the ratio of the minor to major road flow (split) with emphasis on peak hour conditions. However, the traffic flows in the studied intersections and roundabouts were generally low with quite limited flow variation. Hence the data could not be used to assess capacity, and estimates of delay-flow relationships were generally uncertain.

All surveyed intersections were four-way with very large intersection areas, flared approaches and big radii (reportedly to facilitate a future conversion of the intersections to roundabouts by just adding a central island). This also applied to the roundabouts. Vehicles typically made use of the whole area by short-cutting to avoid conflicts, pushing through an intersecting flow rather than waiting for longer gaps, etc. No clear priority rules were observed as shown in Section 3.3 below. The same type of traffic behavior was observed for a much larger number of sites in the Indonesian Highway Capacity Manual project (Bergh 1994).

The analysis described below focused on two performance measures of particular interest for both unsignalized intersections and roundabouts:

- the average delay for all traffic, and
- the average delay for major road traffic only.

The average delay for all traffic is primarily of interest for comparison of different intersection types, while the average delay for the major road traffic only can be used to calculate the travel speed along a highway which includes both links and intersections. The analysis considered "delay" as including both traffic delay (resulting from vehicle interactions between crossing conflicts) and geometric delay (resulting solely from the need to slow down to navigate the geometrics of the intersection, e.g. making a turning movement).

All traffic flows were expressed in pcu/hour with a passenger car equivalent (pce) of 1.0 for light vehicles and 1.5 for heavy vehicles (estimated for an average mix of such vehicles using traffic signal headway data).

3.2 Delay-Flow Analysis For Unsignalized Intersections

a) Average delay for all traffic

Figure 1 below plots the average delay for all traffic entering the intersection versus the total traffic flow. Each point represents one 15 minute period in one of eight unsignalized intersections.

A delay-flow relationship with delay increasing with flow can be spotted in the Figure as well as different levels of delay at the same level of the total traffic flow in some intersections.

A correlation analysis was undertaken to identify any significant relationships between different factors. The variables included delay and vehicle speeds in total and for each road separately; as well as the total traffic flow, the ratio of minor to major road traffic, the percentage of vehicles turning right or left, the class of the major road, the intersection area, the existence of special bicycle lanes, and an indicator of the level of side friction close to the intersection.

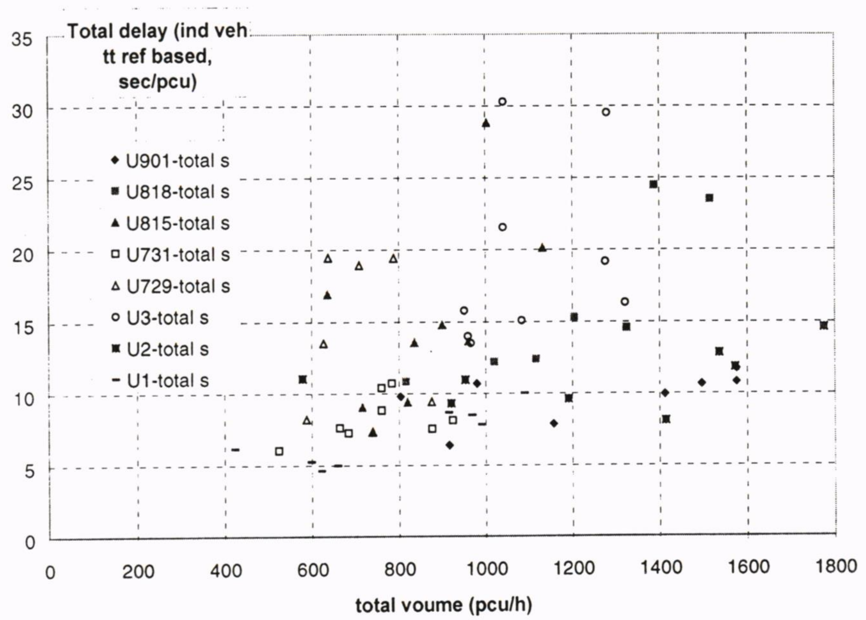

Figure1 Average Delay for All Vehicles Plotted Against the Total Traffic Flow

The average delay to all vehicles was found to be significantly correlated with the following variables:

\+ *(with a positive sign, i.e. the delay increases when the variable increases)*

- total traffic flow;
- level of side friction, assessed on a scale 1-3;

\- *(with a negative sign)*

- average reference speed in all intersection arms measured at the survey stations upstream and downstream of the intersection.

