LOS FOR OVERSATURATED CONDITIONS,

A PROPOSED SOLUTION FOR SIGNALIZED INTERSECTIONS

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ABSTRACT

There are many congested signalized intersections where peak period delay is excessive and vehicles must wait through multiple cycles. Unfortunately, all delay levels past 80 sec/vehicle are reported as LOS F by current *Highway Capacity Manual* procedures, regardless of the extent to which capacity is exceeded. In addition, the HCM does not differentiate between two intersection approaches operating with identical delay wherein one approach experiences multiple phase failures and recurring queues while the other does not. A technique is presented for classifying signalized operation beyond LOS F that accounts for the negative effect of phase failures as well as delay.

INTRODUCTION

The latest edition of the *Highway Capacity Manual*[1] provides a well-recognized analytical procedure for calculating control delay at signalized intersections, with control delay being defined as the sum of deceleration delay, stopped delay, queue move-up delay, and acceleration delay. This procedure has been automated in the form of the signalized intersection module of the HCS+ software suite. The HCS+ software offers a direct, user-friendly procedure for calculating lane group, approach, and intersection control delay and their associated levels of service.

Unfortunately, increasing levels of traffic congestion have become commonplace, both in the United States and abroad. It is not unusual to encounter signalized intersections where per-vehicle delay levels on one or more approaches exceed capacity (the LOS E/LOS F boundary) by a large amount. Vehicles traversing signalized intersections during peak periods not only experience high levels of delay but, in many instances, these vehicles are also forced to wait through multiple cycle changes before they are able to clear the intersection. Unfortunately, all delay levels past 80 sec/vehicle are reported as LOS F by current *Highway Capacity Manual* procedures, regardless of the extent to which this 80 sec/vehicle boundary is exceeded. An approach with a 95 sec/vehicle delay and an approach with a 250 sec/vehicle delay both fall into the LOS F category, even though the operational characteristics are very different for these two approaches. In addition, no means currently exists within the *Highway Capacity Manual* or the HCS+ software to differentiate between two signalized intersection approaches operating at identical per vehicle delay levels, wherein one approach experiences a high incidence of multiple phase failures and recurring queues (or re-queues) while the other does not. The need clearly exists for the development of level of service measures past F, measures that account for the negative effect of phase failures as well as the negative effect of increasing control delay.

BACKGROUND

Current level of service categories are labeled A through F, which is a rough emulation of the grading system used in most American schools. This grading system is familiar to the American public, and the average citizen does not have a hard time understanding that an A rating for a highway segment or intersection is very good while an F rating is very bad. Extending the F category will, by necessity, disconnect somewhat our level of service grading system from the scholastic grading system. However, such an extension is necessary if proper differentiation is to be made between the operational characteristics of over-saturated facilities.

One option for extending the current rating system would be to continue along the alphabet, using G, H, I, J, etc. to depicted increasingly undesirable levels of operation. Another option is to simply add a numerical suffix to the LOS F rating, such as F1, F2, or F3. The numerical suffix has the advantage of maintaining the well-understood “F is very bad” connotation while also allowing relatively quick comparison of F levels. For example, level of service F6 is quickly recognized as four performance categories worse than level F2. Such quick recognition does not hold true for levels of service K and G.

There has been some discussion of abandoning level of service ratings entirely and replacing them with a simple reporting of the appropriate measure of effectiveness (such as per vehicle delay). However, the reality of the situation is that many cities, counties and states find the level of service concept to be an attractive one and have established development codes and statutes that directly rely on level of service. It can also be argued that, at some point, a decision must be made as to what is an acceptable level of signalized intersection performance and what is not. The level of service concept is a very handy tool for making this important policy decision.

OVERSATURATED LEVELS OF SERVICE

Analyzing over-saturated conditions in the field can be extremely difficult. The physical extent of queues that occur during over-saturated conditions make them difficult to monitor. In addition, real-world conditions often result in queues associated with one movement intermingling with queues from another movement. Such mixed queues are encountered when vehicles extend beyond a short left turn lane and intermingle with vehicles queued in the adjacent thru lane. This queue intermingling can also be problematic when attempting to analyze over-saturated conditions. For this situation, the use of computer simulation was chosen as a reasonable method for analyzing oversaturated operations. Important variables, such as approach volume and cycle length, can be controlled using simulation, something that is impossible to do in the field.

