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COUNTERMEASURES WITH PROMISE (CWIP) - LEFT TURN PROTECTION

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16. Abstract:

An important task in road safety management is to monitor where accidents occur on the road system and to assess whether safety at the high-accident sites can be cost-effectively improved. The weak point of the customary process is that the list of high-accident sites is prepared without considering what countermeasures, if any, could apply at the sites on the list. An alternative approach is the ‘Countermeasures with Promise’ (CWiP) process, which involves choosing countermeasures known to be effective and then seeking sites where these could be implemented to best effect.

The countermeasure chosen for examination in this study was that of changing left-turn phasing at signalized intersection to ‘Protected’ phasing. The target accidents were those involving left-turning vehicles. Several ranked lists were produced.

Implementation:
The next step should be to forward the ranked lists to the CDOT offices with jurisdiction over signalized intersections. Those intersections near the top of the lists which are presently without full left-turn protection should be considered for full protection implementation.

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COUNTERMEASURES with PROMISE (CWiP)
Left Turn Protection

by

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Executive Summary

An important part of road safety management is to monitor where accidents occur on the road system and to assess whether at the high-accident sites safety can be cost-effectively improved. Traditionally this amounts to preparing a ranked list of those sites where many (or unusually many) accidents occurred. These sites are the ‘Sites with Promise’ (SWiPs). At the SWiPs a ‘Detailed Engineering Study’ (DES) is to be conducted. The purpose of the DES is to examine the sites and their accidents in detail in order to identify suitable countermeasures. The weak point of this process is that the list of SWiPs is prepared without considering what countermeasures, if any, could apply at the sites on the list. As a result those whose responsibility it is to do the relatively costly DES often complain that the SWiPs are not the ideal set of sites for the implementation of countermeasures.

This weakness could be obviated by structuring the process differently. Instead of first selecting the sites and only later, during the DES, asking what countermeasures could be applied at these, one could begin by choosing effective countermeasures and then seeking sites where these could be implemented. To illustrate this ‘Countermeasures with Promise’ (CWiP) process, suppose that we will find sites where accidents can be reduced cost-effectively by, say, reducing the slope of the embankment. The cost of slope reduction is a function of fill height, existing slope, and a local cost factor (cost of fill). The benefit of slope reduction is proportional to the frequency of target accidents (off-the-road accidents involving loss of control) and the corresponding ‘Accident Modification Factors’ (AMFs). Screening now would involve examining all roads sections on fill, and for each such section computing the benefit/cost ratio. The process illustrated earlier (for slope reduction on fill) would be repeated for, shoulder paving, illumination, winter maintenance etc. Once all countermeasures are considered in this manner, one can merge all benefit/cost estimates into one overall ranking. The main weakness of the CWiP process is that it may require information that is currently not in electronic data bases (e.g., whether a road section is in fill, what the height and slope of fill is, what is the local cost factor for fill etc.). Its main promise is in the ability to identify better sites; sites at which safety money will be spent to more effect. Even though the idea is simple and its attraction obvious, one can only assess practicality through a pilot implementation.

The countermeasure chosen for examination was that of changing left-turn phasing at signalized intersection to ‘Protected’ phasing. The target accidents are those involving left-turning vehicles. Review of past research suggests that the change from ‘Permissive’ or ‘Protected/ Permissive’ to ‘Protected’ phasing has a clear benefit. Both phasing changes are estimated to have an AMF of 0.3 – a 70% reduction in target accidents. The effect of this change in left-turn phasing on non-target is not clear in the extant literature and is assumed to be about zero. To estimate the benefit of the conversion at a site one has to determine how many target accidents (PDO, Injury and Fatal) in a year are expected To do so by the Empirical Bayes method requires the knowledge of the history of accidents involving left turning vehicles at each site and also a model for predicting the expected number of such accidents based on the traits of each site. That PDO, Injury and Fatal accidents carry differing weights is accounted for by the notion of ‘Equivalent Property Damage Only’ (EPDO) accidents. Assuming accidents costs of $6,500, $35,000 and $1,000,000 for PDO, Injury and Fatal accidents respectively, one Injury accident is equivalent to about 5.4 PDO accidents and one fatal accident counts for about 154 PDO

