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A COMPARISON OF DELAY ON ARTERIALS BY SIMULATION AND HCM COMPUTATIONS

By

Elena S. Prassas, PhD
Associate Professor
Civil Engineering Department
Polytechnic University
6 MetroTech Center
Brooklyn NY 11201
Ph: (718) 260-3788
Fax: (718) 722-7271
eprassas@poly.edu

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**Elena S. Prassas, Polytechnic University, 6 MetroTech Center, Brooklyn, NY
11201, Ph: 718-260-3788, Fax: 718-722-7271, eprassas@poly.edu**

Abstract

A comparison of delay on arterials was made using simulation and HCM computations. An extensive set of cases was defined over a range of flow rates, free flow speeds, and signals per mile. Delay was computed based upon the HCM computation, for the specified signal progressions. The same cases were run using a specially revised version of the NETSIM microscopic simulation model.

Detailed analysis showed that the discrepancies were traceable to the progression factor PF. Corrections can be made (and are outlined), but must be used with care. There are a number of complex mechanisms at work. The primary result of this paper may be making clear the insufficiency in the present PF algorithm.

The expectation that a single multiplicative factor can provide the needed correction to a long-link random-arrival steady-state delay model (that is, the existing HCM delay model), so that it can be a network-based model for delay estimation, appears to be simply too much to expect.

For these and other reasons, the author is now focusing research on the creation of a time-varying intersection delay model, building from basic principles.

INTRODUCTION

A comparison of delay on arterials was made using simulation and HCM computations. An extensive set of cases was defined over a range of flow rates, free flow speeds, and signals per mile. Delay was computed based upon the HCM computation, for the specified signal progressions. The same cases were run using a specially revised version of the NETSIM microscopic simulation model.

Detailed analysis showed that the discrepancies were traceable to the progression factor PF. Corrections can be made (and are outlined), but must be used with care. There are a number of complex mechanisms at work. The primary result of this paper may be making clear the insufficiency in the present PF algorithm.

BACKGROUND

The Basic Relation The *Highway Capacity Manual* in the last several releases [1,2,3,4] has used a relation for intersection delay by lane group of the form

$$d = (PF) d_1 + d_2 + d_3 \quad (1)$$

where

- d = control delay per vehicle, s/veh
- PF = uniform delay progression adjustment factor which accounts for the effects of signal progression
- d_1 = uniform control delay assuming uniform arrivals and no overflow, s/veh
- d_2 = incremental delay to account for the effect of random and oversaturation queues, adjusted for the duration of the analysis period and type of signal control. This delay component assumes that there is no residual demand for the lane group at the start of the analysis period, s/veh
- d_3 = supplemental delay to account for oversaturation queues that exists prior to the analysis period, s/veh

and

$$d_1 = \frac{0.50C (1 - g/C)^2}{1 - [Min(1, X) g/C]}$$

$$d_2 = 900 T \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right]$$

The same relation is used in computing the average travel speed on arterials, which can be written for equal signal spacing and traffic in the form

$$\text{Average Travel Speed} = \frac{3600}{\text{RTPKM} + Nd} \text{ km/hr}$$

where RTPKM is running time per kilometer, N is the number of signals per kilometer, and d is the delay per signal (or link). For this application, only the lane group containing the thru vehicles is used in computing “d”, because the HCM explicitly defines arterial level of service in terms of the average travel speed of thru vehicles.

Analytic and Other Relations for Delay Equations of the form shown in Equation 1 and their use in modeling delay have been addressed in the literature [e.g., 5, 6]. In addition, traffic simulators have been constructed that imbed analytic models for delay [e.g., 7], while others depend upon microscopic interactions to generate delay as an effect [e.g., 8].

Issues of Interest There are two central issues to consider in using the delay relation of Equation 1 in the estimation of average travel speed:

- 1) Given that the HCM delay as formulated provides a result for the overall thru lane group (TLG), does it apply to the vehicles that are truly “thru” vehicles as defined below? Or does it incorporate adjustments (such as the progression factor) which are better suited to the aggregate of all vehicles in the thru lane group?
- 2) Does the relation reflect the effects of all delay experienced along the arterial not explicitly taken into account in the running time (RTPKM)?

The purpose of this paper is to report some insights into these questions, arrived at by a series of simulation investigations.

Definition of Thru Vehicles The author has previously suggested [9] that for the purpose of the arterial performance, only a subset of all arterial travelers are truly “thru” vehicles. Specifically, only those vehicles that enter and exit an arterial link as non-turning vehicles should be considered as “thru” vehicles for the purpose of arterial performance. Refer to Figure 1 for an illustration of the concept. Only one of the possible nine O-D pairs from the numbered movements shown in Figure 1 would be “thru” vehicles by this definition. (namely, O5).

METHODOLOGY

In earlier work [9], the author reported an extensive simulation effort by which the original default running times and running speeds of the HCM [1] were assessed, and recommendations were made for improvements. These recommendations have been incorporated into the *Florida Level of Service Handbook* [10].