Corsim was used to make the necessary simulation runs. Twelve different sets of 15-minute volume levels were run using Corsim. Each volume set was run three time using three different sets of random number seeds with the results averaged. To isolate theoretical considerations, the Corsim runs were made based on a very simple case, the intersection of two one-way streets, each having a single approach lane. No trucks were placed into the traffic stream and no turns were allowed. A random (Poisson) arrival pattern was selected with arrival rates varying each 15-minutes during a one-hour analysis period. The intersection was controlled by a two-phase, semi-actuated traffic signal, and delay data was collected and analyzed only for the actuated side street approach, which is the approach under study.

A set of visual basic application programs for Excel were developed to read the data provided by Corsim and to produce a variety of useful information. For a one-hour analysis time frame having four 15-minute periods, the programs produce a second-by-second tabulation of items such as queue length, back of queue position, phase failures, stopped delay, move-up delay and control delay. The programs also provide a host of ancillary capabilities including automated calculation of: start-up-lost-time, saturation flow, and capacity by cycle; HCS+ queuing and delay information by 15-minute period; and arrival type by 15-minute period.

The results of the Corsim simulation runs are summarized in Table 1. The input volumes for the first three 15-minute periods of the analysis hour were established at levels near or over capacity (from 99% to 115% of capacity) so that recurring queues would occur. The volume level for the last 15-minute period was set well under capacity so that queues would dissipate by the end of the analysis period, ensuring that all delay is accounted for.

In Table 1, the top contains the results for an 80 second cycle, the middle provides the results for a 120 second cycle, and the bottom shows the results for a 160 second cycle. The g/C value remained close to 0.3 for all runs. The resulting per vehicle control delay varied between 51.9 sec/vehicle and 231.4 sec/vehicle with the percentage of cycles during the analysis hour that experienced a phase failure varying between 52% and 93%.

To aid in interpreting this table, the following sample explanation is provided for volume set 700_625_725_350vph of the 80 second cycle. The average Corsim input volume is 682 vph (average of 700 vph, 625 vph, and 725 vph) for the first 45 minutes of the analysis period. The capacity for the same period is 641 vph, which produces a volume to capacity ratio (degree of saturation) of 1.06 for the first 45 minutes of the analysis period. The associated control delay for the analysis hour is 123.8 seconds per vehicle, with 39 of the 45 cycles during the hour (86%) experiencing a phase failure. The control delay is based on the number of vehicles (593) that exit the system (cross the stop bar). Of these 593 vehicles, 100 vehicles do not re-queue while 493 (83%) do. In other words, 100 vehicles either do not stop at all or stop only once while 241 vehicles re-queue once (stop twice), 146 vehicles re-queue twice (stop three times), 97 vehicles re-queue three times (stop four times), and 9 vehicles re-queue four times (stop five times). The total number of times that vehicles re-queue (total number of re-queues) is obtained by multiplying the number of vehicles by the number of re-queues for each category and then summing up these values (100 x 0 + 241 x 1 + 146 x 2 + 97 x 3 + 9 x 4 = 860). Finally, the number of per vehicle re-queues (1.45) is obtained by dividing the total vehicle re-queues (860) by the total number of vehicles (593).

With these simulation results in hand, an investigation was made to determine if a relationship exists between control delay, cycle length, and the total number of vehicle re-queues. Figure 1 summarizes the results of this investigation. Once cycle length is taken into account, a very strong linear relationship exists between control delay and total vehicle re-queues.

A review of Figure 1 shows the important effect of cycle length on both delay and phase failures. During near-saturated conditions when the total number of vehicle re-queues is low, shorter cycle lengths minimize control delay without producing recurring queues. For example, as can be seen by examining the once circled equivalent-input-volume data points in Figure 1, when the total number of vehicle re-queues during the analysis period is relatively low, an 80 second cycle length produces only two-thirds the delay of a 120 second cycle length and only half the delay of a 160 second cycle length.

The situation changes as congestions levels increase. Under grossly over-saturated conditions, the shorter cycle length produces a much higher level of recurring queues. For example, as can be seen by examining the twice circled equivalent-input-volume data points in Figure 1, when the control delay rises to a value of around 200 seconds per vehicle, an 80 second cycle length produces about twice the number of vehicle re-queues as either a 120 or 160 second cycle, with little or no delay advantage. This type of analysis underscores the importance of proper cycle length selection.