accidents. The cost of this countermeasure is mainly that of added delay. The 'cost-relevant features' of a site (approach) are all the features that affect the delay at all the affected intersection approaches. Here one must remember that we are dealing with a screening process for which the central idea is that it makes use only of <u>readily available information</u>. What one may hope for in this case is to have information about ADT on the principal approaches, the number of lanes on the approaches, the presence of turning lanes, type of control (i.e., fixed time, semi-actuated, actuated) and perhaps number of phases. From this information one has to produce a delay estimate. Thus, the main problem is how to estimate the change in average delay on the basis of the limited information available in electronic form.

Data to perform the tasks of estimating EPDO and of average delay estimation was requested, obtained, verified, and modified as necessary. An example of the modified data for three intersections is in Table 1. As may be seen, accident counts are for the fourteen years 1990 to 2003 and the ADT estimates for some of these years.

Table 1. Modified Data

Intersection	Approach	1990						1991	...	2003	Legs	Lanes	ΣLt	ΣAll
		PDO	Inj	Fat	Lt	All	ADT	PDO		ADT				
51	1	0	0	0	0	2	5552.5	0		0	3	1	0	65
51	5	0	0	0	0	0	0	0		0	3	0	0	0
51	3	0	0	0	0	0	5552.5	0		0	3	1	0	0
51	4	0	0	0	0	0	0	0		0	3	0	0	0
52	1	0	0	0	0	1	6419	0		7766.5	3	1	0	37
52	5	0	0	0	0	0	0	0		0	3	0	0	0
52	3	0	0	0	0	0	6419	0		7766.5	3	1	7	0
52	4	0	0	0	0	0	0	0		0	3	0	0	0
53	1	0	0	0	0	0	0	0		11230	3	1	0	17
53	5	0	0	0	0	0	0	0		0	3	0	0	0
53	3	0	0	0	0	0	0	0		11230	3	1	0	0
53	4	0	0	0	0	0	0	0		0	3	0	0	0
54	1	0	0	0	0	6	12270	0		11144	3	1	2	101

Using the available ADT estimates a Visual Basic code was written to generate estimates for the years for which they are not available. An example of the data available and of the ADT estimates generated for ten intersections is in Table 2 and Table 3. **The code may be of interest to CDOT for other purposes.**

Table 2. Original ADT Data for Ten Intersections

Intersection	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1												3228		
2									4840	4746	4564	3633		
3										4358				
4	4678	4728	4919	4725	6444	5139	6502	5464	5633	5714	6395	6187	7876	7603
5										2046				
6										1449	1451	1450		
7									5751	7385	4857	5482		
8								5116	5340	5239	5243	5134	5357	5103
9									1657					
10									6354	6259	6298	6053	6124	6125

Table 3. Estimated ADT Data for Ten Intersections

Intersection	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228
2	7510	7187	6865	6542	6220	5897	5575	5252	4930	4607	4284	3962	3639	3317
3	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358
4	4535	4738	4942	5145	5349	5552	5756	5959	6163	6366	6569	6773	6976	7180
5	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046
6	1442	1443	1444	1444	1445	1446	1447	1447	1448	1449	1450	1450	1451	1452
7	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868
8	5219	5219	5219	5219	5219	5219	5219	5219	5219	5219	5219	5219	5219	5219
9	1657	1657	1657	1657	1657	1657	1657	1657	1657	1657	1657	1657	1657	1657
10	6735	6684	6634	6583	6532	6481	6430	6380	6329	6278	6227	6177	6126	6075