That simulation effort also resulted in a wealth of information on delay as estimated by the microscopic simulator used. Additional runs were made since then for different turn percentages and offsets, expanding the information available. Refer to

Table 1 for a summary of the runs undertaken. The specific runs were designed to avoid oversaturation, lest the d_3 term become relevant.

For each run, the HCM equations were used to estimate d_1 , d_2 , and d . In order to estimate “ d ”, it was necessary to estimate the progression factor “PF” according to the guidelines of the HCM. This was done as outlined in Table 2, with “P” obtained as an output from the simulation output (added as a feature by the developer, in support of this work).

As cited in [9], a well-established simulation model, namely NETSIM, was used. NETSIM is now incorporated into a tool known as CORSIM. This model has evolved over decades, and has been used extensively. There have been cautions on its use, for it does have limitations, but it can be a powerful tool when used suitably.

In all of the runs, “free flow speed” as used in the HCM was taken to mean the prevailing speed under excellent progression, with no turns, and with 200 vphpl demand volume. To achieve speeds of 90, 70, and 55 km/hr as specified in the Table 1 design, under these conditions, it was necessary to set the NETSIM “free flow” speed parameter higher, because the NETSIM parameter of this name has a somewhat different meaning than just specified.

Neither NETSIM in its original form nor the version now included in CORSIM provides estimates of the travel time, speed, or stopped delay of thru vehicles alone. It was arranged with the initial developers of NETSIM to have an adaptation created from the current version of NETSIM (at the time of this research) [11] that provided the vehicle identifications shown in Figure 1 for each vehicle in each link, so that the analyses in this work could be conducted. The support was greatly appreciated.

Table 3 shows the variables and parameters used in this analysis. The NETSIM delays were computed based upon the specified link lengths and obtaining the running time per kilometer from [9]. The HCM values were computed from Equation 1.

ANALYSIS

The most enticing initial question is the relation of the two forms of “delay” ---- microscopic simulator, and HCM equation --- to each other, and to the physical and traffic parameters selected. To this end:

- The d_1 and d_2 terms are strongly related over the range of cases studied, even with the balanced set of cases and ranges used in the analysis (Table 3). This is logical, given their dependence on comparable terms, to different degrees;
- The NETSIM delay (D14) is most strongly related to signal spacing, progression factor, and free flow speed.

- For HCM computed delay (D16), indicating the primacy of progression factor and signal spacing.

Turns and offsets are also important, when they are varied.

The third observation above contains two logical parts, but the inter-relation with the progression factor PF is interesting. It is clear that the NETSIM delay should depend upon such elements as

- signal spacing
- progression quality
- free flow speed

but the finding is that the NETSIM delay is related explicitly to the HCM-established progression factor PF.

This is enticing. If the simulation and HCM results are related, it is the factor PF that correlates to the simulation results (albeit only with a linear correlation of + 0.46). Either there is a linear relation and much scatter or there is a more complicated relation (e.g. nonlinear in some way).

Remember that the HCM delay model traces its roots to an isolated intersection model. It is the PF factor in $d = (PF) d_1 + d_2 + d_3$ which takes the isolated intersection results and introduces the network environment. It is therefore entirely logical --- and promising --- that this factor is clearly correlated to the simulation results, which are generated by an independent, microscopic model that reflects individual vehicles.

Alas, the linkage is not total. As now illustrated, and drawing on the linear correlation coefficients, the relationships shown in Table 4 exist.

It would be very nice if the last two columns related to each other strongly, through the same parameters. But they do not, and there is great scatter (and not strong patterns) in a plot of NETSIM delay versus HCM delay for the same parameters. Given the results shown in Table 5 for 1620 observations, it follows that there would be a much nicer match if the average PF had been about 0.224, or 63% lower.

Of course, this implicitly assumes that the NETSIM delays have more validity than the HCM-computed delays. But it is the HCM values of “d” which carry the heavy burden of using primarily a single multiplicative factor PF to imbed virtually all awareness that the signal is not in an isolated location, particularly given that the d_1 term is dominant (see Table 5).

Continuing along this path of reasoning, the difference between the HCM thru-vehicle delay and Netsim thru-vehicle delay $\{D_{\text{HCM TLG}} - D_{\text{NETSIM THRU}}\}$ was constructed and related to PF. This is shown in Figure 2.

ADDITIONAL ANALYSIS

Figure 2 has three regimes in which the difference $\{D_{HCM\ TLG} - D_{NETSIM\ THRU}\}$ relates to the progression factor in fundamentally different ways, as shown in Table 6. The insight of the previous section of a single “better” average PF is an oversimplification. Even a revised summary as shown in Table 7 is insufficient. A more detailed analysis by regime is now presented.