In terms of seconds per vehicle, the current signalized intersection level of service thresholds provided in Chapter 16 of the *Highway Capacity Manual* are as follows: A < 10 < B < 20 < C < 35 < D < 55 < E < 80 < F . Figure 2 shows how these current thresholds could be extended to cover a wide area of over-saturation while continuing to use only control delay as the classification variable. The basic LOS thresholds for F2, F3, F4 and F5 simply follow the numerical pattern found in the *Highway Capacity Manual*, wherein the difference between the LOS A and LOS B upper limits is 10 sec/veh, then 15 between B and C, then 20 between C and D, and then 25 between D and E. Consequently, we have selected 30 sec/veh between the upper limits of LOS E and LOS F1, 35 between F1 and F2, 40 between F2 and F3, and 45 between the upper limits of F3 and F4.

Expanding the concept of over-saturated level of service to include vehicle re-queues produces the two-dimensional level of service areas shown in Figure 3. The horizontal lines separating level of service categories are the same as in Figure 2 while the vertical lines are obtained from Table 2, which shows the relationship between the total number of vehicle re-queues and the maximum number of re-queues. In the limiting summary at the bottom of this table we see that, in general, when the total number of vehicle re-queues exceeds 230, the maximum number of re-queues that are encountered increases from 1 to 2. Then, as the total number of re-queues exceeds 570, the maximum number of re-queues increases from 2 to 3. Likewise, as the total exceeds 760, the maximum increases from 3 to 4, and so on. The resulting LOS categories depicted in Figure 3 can be represented in tabular form as shown in Table 3.

The traditional LOS E category has been modified so that any signalized approach that contains vehicles which experience two or more re-queues is reclassified as LOS F1, even though control delay is within LOS E limits.

Another approach to establishing categories for over-saturated levels of service is to translate the effects of vehicle re-queues into equivalent levels of delay to obtain a composite delay value that accounts for the negative effect of phase failures. A one-dimensional delay-only level of service categorization could then be used given this composite delay. Research would need to be conducted to establish the relative discomfort that motorists associate with phase failures. For example, it might be determined through appropriate research that motorists value the delay experienced after a phase failure at twice the level as the delay experienced before a phase failure. Post-phase failure delays would then be doubled to calculate the composite control delay.

Motorists are usually quite averse to not getting through a signalized intersection on the first green indication with their level of anxiety rising as the number of re-queues increases. Given the average motorist's obvious frustration with phase failures and associated re-queues, the weighting of delay to reflect this increasing frustration seems quite reasonable. It is akin to the approach taken in evaluating transit travel times wherein waiting time is valued at some multiple of in-vehicle travel time because transit patrons find waiting time to have a much higher discomfort than in-vehicle time. Developing the appropriate delay weighting factors based on the number of phase failures that occur would be a fertile area for future research.

SUMMARY

A reasonable method for classifying level of service categories past F is documented in Figure 3 (or Table 3). The method takes into account the negative effects of phase failures and recurring queues, as well as control delay, when establishing level of service. Accounting for the effect of recurring queues is particularly important during over-saturated conditions. This importance stems from the fact that, even under identical volume conditions, two different cycle lengths may produce vastly different levels of vehicle re-queuing even though they exhibit the same control delay. Consequently, the degree of motorist frustration (which is associated with this re-queuing) can vary considerably depending on the cycle length that is chosen. The proposed two-dimensional level of service categorization process presented in this paper encourages the selection of a cycle length that minimizes this frustration.

REFERENCES

1. *Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington, D.C., 2000

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TABLE 1 - Corsim Control Delay and Phase Failure Results