The average delay was expected to increase stronger than linearly with traffic flow, i.e. at an increasing rate as the flow approached the capacity of the intersection. It was however difficult to assess the shape of this relationship due to the low level and limited range of the total traffic flows in the survey data. All observations were well below capacity (700-1,200 pcu/h). Two alternative regression models that both allow for increasing rates of increase were tested:

Power model: [Dtot] = a * [Variable_1]^b1 * [Variable_2]^b2 * … [3]

Exponential model: [Dtot] = a * exp{b1*[Variable_1] + b2*[Variable_2] + ..} [4]

where
[Dtot] = average delay for the intersection as a whole
a, b1, b2.. = coefficients to be determined.

Step-wise regression using both models showed statistically significant results for the following variables:

Power model:
- QT = total traffic flow
- FRIC = assessed level of side friction (1-3)
- Wmaj = width of major road
- Wmin = width of minor road

Exponential model:
- Qtot = total traffic flow
- FRIC = assessed level of side friction
- Wmin = width of minor road
- Vmin = average minor road speed

The power model gave slightly higher R^2 value with 0.46 as compared to 0.43. Some other variables were nearly significant but different for the two models and not all with the expected sign. This may be due to the interdependencies between the variables, which left some arbitrariness regarding the selection. For example, the split depends as per definition only on the ratio of the minor to the major road flow Qmin/Qmaj, but not on the total flow Qtot = Qmin+Qmaj. Alternatively Qmin and Qmaj could be selected as two independent variables, but for the purpose of the applications it is preferable to use Qtot and S=Qmin/Qmaj.

In a second step, a partly new set of variables was defined based on such considerations and entered step-wise in the power model. This resulted in:

$$Dtot = 0.025 * Qtot^{0.94} * S^{0.23} * B^{(-0.28)} \quad [5]$$

where
- Dtot = average delay for all traffic movements in the intersection
- Qtot = total flow in the intersection
- S = split between minor and major road traffic
- B= degree of bicycle separation: 3 if separate bicycle lanes are provided, 2 if the shoulders can be used by bicycles, and 1 if there are no such facilities.

The resulting R^2 was 0.38, which could be improved to 0.45 if the following variables were also added:
- RT = % vehicles turning right, in total for all approaches: exponent 0.75
- LT = % vehicles turning left: exponent –0.27
- A = intersection area Wmaj*Wmin: exponent 0.35

The addition of the three additional variables is questionable, however, since at least RT appears to have the wrong sign: the predicted delay increases with an increasing share of traffic turning right. The probably reason is that the variables RT, LT and A are all correlated in the survey data.

Figure 2 compares the delays predicted by this model with those measured empirically. The figure shows that the estimated power model is not applicable for delays exceeding about 20 seconds per vehicle, which according to the model corresponds to a total traffic flow in the order of 1,500 pcu/h. Higher flows than 1,500 pcu/h were not observed and could not be considered statistically on the basis of these data. Very similar results were obtained with the exponential model.

Within its range of validity 500-1,500 pcu/hour, however, the model predicts the following effects for the average intersection delay:

- the effect of the total traffic flow is nearly linear, with an increase of about 1.5 sec/vehicle per 100 pcu/hour;
- an increase in the ratio of minor road traffic to major road traffic from 0.5 to 1.5 (i.e. from 25% to 75% of the total traffic) increases the average delay by about 25%;
- the provision of separate bicycle lanes, as compared to no facilities at all for bicyces, reduces the average delay by the order of 25%.

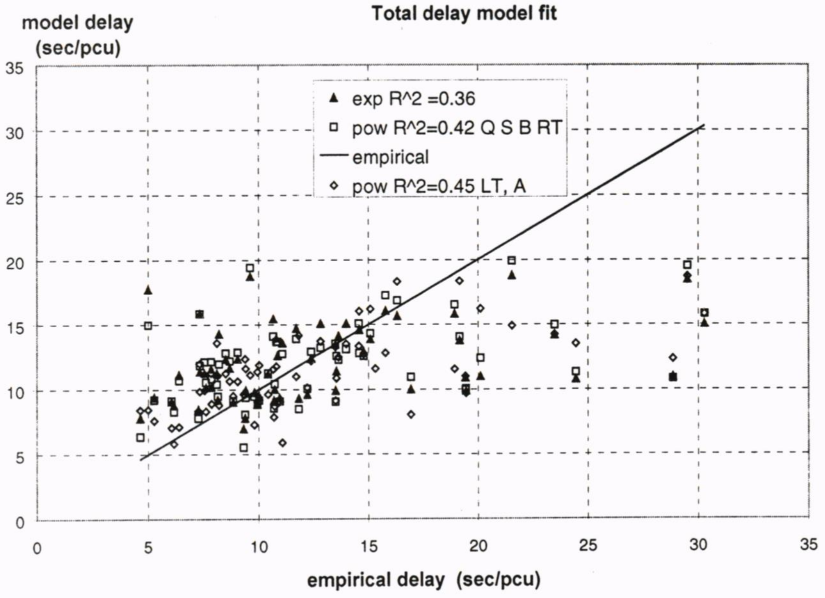

Figure 2. Comparison Between Estimated and Empirical Delay for all Traffic.