The methodology in each regime is fundamentally the same:

- 1) A new “estimate” of the progression factor is constructed by finding the progression factor PF2 that is needed in order for the observed value of d_{NETSIM} to have been the answer, rather than d_{HCM} . That is,

$$d_{NETSIM} = (PF2) (d_1) + d_2$$

or

$$PF2 = \{ d_{NETSIM} - d_2 \} / d_1 \quad (2)$$

This is done for each and every observation.

- 2) The relation of PF2 to physical and traffic parameters is investigated by correlations, cluster analysis, and regression;
- 3) If possible, a means of adapting PF so as to create a “better” progression factor PF_{REV} is devised;
- 4) Values of a new quantity d_{HCM2} are generated by

$$d_{HCM2} = (PF_{REV}) (d_1) + d_2 \quad (3)$$

and compared to both d_{NETSIM} and $d = d_{HCM}$. (Of course, this is more a reality check than a separate result, because the same database used to find PF_{REV} is being used to compute d_{HCM2} and compare it to d_{NETSIM}).

In Step 3, note that the decision was made to adapt PF rather than replace it, because the data set needed for that task (and the concurrent need for confirming field data) is beyond the present scope. Rather, therefore, the results below are intended to point the way to such a more extensive investigation.

Regime 1 ($PF \leq 0.14$) As shown in Figure 2, this regime had a very wide range of discrepancies between d_{NETSIM} and d_{HCM} . Much of this was traceable to the following cases:

- very long signal spacing, leading to platoon dispersal in NETSIM;
- very small differences between the two methods (generally at high free flow speeds), which led to very small or negative PF2 values in Equation 2.

With these eliminated, only 179 cases remained.

Correlations were inspected, and a regression conducted. As a result, a revised progression factor defined by

$$PF_{REV} = 4.9 (L) (PF) \quad (4)$$

would improve the relation between d_{NETSIM} and d_{HCM2} , where “L” is the spacing between signals, ranging between 0.18km and 0.54 km in the observations.

Specifically, the correlation between d_{NETSIM} and d_{HCM2} was 0.78, and was statistically significant at the 0.01 level. This is an improvement from 0.46 between d_{NETSIM} and d_{HCM} . That is, with the revised definition, 61% of the variance is explained, rather than 21%. Given that the observations include several replications of the NETSIM runs, some variance due to the randomness intentionally introduced must be expected.

Regime 2 ($0.14 < PF < 1.50$) As shown in Figure 3, this regime had cases in which the discrepancy $\{d_{HCM} - d_{NETSIM}\}$ steadily increased with PF.

Figure 3 shows the discrepancy in more detail. Based upon the trend line, if a d_{HCM} of 15 seconds/vehicle were computed, the d_{NETSIM} is likely to be in the range of 2.0 to 8.0 seconds/vehicle, centering on 4.0 seconds/ vehicle¹.

Of course, it would be nice if the two methods provided consistent numbers. Actually, the derivation to follow will yield the adjustments shown in Table 8, and the improvement shown in Figure 4.

It was interesting to note that d_{HCM} correlated most strongly to PF ($r = 0.93$), and not very strongly to either d_1 or d_2 ($r = 0.33$ and 0.20 , respectively). Indeed, it is dominated by PF. That is, it is the progression factor and not the delay terms that are responsible for the d_{HCM} results.

Again, correlation and other analyses were conducted to find a pattern by which a progression factor correction would link to observed physical or traffic parameters. An interesting pattern was observed, in which flow rate and free flow speed were elements. Consider the following, as shown in Table 9:

¹ Actually, centering on 5.0 seconds/vehicle, but the trend line is skewed by the higher values.

- form $\{d_{\text{NETSIM}} - d_2\}$ from the observations, showing the average in the top of the display in Table 8. If $d_{\text{NETSIM}} = d_{\text{HCM}}$, then this is also $(\text{PF})(d_1)$, by the defining Equation 1;
- note the computed d_1 in the same display;
- compute what the progression factor needs to be, in order for the assumption of $d_{\text{NETSIM}} = d_{\text{HCM}}$ to be valid. Call this PF2;
- compare it to the actual computed PF.

The values for the highest flow rate are not considered. Further, the PF2 does not have large variations with respect to flow rate. In the interests of simplicity, a correction based only on the free flow speed is suggested:

$$\text{PF}_{\text{REV}} = \alpha (\text{PF}) \quad (4)$$

where “ α ” is shown in Table 8.

Using the PF_{REV} to generate d_{HCM2} , the improved relation of Figure 4 results. The linear correlation coefficient is 0.88, explaining 77% of the variance.

The discrepancies at higher values of d_{HCM2} tend to be under-estimates of the delay, using d_{NETSIM} as the reference. These tended to occur at one signal spacing and the lowest free flow speed.

Regime 3 ($\text{PF} \geq 1.50$) As shown in Figure 2, this regime had cases in which the discrepancy $\{d_{\text{HCM}} - d_{\text{NETSIM}}\}$ steadily decreased with PF.

Following the same chain of reasoning as for Regime 2, it was found that a PF_{REV} of the same form as Equation 4 was justified, with the “ α ” as shown in Table 10. Figure 5 shows the relation after the adjustment.