File Name	Volume	Capacity	v/c	Per Vehicle	Cycles With Phase	% of Cycles With Phase	Number of Vehicles Experiencing Various Re-Queue Levels							Total Number of	Total Number of	Number of Vehicles	% of Total Vehicles	Per Vehicle
15 Min Input Volumes	First 45 minutes			Control Delay	Failures	Failures	No Re-Q	1 Re-Q	2 Re-Q's	3 Re-Q's	4 Re-Q's	5 Re-Q's	6 Re-Q's	Vehicle Re-Queues	Vehicles	That Re-Q	That Re-Q	Re-Q
12FOV	v	c	v/c				a	b	c	d	e	f	g	h=b+2c+3d+4e+5f+6g	i=sum(a:g)	j=sum(b:g)	k = j / i	l = h / i
80 SECOND CYCLE																		
625_675_600_350vph	633	637	0.99	51.9	24	53%	426	130	0	0	0	0	0	130	556	130	23%	0.23
650_675_625_350vph	649	637	1.02	74.2	35	77%	293	215	61	0	0	0	0	337	569	276	49%	0.59
630_695_650_350vph	657	639	1.03	90.0	32	71%	241	208	86	38	0	0	0	494	573	332	58%	0.86
625_700_650_350vph	657	639	1.03	75.4	29	64%	265	263	45	0	0	0	0	353	573	308	54%	0.62
625_700_675_350vph	665	641	1.04	81.2	30	67%	255	239	87	0	0	0	0	413	581	326	56%	0.71
675_700_625_350vph	665	641	1.04	107.6	36	81%	156	225	127	70	0	0	0	689	578	422	73%	1.19
700_625_725_350vph	**682**	**641**	1.06	**123.8**	**39**	**86%**	100	241	146	97	9	0	0	**860**	**593**	**493**	**83%**	**1.45**
700_725_625_350vph	683	641	1.07	159.7	39	86%	65	137	151	149	87	4	0	1254	593	528	89%	2.11
700_750_600_350vph	683	641	1.07	169.6	39	86%	65	132	121	143	100	30	0	1353	591	526	89%	2.29
725_675_700_350vph	699	641	1.09	174.1	41	90%	40	121	183	137	107	15	0	1401	603	563	93%	2.32
700_700_700_350vph	698	641	1.09	165.8	41	90%	48	149	153	146	86	21	0	1342	603	555	92%	2.23
725_700_700_350vph	708	640	1.11	187.4	42	93%	30	123	149	143	112	47	6	1569	610	580	95%	2.57
120 SECOND CYCLE																		
625_675_600_350vph	633	626	1.01	78.3	16	52%	399	149	4	0	0	0	0	157	552	153	28%	0.28
650_675_625_350vph	649	627	1.04	84.2	19	63%	381	179	7	0	0	0	0	193	567	186	33%	0.34
630_695_650_350vph	657	626	1.05	100.0	19	64%	293	248	31	0	0	0	0	310	572	279	49%	0.54
625_700_650_350vph	657	626	1.05	102.1	19	63%	297	236	40	0	0	0	0	316	573	276	48%	0.55
625_700_675_350vph	665	627	1.06	104.4	18	60%	311	203	59	0	0	0	0	321	573	262	46%	0.56
675_700_625_350vph	665	626	1.06	117.9	23	77%	257	248	71	0	0	0	0	390	576	319	55%	0.68
700_625_725_350vph	683	624	1.09	113.9	22	72%	278	228	88	0	0	0	0	404	594	316	53%	0.68
700_725_625_350vph	683	623	1.10	156.8	22	74%	183	163	216	25	0	0	0	670	587	404	69%	1.14
700_750_600_350vph	683	623	1.10	167.0	22	74%	180	141	198	69	0	0	0	744	588	408	69%	1.27
725_675_700_350vph	699	624	1.12	156.0	24	79%	173	207	193	28	0	0	0	677	601	428	71%	1.13
700_700_700_350vph	698	627	1.11	174.6	26	86%	153	177	181	87	2	0	0	808	600	447	75%	1.35
725_700_700_350vph	708	630	1.12	192.5	26	86%	120	153	214	117	0	0	0	932	604	484	80%	1.54
160 SECOND CYCLE																		
625_675_600_350vph	633	616	1.03	112.3	13	58%	364	171	15	0	0	0	0	201	550	186	34%	0.37
650_675_625_350vph	649	616	1.05	114.9	14	61%	353	210	1	0	0	0	0	212	564	211	37%	0.38
630_695_650_350vph	657	615	1.07	143.0	16	70%	269	251	55	0	0	0	0	361	575	306	53%	0.63
625_700_650_350vph	657	617	1.06	141.4	15	68%	278	242	55	0	0	0	0	352	575	297	52%	0.61
625_700_675_350vph	665	616	1.08	140.7	16	70%	287	243	50	0	0	0	0	343	580	293	51%	0.59
675_700_625_350vph	665	616	1.08	150.6	16	71%	247	276	58	0	0	0	0	392	581	334	57%	0.67
700_625_725_350vph	683	616	1.11	156.9	17	77%	234	277	75	0	0	0	0	427	586	352	60%	0.73
700_725_625_350vph	683	616	1.11	191.3	17	77%	189	192	194	11	0	0	0	613	586	397	68%	1.05
700_750_600_350vph	683	615	1.11	205.2	19	83%	172	187	204	23	0	0	0	664	586	414	71%	1.13
725_675_700_350vph	699	615	1.14	233.1	20	90%	128	186	230	57	0	0	0	817	601	473	79%	1.36
700_700_700_350vph	699	618	1.13	223.3	20	87%	150	180	223	47	0	0	0	767	600	450	75%	1.28
725_700_700_350vph	708	618	1.15	231.4	20	89%	140	182	219	66	0	0	0	818	607	467	77%	1.35
	vph	vph		secs/veh	cycles													