To generate the information needed for EPDO estimation by the Empirical Bayes method, Negative binomial models were estimated for six intersection types and two alternative functional forms:

$$\text{Expected yearly left-turn accidents per approach} = \boldsymbol{\alpha}_y \mathbf{X}^{\beta_1} \qquad \textbf{Eqn. 1}$$

$$\text{Expected yearly left-turn accidents per approach} = \boldsymbol{\alpha}_y \mathbf{X}^{\beta_1} \mathbf{e}^{\beta_2 \mathbf{X}} \qquad \textbf{Eqn. 2}$$

In these α_y is the multiplier for year y (=1,2,....,14), X is the mainline ADT/10,000 for one approach, and β1, β2 are estimates of parameters. The estimated overdispersion parameter is φ. Parameter estimates for mainline approaches are in Table 4.

Table 4. Estimated Model Parameters

	One β						Two βs					
	3Legs Mainline PDO	3Legs Mainline I&F	4 Legs Mainline PDO	4 Legs Mainline I&F	4 Legs Non-Mainline PDO	4 Legs Non-Mainline I&F	3Legs Mainline PDO	3Legs Mainline I&F	4 Legs Mainline PDO	4 Legs Mainline I&F	4 Legs Non-Mainline PDO	4 Legs Non-Mainline I&F
φ (overdispersion)	0.110	0.109	0.569	0.563	0.272	0.215	0.106	0.107	0.556	0.560	0.271	0.214
Average α	0.051	0.037	0.227	0.162	0.100	0.057	0.189	0.101	0.942	0.552	0.216	0.150
β_1	1.46	1.36	1.31	1.35	0.71	0.62	2.65	2.31	2.74	2.59	1.41	1.48
β_2							-1.084	-0.841	-1.217	-1.048	-0.643	-0.810
Log-likelihood	-1042	-932	-16609	-15340	-9364	-6605	-1040	-922	-16552	-15305	-9354	-6594
α_1	0.022	0.024	0.159	0.130	0.060	0.038	0.079	0.065	0.640	0.432	0.127	0.099
α_2	0.032	0.023	0.170	0.126	0.072	0.032	0.115	0.061	0.687	0.420	0.152	0.084
α_3	0.036	0.025	0.182	0.151	0.068	0.041	0.130	0.068	0.739	0.502	0.144	0.106
α_4	0.040	0.027	0.207	0.163	0.093	0.044	0.144	0.072	0.842	0.543	0.198	0.114
α_5	0.036	0.022	0.235	0.175	0.093	0.063	0.132	0.059	0.960	0.585	0.199	0.164
α_6	0.033	0.020	0.233	0.193	0.095	0.051	0.121	0.055	0.956	0.650	0.203	0.132
α_7	0.023	0.030	0.216	0.150	0.086	0.054	0.085	0.081	0.890	0.507	0.185	0.142
α_8	0.049	0.027	0.228	0.143	0.093	0.054	0.179	0.073	0.942	0.485	0.200	0.143
α_9	0.056	0.049	0.270	0.187	0.135	0.073	0.207	0.133	1.123	0.637	0.291	0.192
α_{10}	0.084	0.069	0.265	0.192	0.136	0.082	0.313	0.188	1.113	0.659	0.296	0.217
α_{11}	0.105	0.059	0.282	0.195	0.142	0.073	0.393	0.161	1.190	0.672	0.308	0.195
α_{12}	0.096	0.070	0.284	0.183	0.135	0.080	0.361	0.193	1.207	0.637	0.294	0.213
α_{13}	0.071	0.045	0.234	0.152	0.099	0.062	0.267	0.125	1.005	0.530	0.217	0.166
α_{14}	0.033	0.028	0.207	0.133	0.096	0.050	0.123	0.077	0.896	0.469	0.211	0.135

The two-β models have a somewhat larger log-likelihood. However, the two-β models also have consistently poorer cumulative residual (CURE) plots and illogical predictions in the high-ADT range where data is sparse. Therefore, the one-β models were used.