POTENTIAL USE OF PRESENT FINDINGS

The present work does have limits that preclude simply substituting the PF_{REV} for the PF in all future delay computations:

- The insights are good, but the set of “observations” primarily cover two ranges:
 - ideal progressions, impacted by left and right turn percentages from 0% to 8% each;
 - for the 8% turn cases, deviations from the ideal progressions ± 15 seconds;
- There is no field data to compare with either d_{HCM} or d_{NETSIM} or d_{HCM2} .
- The d_{HCM2} results are computed from the same set of observations used to create the PF_{REV} , so the improvement is expected. Another, independent set of runs is needed.

Nonetheless, the discrepancies do cause concern, and should justify further investigation, because the single multiplicative factor PF is the current state of the practice. And the progression factor PF as currently designed does not seem to be doing the needed task.

Having generated illustrative corrections, particularly in Regimes 2 and 3, it is interesting to see the net effect on the progression factor. Figure 6 shows the PF_{REV} computed for a range of PF values, given Tables 8 and 10.

Now clearly the discontinuity between Regimes 2 and 3 near $PF = 1.50$ is dissatisfying. One can hypothesize that a refined analysis could justify a smoother taper, such as tapering the curves from $PF_{HCM} \simeq 0.90$ to $PF_{HCM} \simeq 1.50$ so as to provide some continuity. But given the emphasis on insight rather than a short-term generalized substitution, this was not pursued at this time.

CONCLUSIONS

The fact that it is PF that dominates the d_{HCM} computation in Regime 2 draws attention, because this means that the delay estimate depends primarily on the algorithm of Table 2, and not on the delay terms d_1 and d_2 . Additionally, the result is inconsistent with the simulation results, as shown by d_{NETSIM} .

This is the most acute display of a phenomenon common to all of the regimes:

The progression factor is of great importance, and --- despite its own calibration --- yields results that are inconsistent with a well-established microscopic simulator.

Corrections can be made, but must be used with care. There are a number of complex mechanisms at work, which may make the specific results of this paper of limited short-term value, *other than pointing to a clear insufficiency in the PF algorithm.*

The mechanisms include:

- Given that d_1 and d_2 can increase without awareness of link length means that the computed d_{HCM} may not occur, simply because the queue implied cannot fit into the links considered. For instance, can the queue implied by a 40 sec/vehicle average delay actually fit into a link of 0.3 or 0.5 km?
- The microscopic simulator of course does yield only the delay that occurs within the link, and it intrinsically takes into account the effects of link length, dissipation of the platoon due to turns, and other factors.
- The effect of free flow speed on link travel times and vehicle interaction are imbedded in the microscopic simulator.

The primary conclusion is therefore:

The expectation that a single multiplicative factor can provide the needed correction to a long-link random-arrival steady-state delay model, so that it can be a network-based model for delay estimation, is simply too much to expect.

For these and other reasons, the author is now focusing research on the creation of a time-varying intersection delay model, building from basic principles.

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LIST OF TABLES

TABLE 1: SUMMARY OF SIMULATION RUNS

TABLE 2: ESTIMATION OF PROGRESSION FACTOR “PF”

TABLE 3: “DATA” RECORD FROM SIMULATION RESULTS

TABLE 4: RELATIONSHIPS OBSERVED

TABLE 5: COMPARISON OF RESULTS (AVERAGES)

TABLE 6: THREE REGIMES, BASED UPON THE DIFFERENCE IN RESULTS

TABLE 7: COMPARISON OF RESULTS (AVERAGES), THREE REGIMES

TABLE 8: CORRECTION TO OBTAIN PF_{REV} IN REGIME 2

TABLE 9: ESTIMATION OF A CORRECTION TO PROGRESSION FACTOR IN REGIME 2

TABLE 10: CORRECTION TO OBTAIN PF_{REV} IN REGIME 3

LIST OF FIGURES

FIGURE 1: THE CONCEPT OF THE THRU VEHICLE

FIGURE 2: RELATION OF $D_{25} = \{d_{HCM\ TLG} - d_{NETSIM\ THRU}\}$ AND $X_6 = PF$

FIGURE 3: RELATION OF TWO DELAYS IN REGIME 2

FIGURE 4: IMPROVED RELATION IN REGIME 2

FIGURE 5: IMPROVED RELATION IN REGIME 3

FIGURE 6: PF_{REV} FOR VARIOUS FREE FLOW SPEEDS (km/hr)

TABLE 1: SUMMARY OF SIMULATION RUNS

RUN SET ONE: GOOD PROGRESSIONS, ZERO TURNS Free Flow Speed (90km/hr, 70km/hr, 55km/hr) Number of Signals per Mile (9, 7, 5, 3, 1) Flow Rates (200 to 700 vphpl in steps of 100 vphpl) Total		180
RUN SET TWO: NON-ZERO TURNS Turns (4% and 8%, lefts and rights (both))		120
RUN SET THREE: DIFFERENT OFFSETS Offsets +15 and –15 sec from Run Set One		24
Total Number of Combinations		324
Replications, One Hour Runs		@ 5
Total Hours of Simulated Time		1,620

Note: All runs done with 3 thru lanes in each direction.