TABLE 2 - Relationship Between Total Vehicle Re-Queues and Maximum Number of Re-Queues

80 Second Cycle

Total Vehicle Re-Queues	1 Re-Q	2 Re-Q's	3 Re-Q's	4 Re-Q's	5 Re-Q's	6 Re-Q's
130	130	0	0	0	0	0
337	215	61	0	0	0	0
494	208	86	38	0	0	0
353	263	45	0	0	0	0
413	239	87	0	0	0	0
689	225	127	70	0	0	0
860	241	146	97	9	0	0
1254	137	151	149	87	4	0
1353	132	121	143	100	30	0
1401	121	183	137	107	15	0
1342	149	153	146	86	21	0
1569	123	149	143	112	47	6

120 Second Cycle

Total Vehicle Re-Queues	1 Re-Q	2 Re-Q's	3 Re-Q's	4 Re-Q's	5 Re-Q's	6 Re-Q's
157	149	4	0	0	0	0
193	179	7	0	0	0	0
310	248	31	0	0	0	0
316	236	40	0	0	0	0
321	203	59	0	0	0	0
390	248	71	0	0	0	0
404	228	88	0	0	0	0
670	163	216	25	0	0	0
744	141	198	69	0	0	0
677	207	193	28	0	0	0
808	177	181	87	2	0	0
932	153	214	117	0	0	0

160 Second Cycle

Total Vehicle Re-Queues	1 Re-Q	2 Re-Q's	3 Re-Q's	4 Re-Q's	5 Re-Q's	6 Re-Q's
201	171	15	0	0	0	0
212	210	1	0	0	0	0
361	251	55	0	0	0	0
352	242	55	0	0	0	0
343	243	50	0	0	0	0
392	276	58	0	0	0	0
427	277	75	0	0	0	0
613	192	194	11	0	0	0
664	187	204	23	0	0	0
817	186	230	57	0	0	0
767	180	223	47	0	0	0
818	182	219	66	0	0	0