It is not practical to estimate a separate model for fatal accidents. Therefore the assumption was that the expected number of fatal accidents can be predicted by multiplying the expected number of fatal + injury accidents by a proportion. The values in Table 5 were used.

Table 5. Predictions for Fatal Accidents.

Model prediction for fatal accidents	Mainline Approaches	0.0091×Model Prediction for Injury & Fatal Accidents on Mainline Approaches
	Non-Mainline Approaches	0.0034×Model Prediction for Injury & Fatal Accidents on Non-Mainline Approaches
Model prediction for injury accidents	Mainline Approaches	0.9909×Model Prediction for Injury & Fatal Accidents on Mainline Approaches
	Non-Mainline Approaches	0.9966×Model Prediction for Injury & Fatal Accidents on Non-Mainline Approaches

The procedure for EPDO estimation in which accident counts are combined with model predictions to obtain Empirical Bayes estimates was also coded in Visual Basic. Sample output for the first five intersections and their approaches is in Table 6. EB estimates are deemed to be more accurate than estimates based on accident counts only and are not subject to regression-to-the-mean bias. **This procedure too may be of interest for wider implementation in CDOT.**

Table 6. EB Estimates and EPDO.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1	1	3	1	0.028409	0.030145	0.000054	0.198933
1	1	3	5	0.005089	0.003229	0.000027	0.026549
1	1	3	3	0.002815	0.002963	0.000054	0.027098
1	1	3	4	0.005089	0.003229	0.000027	0.026549
2	2	3	1	0.001938	0.002153	0.000056	0.022111
2	2	3	5	0.005089	0.003229	0.000027	0.026549
2	2	3	3	0.001938	0.002153	0.000056	0.022111
2	2	3	4	0.005089	0.003229	0.000027	0.026549
3	3	3	1	0.003343	0.003556	0.000081	0.034965
3	3	3	5	0.005089	0.003229	0.000027	0.026549
3	3	3	3	0.003343	0.003556	0.000081	0.034965
3	3	3	4	0.005089	0.003229	0.000027	0.026549
4	4	3	1	0.004844	0.005179	0.000159	0.057142
4	4	3	5	0.005089	0.003229	0.000027	0.026549
4	4	3	3	0.048879	0.052688	0.000159	0.356780
4	4	3	4	0.005089	0.003229	0.000027	0.026549
5	5	3	1	0.001982	0.002076	0.000029	0.017656
5	5	3	5	0.005089	0.003229	0.000027	0.026549
5	5	3	3	0.001982	0.002076	0.000029	0.017656
5	5	3	4	0.005089	0.003229	0.000027	0.026549

A change in left turn phasing at one or more intersection approaches entails a change in signal timing and thus a change in intersection delay. To properly estimate this change in intersection delay requires fairly complex computations and detailed information about the intersection and its traffic. The challenge was to find a reasonable way for estimating this change in delay when only very limited information is available (mainline ADT, number of intersection approaches and number of lanes on mainline approaches) such that it could be performed easily for a large number of intersections. The approach chosen was to estimate the added delay using the Brondum-Martin equation described in Working paper 1 (07/03/2005). The equation is:

$$\begin{aligned} D &= \beta_1 (V_L + K)^1 + \beta_2 (V_L + K)^2 + \ldots + \beta_{n-1} (V_L + K)^{n-1} + \beta_n (V_L + K)^n + M \\ K &= \alpha_0 + \alpha_1 V_T + \alpha_2 {V_T}^2 + \alpha_3 {V_T}^3 \end{aligned}$$

Eqn. 3

In this, D=Delay in seconds/vehicle, V_L=left-turn volume in vehicles/hour, M=vertical shift, K=horizontal shift as a function of the opposing volume V_T in vehicles/hour, n the degree of the polynomial, usually 4 and α_0 to α_3, β_0 to β_n and M are the estimated regression coefficients obtained by Brondum and Martin and are based on the Highway Capacity Manual method of delay estimation. The approach is far from ideal and, given the paucity of information available, its implementation required a large number of assumptions to be made.