TABLE 2: ESTIMATION OF PROGRESSION FACTOR “PF”

Relation	Source
$R_p = P / (g_i/C)$	HCM Equation 16-1 R_p = platoon ratio P = proportion of all vehicles in movement arriving during the green phase g_i = effective green time for the movement/lane group i, s C = cycle length, s
R_p yields AT	HCM Exhibit 16-11 AT = Arrival Type
AT yields f_{PA}	HCM Exhibit 16-12 f_{PA} = supplemental adjustment factor for platoon arriving during the green
$PF = (1 - (g/C) R_p) f_{PA} / (1 - g/C)$	HCM Equation 16-10 PF =progression adjustment factor

Note: “P” is obtained from the simulation output.

TABLE 3: “DATA” RECORD FROM SIMULATION RESULTS

	COMMON NAME/LABEL	DESCRIPTION	MOVEMENT OR VEHICLE	UNITS OR VALUES																		
X4	V	Flow rate (vphpl) ²	----	Vphpl																		
X6	PF	HCM progression quality (Table 2)	----	Number (0,2)																		
X17	L	Signal Spacing	----	Km																		
X27	FFS	Free Flow Speed	----	Km/hr																		
X30	--	Code based upon Turns = <table><tr><td>0%</td><td>4%</td><td>8%</td></tr><tr><td>Offset</td><td></td><td></td></tr><tr><td>-15</td><td>1</td><td>4</td><td>7</td></tr><tr><td>0</td><td>2</td><td>5</td><td>8</td></tr><tr><td>+15</td><td>3</td><td>6</td><td>9</td></tr></table>	0%	4%	8%	Offset			-15	1	4	7	0	2	5	8	+15	3	6	9	----	----
0%	4%	8%																				
Offset																						
-15	1	4	7																			
0	2	5	8																			
+15	3	6	9																			
D2	Non-stop delay, NETSIM	(TT - RT – SD _{NETSIM})	Thru	Sec/veh																		
D3	Stopped Delay, NETSIM	SD _{NETSIM}	Thru	Sec/veh																		
D14	D2 + D3	Delay, NETSIM	Thru	Sec/veh																		
D16	D, HCM	Delay, HCM, TLG	TLG	Sec/veh																		
T23	Travel Time, NETSIM	Travel Time, NETSIM	Thru	Sec/veh																		
D25	D16 - D14	D _{HCM TLG} – D _{NETSIM THRU}	---	Sec/veh																		
D21	d ₁	Uniform delay	TLG	Sec/veh																		
D22	d ₂	Incremental delay	TLG	Sec/veh																		

Notes:

- 1) TLG = Thru Lane Group (excludes left turns in these analyses)
- 2) The variables are numbered due to the way the analysis was done, but “T” designates “time”, “S” designates “speed”, and “X” designates a probable independent variable, or parameter, comparison to values in the literature.

² Given the one-hour duration of the runs, this is also the demand volume and can be referred to in the present context simply as “volume”.

TABLE 4: RELATIONSHIPS OBSERVED

<u>d_1 relates to</u>		<u>NETSIM delay relates to</u>		<u>HCM “d” relates to</u>	
flow rate	0.98	signal spacing	0.73	progression factor	0.96
		progression factor	0.46	signal spacing	0.58
		free flow speed	-0.41	turns & offsets	0.58

TABLE 5: COMPARISON OF RESULTS (AVERAGES)

		<u>Average</u>
NETSIM Delay	D14	6.71
HCM Delay	D16	15.76
PF	X6	0.60
d_1	D21	23.87
d_2	D22	1.40

TABLE 6: THREE REGIMES, BASED UPON THE DIFFERENCE IN RESULTS

<u>Regime</u>	<u>Range of PF</u>	<u>Nature of Relation</u>	<u>Observations</u>
1	≤ 0.14	D25 ranges over +10 to -40	444
2	0.14 to 1.50	D25 increases with PF	1037
3	≥ 1.50	D25 decreases with PF	139

TABLE 7: COMPARISON OF RESULTS (AVERAGES), THREE REGIMES

		<u>Regime 1</u> <u>Average</u>	<u>Regime 2</u> <u>Average</u>	<u>Regime 3</u> <u>Average</u>
NETSIM Delay	D14	6.67	4.76	21.5
HCM Delay	D16	4.72	17.0	41.6
PF	X6	0.135	0.65	1.73
d_1	D21	23.6	24.1	23.4
d_2	D22	1.53	1.36	1.23
Average PF _{REV} for match		0.218	0.141	0.866