b) Major road delay

The same correlation analysis as presented above was performed for major road delay resulting in the following relationship (R^2=0.40):

$$Dmaj = 0.190 * Qtot^{0.624} * S^{0.413} * FRIC^{0.286} \quad [6]$$

where

Dmaj =	average delay for the major road traffic
Qtot =	total flow in the intersection
S =	split between minor and major road traffic
FRIC=	subjective estimate of side friction, on a scale 1 (=little or none) to 3 (=high)

c) Comments regarding obtained results

The empirical models based on regression analysis shown above had no explicit link to the study of driver behavior described in Section 4 below. Figure 1 with the observed delay-flow data shows a considerable scatter, leading to rather weak models for prediction of delay. Comparison with studies from Indonesia (Bergh, Dardak 1994), where similar driver behavior exists, showed that the delays were normally higher in spite of the considerable size of the studied intersections (see Table 1). A possible reason for this may be the poor lane discipline including a tendency of the drivers to try to "cut corners" while making left-turns in spite of the blockages to other traffic movements that this behavior may cause. However, none of the studied intersections had a traffic load that made it possible to observe conditions close to capacity.

3.3 Delay-Flow Analysis For Roundabouts

A similar regression analysis was performed on the delay-flow data including a total of 50 records (15-minute periods) for six different roundabouts. Five of the six roundabouts were relatively small and had light to moderate traffic, while the sixth was large and often saturated to capacity. Due to the small size and range of the samples the results may not be applicable for other roundabouts, particularly regarding the effects of individual variables related to geometric and other factors.

Considering observed correlations between the dependent variable Dtot and other variables as well as between these other variables, three types of independent variables could be identified:

- measures of the traffic flow: Qtot, Qmaj, Qmin, and SPLIT (=Qmin/Qmaj). Only two of these can be independent and appear in the same regression equation, namely either Qtot and SPLIT or Qmaj and Qmin;
- geometric variables including the road widths Wmaj and Wmin as well as the inner and outer diameter of the roundabout (RI, RO). These are all interdependent, and also correlated with some other variables in the data set such as the percentage of turning vehicles (RT and LT). Probably at the most two of the geometric variables can be significant in the same regression equation;
- other variables which are more or less independent but still affect the delay to various extents, e.g. SEP = separation of bicycles.

Step-wise regression was used to successively identify variables that contributed most towards reducing the variance in the delay Dtot. The same power function was tested as for the unsignalized intersections. Since the relationship between flow and delay was found to be nearly linear for those intersections, a linear relationship was also tested for roundabouts with the following results:

Linear Dtot = 8.7 + 0.008*Qtot + 0.7*SPLIT + 4.0*SEP – 0.9*Wavg [7]

Power function Dtot = 0.34*Qtot^0.788*SPLIT^0.19*SEP^0.48*Wavg^(-0.80) [8]

The power and the linear regression gave very similar results. The two variables Qtot and SPLIT together uniquely determined Qmaj and Qmin, and resulted in a higher R^2 value than the latter two variables. The degree of separation (SEP) significantly improved the R^2 values, although it appeared to have wrong sign. The variables Wmin (width of the minor road) and RI (the inner diameter of the roundabout) also contributed significantly, but could both be replaced by the single variable Wavg. This was constructed as the average width of the major and the minor road, i.e. Wavg =(Wmaj+Wmin)/2.

In the power regression, the exponent for the total flow Qtot was less than one, indicating that the delay-flow relationship increases less than linearly. This was also found for unsignalized intersections but is more surprising for these roundabouts since one of the sites operates near capacity.

In Figure 3 below calculated results from both these models are compared with the empirical results from the data base. The figure shows very little difference between the two models when applied to the available data. The apparent linearity of the delay-flow relationship over the whole range of traffic flows from about 600 pcu/h to nearly 3,800 pcu/h is surprising.