The estimation of D requires hourly volumes. The average hourly proportions of ADT in Figure 1 are based on data from 20 urban and 54 rural count stations (obtained on Wednesday, August 7, 2002). Since the urban and rural hourly profiles are similar their average was used.

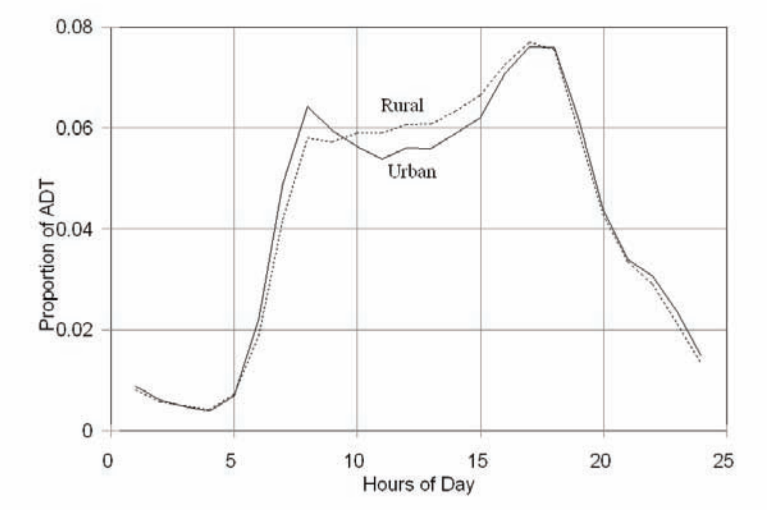

Figure 1. Hourly ADT Proportions.

A Visual Basic code was written the estimate the added delay due to change in left-turn phasing. Sample results are in Table 7.

Table 7. Sample Results for Added Delay

Intersection (Consecutive Numbering)	Original Numbering	Approach Number	Approach Lanes	Mainline ADT	Non-Mainline ADT	Expected Accidents in 14-th year	Daily Delay in 14-th year [seconds]		
							Protected	Permitted	Added= Protected-Permitted
1	1	1	1	3228	2259	0.059	27204.8	9121.8	18083
1	1	5	0	3228	2259	0	0	0	0
1	1	3	1	3228	2259	0.006	27204.8	9121.8	18083
1	1	4	0	3228	2259	0.008	16570	4774.5	11795.5
2	2	1	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	5	0	3317	2322	0	0	0	0
2	2	3	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	4	0	3317	2322	0.008	17173.3	4980.9	12192.3
3	3	1	1	4358	3051	0.007	43451.1	18196.8	25254.2
…	…	…	…	…	…	…	…	…	…

With estimates of EPDO and of added delay in hand, it was possible to create a ranking of all intersection approaches considering both benefit (70% reduction in target EPDO) and cost (added delay). In this manner the aim was to identify approaches to signalized intersections where conversion to protected left-turn phasing promises to be of most benefit. The task was accomplished with the limitation that only electronically available information could be used. While the expected EPDO reduction could be reasonably well estimated by the EB method on the basis of models and accident history, the estimated change in delay was likely to be only a crude approximation. The reason is in that some important data are not available (e.g., number of approach lanes and traffic volume on non-mainline approaches), that use was made of approximating equations which produce bad estimates at low and at high volumes, and that a multitude of assumptions was made to cover for the absence of information.. The question was whether the resulting ranking is good enough to lead engineers to sites where a change to protected phasing will be of benefit. To answer the question a field data collection and delay estimation study was conducted.

The field data collection and delay estimation study was conducted by Felsburg, Holt, Ullevig on 104 approaches of 26 intersections. The purpose was to determine to what extent the delay estimated by the Brondum-Martin equation that uses only electronically available data and an assortment of assumptions resembles the delay estimated produced by the SimTraffic simulation software and using data collected in the field.