TABLE 8: CORRECTION TO OBTAIN PF_{REV} IN REGIME 2

FREE FLOW SPEED (km/hr)	" α " FOR EQUATION 4
55	0.30
70	0.21
90	0.14

TABLE 9: ESTIMATION OF A CORRECTION TO PROGRESSION FACTOR IN REGIME 2

{ d-NETSIM minus d2 }						
FFS(km/hr)	200	300	400	500	600	700 vphpl
5	4.2	4.7	4.7	5.2	5.9	6.7
70	2.2	2.4	3.0	3.4	4.0	3.8
90	1.2	1.2	1.5	1.8	2.5	2.2
d1						
FFS(km/hr)	200	300	400	500	600	700 vphpl
55	19.75	21.10	22.79	24.49	26.49	28.55
70	19.75	21.10	22.79	24.49	26.49	28.55
90	19.75	21.10	22.79	24.49	26.49	28.55
PF2 should be, based upon {d-NETSIM minus d2}/d1						
FFS(km/hr)	200	300	400	500	600	700 vphpl
55	0.21	0.22	0.21	0.21	0.22	0.23
70	0.11	0.11	0.13	0.14	0.15	0.13
90	0.06	0.06	0.07	0.07	0.09	0.08
PF2 AVG						
without 700						
0.22						
0.13						
0.07						
PF from computations						
FFS(km/hr)	200	300	400	500	600	700 vphpl
55	0.78	0.73	0.82	0.76	0.72	0.57
70	0.64	0.58	0.69	0.63	0.61	0.48
90	0.45	0.47	0.59	0.56	0.53	0.39
PF AVG						
without 700						
0.73						
0.61						
0.50						
Ratio						
PF2/PF						
0.30						
0.21						
0.14						