Regression analysis of major road delay Dmaj showed that four variables contributed significantly to the linear model at 95% confidence level:

- Qmin — average minor road flow, pcu/h
- RT — % right turn, average for the roundabout
- LT — % left turn, average for the roundabout
- Wavg — average of the major and minor road widths (linear model only)

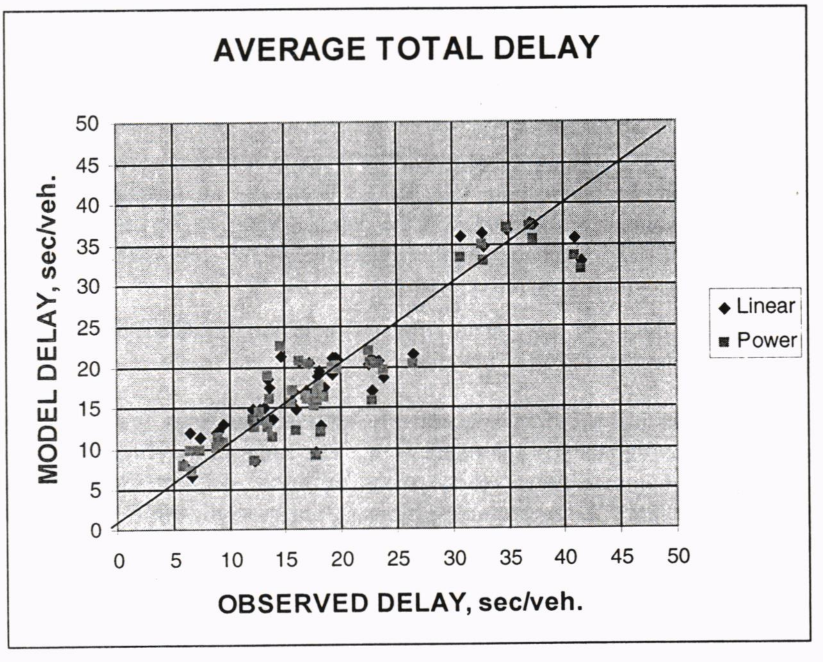

Figure 3 Calculated Delays Using the Two Estimated Models (Linear and Power), Compared to the Observed Total Delays.

The sign for RT and perhaps also for LT are the opposite of what would be expected, probably due to correlations with some other variables (such as SEP) which did not contribute directly in the regression.

The relationship between Dmaj and Qmin is nearly proportional, which due to the strong correlation between Qmin and Qmaj implies a nearly proportional relationship also with the total flow Qtot. Again, this is due to the particular conditions in these six roundabouts and may not apply generally, for example if Qmin is more or less constant while Qmaj varies during the day.

4 DRIVER BEHAVIOR AND GAP ACCEPTANCE

4.1 Introduction

The purpose of these studies was to:

- analyze if the traffic behavior at the studied unsignalized intersections could be described in terms of gap acceptance; and to
- measure, if possible, gap acceptance to support the proposed capacity model.

Video recordings of the vehicle behavior were screened for three unsignalized intersections with traffic flow within the range 500-1,200 vehicles/hour for the major road, and 100-250 vehicles per hour for the minor road. Based on these preliminary screenings, the following hypotheses were formulated:

- vehicles turning left off the major road normally make short cuts through the intersection, thereby avoiding to yield for opposing through traffic;
- vehicles turning left off the minor road also try to short cut in the same manner. When this is not possible, they normally gap to through traffic from the left on the major road, and merge or weave with major road traffic from the right;
- vehicles from the minor road bound straight across the major road sometimes yield ("gap"), and sometimes push their way across the major road;
- vehicles turning right off the minor road sometimes gap and sometimes merge into the major road traffic.

The quantitative evaluation focused on two specific objectives:

(A) to classify the behavior of vehicles crossing from the minor road (percentages that gap, push, etc.); and
(B) to analyze the gap behavior for those vehicles which do gap.

4.2 Traffic Behavior

The behavior in crossing conflicts from the minor road was studied for eight 15-minute periods in five unsignalized intersections. Each vehicle was classified in one of four groups with regard to its observed behavior in the conflict zone:

1. no conflict (large gap in the major road traffic);
2. gapping, meaning the vehicle stops and waits for an acceptable gap;
3. pushing, meaning that the vehicle does not wait but crosses in such a way that traffic on the major road is forced to slow down or swerve;
4. following, after a lead vehicle of type 2 or 3.