The result was disappointing. Thus, e.g., Figure 2 shows the relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations for Protected phasing on Mainline Approaches. The scale was selected so as to shown only points where there is no danger of incorrect estimates due to over-saturation. The Brondum-Martin equation usually estimate a larger delay than the simulation and the correlation between the two estimates is minimal. As already noted, the reasons for the small correlation may be many. Some reasons may be due to discrepancies in input data (number of lanes, hourly ADTs etc.) some may be due to the many assumptions and approximations associated with the use of the Brondum-Martin equations, some may be caused by the differences between the HCM procedure (which is in the background of the Brondum-Martin equations) and the microscopic simulation in SimTraffic. The question was whether there are significant discrepancies in the input data which are perhaps correctible or whether the differences are due reasons that cannot be easily corrected.

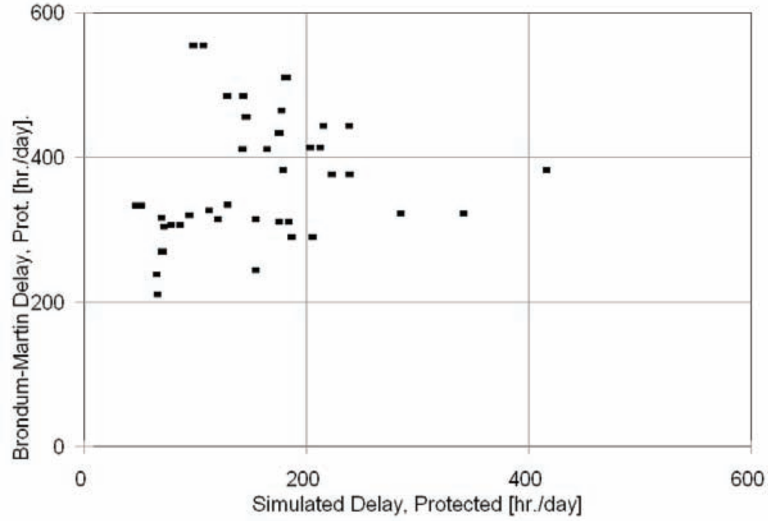

Figure 2. Relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected phasing for Mainline Approaches

When computing delay by the Brondum-Martin equations the assumption was made that the left-turning traffic is 15% of the approach volume. The field data shows that on the 52 mainline approaches the average proportion of left-turning traffic was 7% with a standard error of ±6% while on non-mainline approaches the average proportion was 34% with a standard error of ±15%. This is a major discrepancy which could perhaps explain the disappointing association between the delay estimated by the Brondum-Martin and that by SimTraffic. Therefore the code was modified using 7% left turns for mainline approaches and 34% left turns for non-mainline approaches and the delay estimation repeated.

Unfortunately, even after the correction, the comparison of Delay and Added Delay estimates obtained by SimTraffic and by the Brondum-Martin equations shows that the two produced discrepant results. Therefore, the Brondum-Martin equations cannot be relied upon to give an indication of what change in delay should be expected from the change of left-turn phasing to full protection. The electronically available data when coupled with such equations that cannot be closely matched to the specific conditions in the field are unequal to the task. It follows that, at this time, the task of assessing what change in delay may result from a conversion to full left-turn protection at some intersection must be left to the expert traffic engineer.

Both the simulation when based on field data and the Brondum-Martin equation indicate that under some conditions delay is lesser with protected left-turn phasings. Unfortunately the two methods of estimation do not agree about the intersections where this is the expected outcome. It would be important to know under what conditions full left-turn protection saves delay because at such intersection full left-turn protection is clearly beneficial. To the extent that the conditions have not yet been established, **research of this matter is likely to be of much benefit.**

It is possible that future research could produce a method of added delay prediction which would better match simulation results. However, inasmuch as such a method does not seem to be now available one must conclude that the **ranking at this time should be solely on the basis of the EPDO.** Such ranked lists should be forwarded for detailed engineering examination to consist of two steps. First, intersection approaches at which left-turns are already fully protected should be deleted from the list. Second, using the abridged list the engineer, using her/his familiarity with the sites, should examine in detail the delay consequences of a change in left-turn phasing.