TABLE 10: CORRECTION TO OBTAIN PF_{REV} IN REGIME 3

FREE FLOW SPEED (km/hr)	" α " FOR REGIME 3
55	0.67
70	0.42
90	0.10

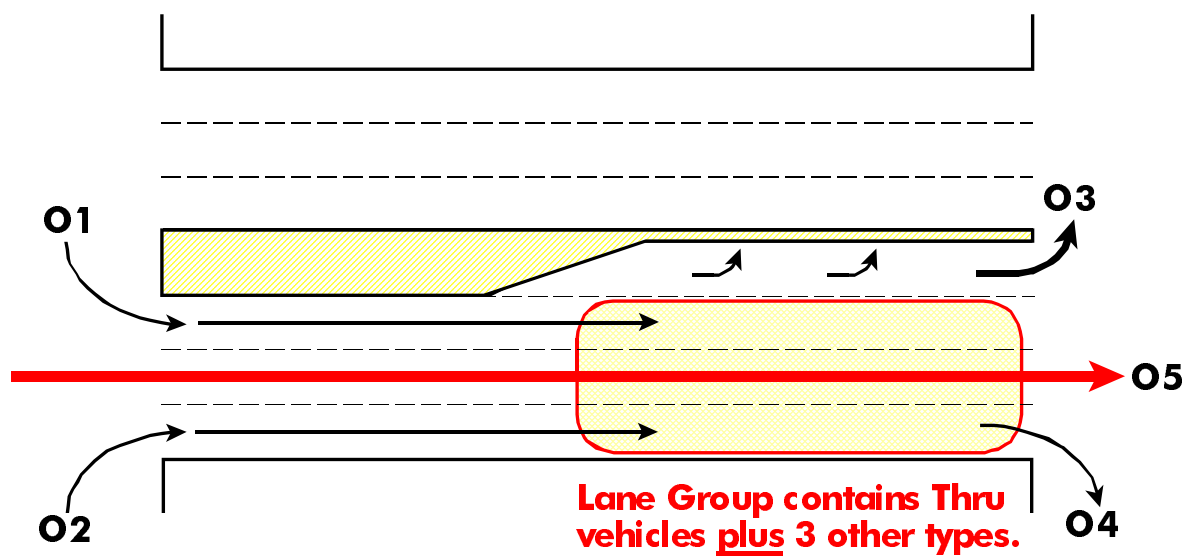


FIGURE 1: THE CONCEPT OF THE THRU VEHICLE

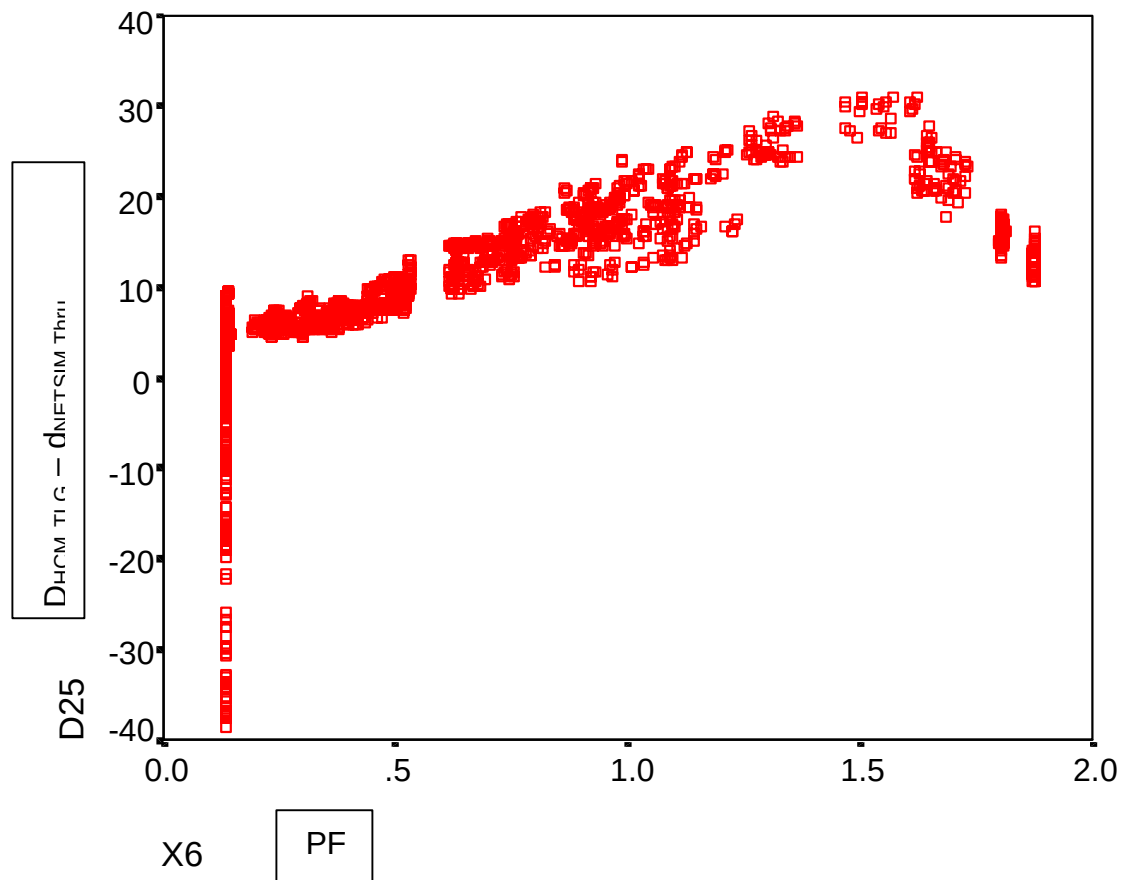


FIGURE 2: RELATION OF $D_{25} = \{d_{HCM TLG} - d_{NETSIM THRU}\}$ AND $X6 = PF$