The results from a total of about 3,000 observations from all five intersections is summarized in Table 2:

Table 2 Classification of Behavior for Vehicles Crossing From a Minor Road

VEHICLE	% of all vehicles				% of gap or push	
TYPE	Alone	Push	Gap	Follow	Gap	Push
- light	52	16	11	21	41	59
- heavy	52	17	11	20	39	61

Of the vehicles that had the choice between "gapping" or "pushing", only about 40% on average actually selected to wait for a gap in the major road flow. This means that a gap acceptance model could not be used to predict the level of traffic performance for the studied unsignalized intersections.

Regression analysis of the percentage gapping vehicles with a choice between gapping or pushing was undertaken in order to explain the behavior. The results were not conclusive but indicated that "pushing" became relatively more frequent with increasing traffic flow in the intersection, and also with an increasing ratio between the minor road traffic and the major road traffic.

4.3 Gap Acceptance

Gap acceptance for minor road through traffic was investigated in more detail for three of the unsignalized intersections. Figure 4 illustrates results from one site.

Statistical methods including Ashworth's correction factor were used to estimate the critical gaps. The results for all three intersections had a range between 3.2 and 5.0 seconds for light vehicles, and between 5.3 and 7.8 seconds for heavy vehicles. The number of lanes in the major road (2 or 4) had no significant impact on the results.

The estimated critical gaps ranged between 3.2 and 5.0 seconds for light vehicles, and between 5.3 and 7.8 seconds for heavy vehicles. This is higher than reported from Indonesia but somewhat lower than as reported from Sweden, Germany and the US for the same traffic movement in intersections of a similar size (Bergh 1994, Kyle 1997).

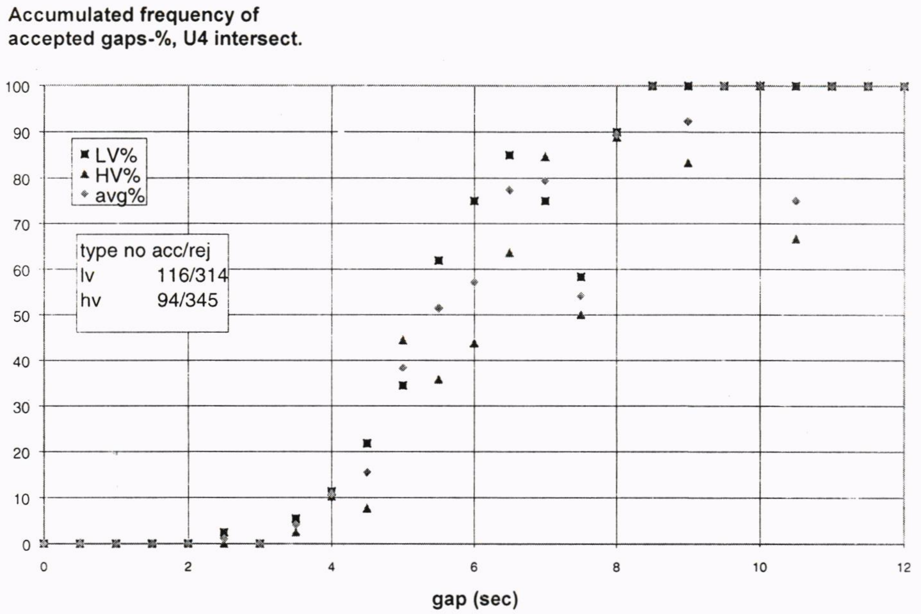

Figure 4 Empirical Gap Acceptance for Minor Road Through-traffic

5 CONCLUSIONS AND RECOMMENDATIONS

The studies of the capacity of unsignalized intersections and roundabouts on interurban and township roads described in this paper was based on a limited number of surveyed intersections with only one intersection experiencing severe congestion. The following preliminary conclusions could however be made:

- reference (ideal) road link speed (assuming no intersection) was best determined based on observed space mean speeds for each class of vehicle;
- intersection delay was primarily a function of 1) total intersection traffic flow, 2) split between major and minor road flow, 3) level of side friction, and 4) width of the intersecting roads;
- the drivers generally did not give way to the traffic from the right or from the major road. Intersection performance therefore could not be analyzed using explanatory models, e.g. based on critical accepted gaps;
- the performance of the unsignalized intersections was generally poor compared to results obtained for Indonesia which has similar driver behavior.

The project resulted in empirical models from with the traffic performance (delay) could be estimated as a function of the variables listed above. At the onset of the project it was also intended to use the results to develop a simulation model for unsignalized intersections. The vast size of the intersection conflict area in combination with the irregular vehicle paths chosen by the drivers to cross it would however make simulation modeling difficult. More comprehensive and in-depth field studies of driver behavior would be required to evaluate if simulation modeling could be at-all suitable for the studied problem.

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