The ranked list of the ten intersection approached with the largest EPDO is in Table 8

Table 8. Ten Approaches with Largest EPDO in Last Year.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1071	1089	4	1	5.50	3.83	0.0028	26.52
1407	1425	4	1	4.46	3.78	0.0040	25.40
1403	1421	4	1	4.97	3.09	0.0047	22.32
1485	1503	4	1	5.25	2.86	0.0053	21.46
298	303	4	1	3.49	2.71	0.0025	18.48
297	302	4	3	3.62	2.56	0.0031	17.90
1534	1552	4	3	4.45	2.40	0.0030	17.84
1378	1396	4	1	4.49	2.32	0.0048	17.74
831	848	4	1	3.37	2.40	0.0032	16.80
1096	1114	4	3	4.95	1.96	0.0028	15.92

A similar ranking by the sum of EPDO estimates for the two mainline approaches is in Table 9.

Table 9. Ranking by Sum of EPDO/year for two mainline approaches.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of 2 Mainline Approach EPDOs/year
1	1407	1425	4	38.80
2	1403	1421	4	31.55
3	1071	1089	4	31.46
4	1485	1503	4	29.25
5	831	848	4	29.17
6	298	303	4	28.23
7	1466	1484	4	27.39
8	1531	1549	4	27.34
9	297	302	4	24.69
10	1118	1136	4	24.25

Ranking by the sum of EPDO estimates for the two non-mainline approaches on four legged intersections is in Table 10.

Table 10. Sum of EPDO/year for two non-mainline approaches of four legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of 2 Non-mainline Approach EPDOs/year
1	1209	1227	4	18.65
2	939	957	4	17.33
3	831	848	4	15.72
4	816	833	4	14.89
5	841	858	4	13.51
6	1385	1403	4	12.39
7	938	956	4	12.01
8	604	621	4	9.95
9	1455	1473	4	9.27
10	421	437	4	9.21

Ranking by EPDO of the non-mainline approach on three legged intersections is in Table 11

Table 11. EPDO/year for non-mainline approach of three legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Non-Mainline Approach EPDO/year
1	21	21	3	1.35
2	222	227	3	0.93
3	7	7	3	0.74
4	211	216	3	0.51
5	58	58	3	0.48
6	46	46	3	0.48
7	243	248	3	0.35
8	107	109	3	0.32
9	345	360	3	0.29
10	378	394	3	0.25

Ranking by the sum of EPDO for all approaches for four legged intersections is in Table 12.

Table 12. EPDO/year for four legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of Approach EPDOs/year
1	831	848	4	44.88
2	1407	1425	4	43.64
3	1403	1421	4	38.74
4	1071	1089	4	38.37
5	1485	1503	4	36.44
6	1209	1227	4	34.43
7	939	957	4	33.47
8	938	956	4	32.65
9	1385	1403	4	32.43
10	298	303	4	29.99

Ranking by the sum of EPDO for all approaches for three legged intersections is in Table 13.

Table 13. EPDO/year for three legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of Approach EPDOs/year
1	382	398	3	8.84
2	305	312	3	6.87
3	327	339	3	6.57
4	309	320	3	5.73
5	57	57	3	5.38
6	379	395	3	4.54
7	47	47	3	4.45
8	307	318	3	4.31
9	303	310	3	3.95
10	318	330	3	3.70

Complete rankings are provided in the spreadsheet ‘Ranking by EB.xls’.