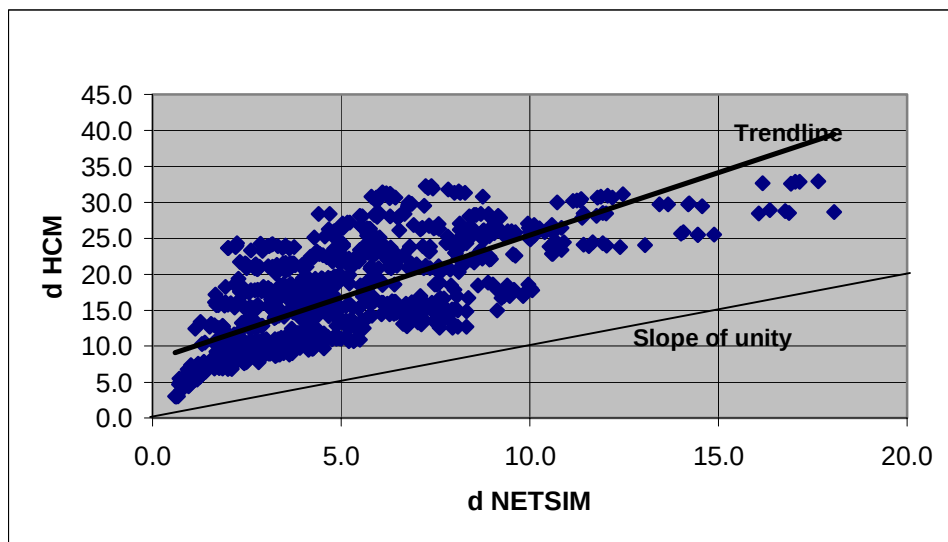


FIGURE 3: RELATION OF TWO DELAYS IN REGIME 2

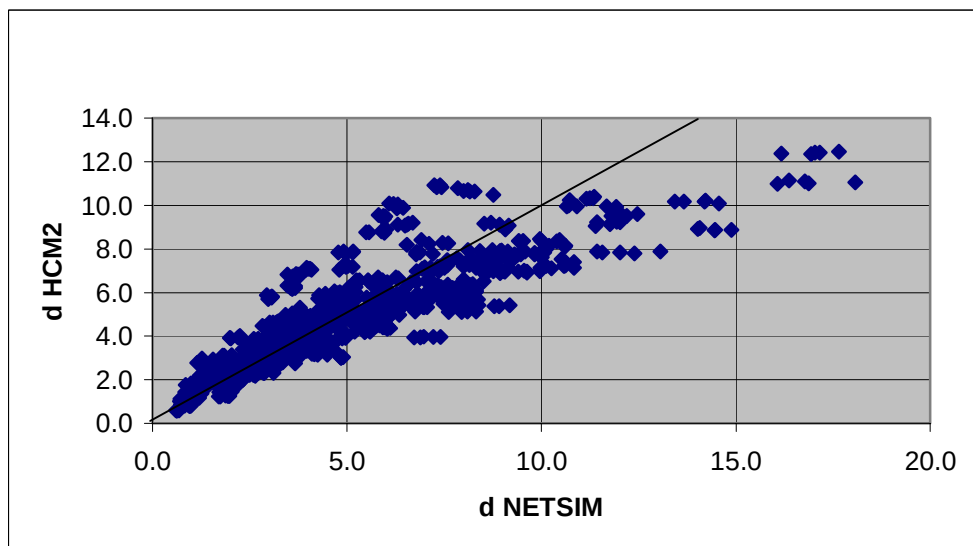
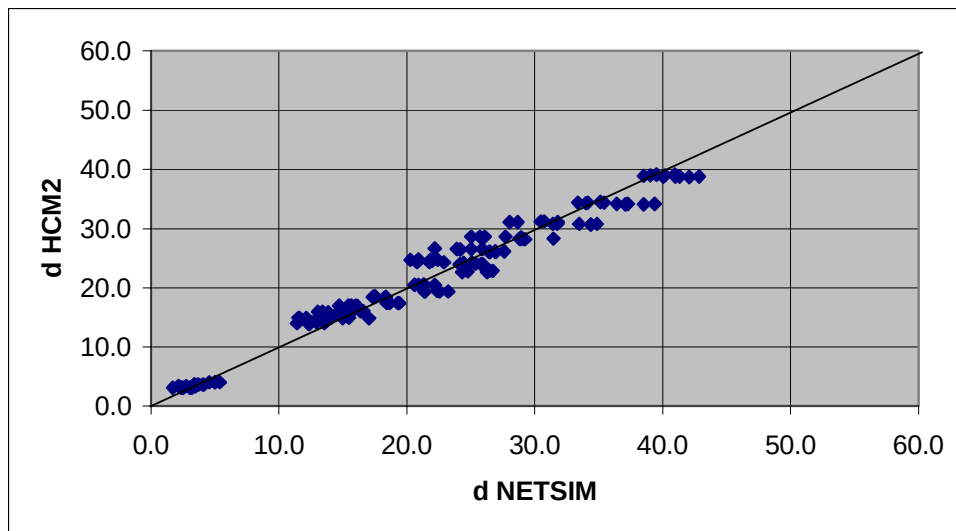
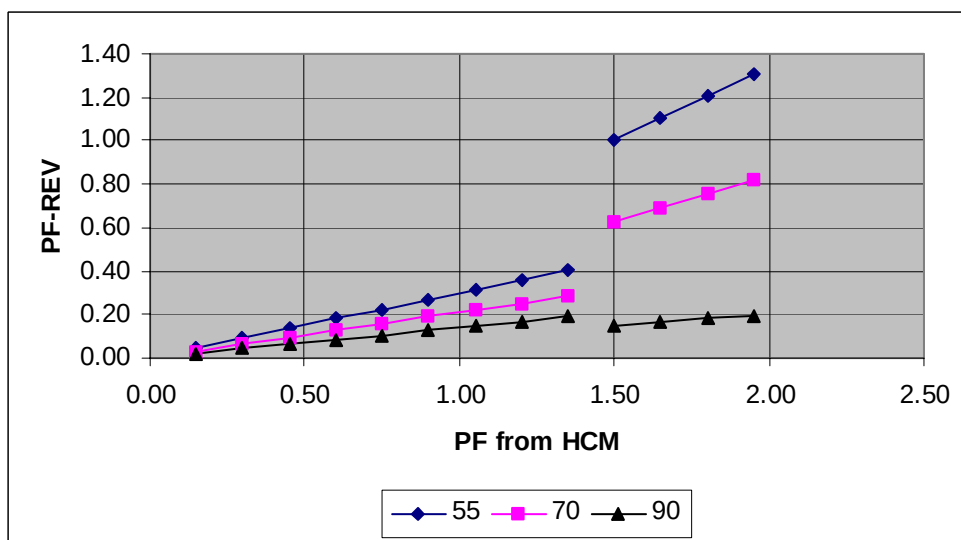


FIGURE 4: IMPROVED RELATION IN REGIME 2

**FIGURE 5: IMPROVED RELATION IN REGIME 3****FIGURE 6: PF_{rev} FOR VARIOUS FREE FLOW SPEEDS (km/hr)**