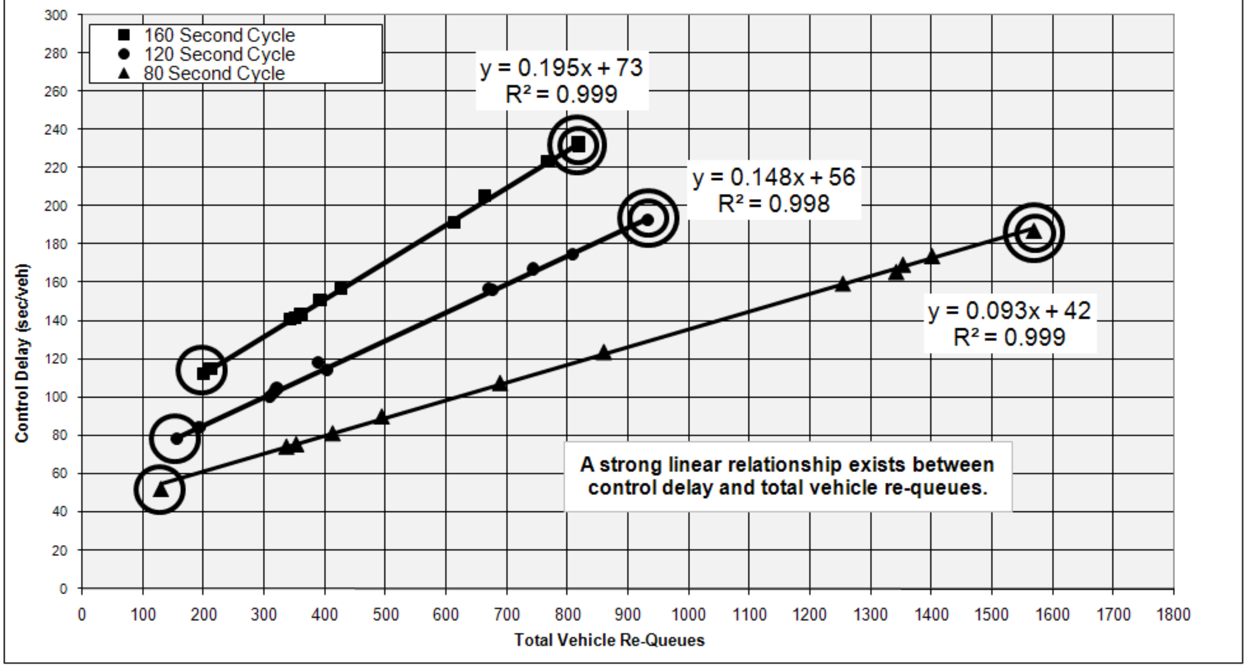
Total Vehicle Re-Queue Boundaries

Max Re-Q	Cycle Length 80	120	160	Average	**Use**
1					
	234				**230**
2					
	637	537	520	565	**570**
3					
	775	743		759	**760**
4					
	1057				**1060**
5					
	1456				**1460**
6					

Table 3 - Two-Dimensional Level of Service Thresholds

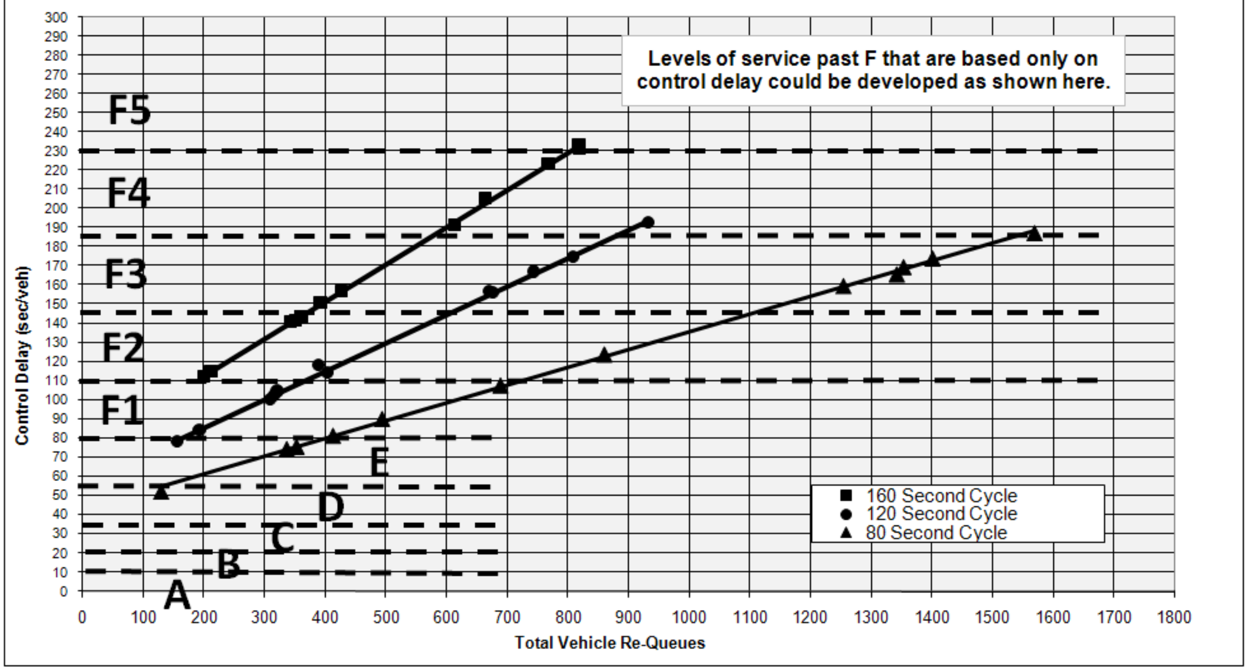
Control Delay (sec/veh)	Total Number of Vehicle Re-Queues <= 230	> 230-570	> 570-760	> 760-1060	> 1060-1460	> 1460
<= 10	A	A	A	A	A	A
> 10-20	B	B	B	B	B	B
> 20-35	C	C	C	C	C	C
> 35-55	D	D	D	D	D	D
> 55-80	E	**F1**	**F1**	**F1**	**F1**	**F1**
> 80-110	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**
> 110-145	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**
> 145-185	**F3**	**F4**	**F5**	**F6**	**F7**	**F7**
> 185-230	**F4**	**F5**	**F6**	**F7**	**F7**	**F7**
> 230	**F5**	**F6**	**F7**	**F7**	**F7**	**F7**

FIGURE 1 - RELATIONSHIP BETWEEN CONTROL DELAY AND TOTAL VEHICLE RE-QUEUES



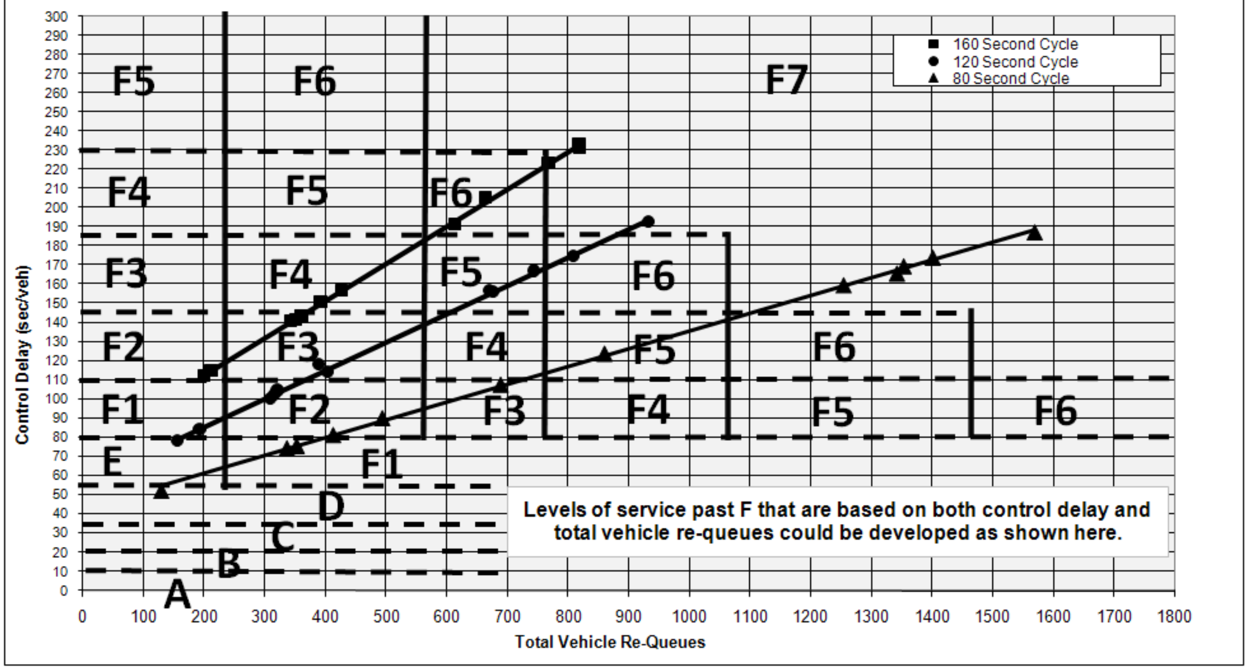
A strong linear relationship exists between control delay and total vehicle re-queues.

FIGURE 2 - LOS THRESHOLDS USING ONLY CONTROL DELAY



Levels of service past F that are based only on control delay could be developed as shown here.

FIGURE 3 - LOS THRESHOLDS BASED ON CONTROL DELAY AND TOTAL RE-QUEUES



Levels of service past F that are based on both control delay and total vehicle re-queues could be developed as shown here.