Table of Contents

1. Countermeasures with Promise (CWIPs)

It is our professional responsibility to monitor and improve the safety of our road system. The habit and tradition are to identify sites where there seems to be an inordinately large number of accidents, to search for possible causes, and to implement what seem to be cost-effective remedies. The process begins by screening the network for ‘Sites with Promise’ (SWiPs). Following that, a DES (Detailed Engineering Study) is done at the top ranked sites. The DES leads to the selection of suitable countermeasures. This sequence of steps and the kind of information used at each step are shown in Figure 1.

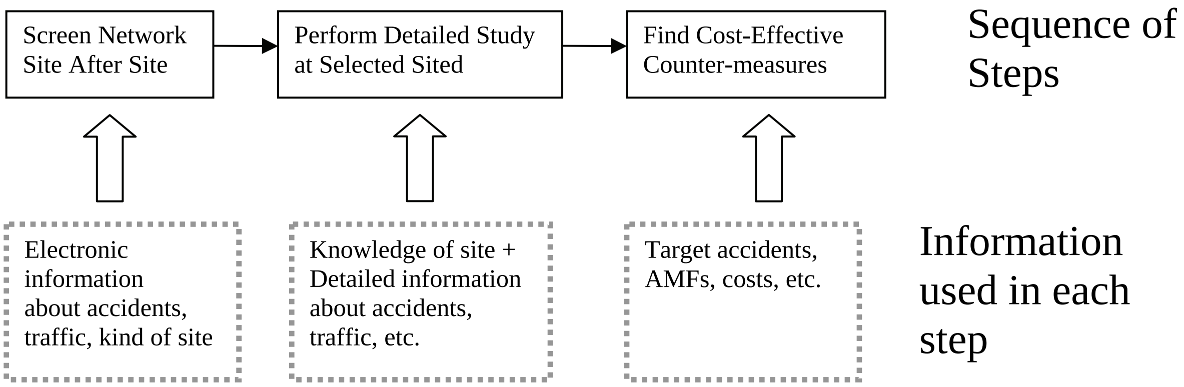

Figure 1. Steps of the ‘Sites With Promise’ Process

The main weakness of structuring the task in this sequence is that the selection of sites for a DES (screening) is done without knowledge of what countermeasures may be suited for these sites.

This weakness could be obviated by structuring the process differently. Instead of first selecting sites and then asking what countermeasures could be applied at these, one could begin by choosing a countermeasure and then asking about the sites where it could be implemented. To illustrate the Countermeasures with Promise (CWiP) process, suppose that we wish find sites where accidents can be reduced cost-effectively by, say, reducing the slope of the embankment. The cost of slope reduction is a function of fill height, existing slope, and a local cost factor (cost of fill). The benefit of slope reduction is proportional to the frequency of target accidents (off-the-road accidents involving loss of control) and the corresponding AMFs. Screening now would involve examining all roads sections on fill, and for each such section computing the benefit/cost ratio.

There exists a fairly large, but certainly finite, set of possible countermeasures. The process illustrated earlier (for slope reduction on fill) would be repeated for, shoulder paving, illumination, winter maintenance etc. Once all countermeasures are considered in this manner, one can merge all benefit/cost estimates into one overall ranking

Conceptually, the search for CWiPs process is sounder than the screening for SWiPs process. (There is nothing very new about it except, as in the story of the Columbus egg, it restores the process to its common sense form). The main weakness of the CWiP process is that it may require information that is currently not in electronic data bases (e.g., whether a road section is in fill, what the height and slope of fill is, what is the local cost factor for fill etc.). Its main strength is in the ability to identify better sites; that is sites at which safety money will be spent to more effect.

A forward looking research strategy should not be deterred by the fact that some data elements are now missing. In many states, not all data is available even for the implementation of the screening for SWiPs process. The hope is that the availability of SafetyAnalyst, technological developments, and other circumstances will spur agencies to improve their data bases. Such improvements can also be influenced by the desire to implement and CWiPs process.

The overall logic and structure of the CWiP Process is straightforward and depicted in Figure 2. It is envisioned that the process will be implemented countermeasure after countermeasure. In the following I refer to the numbers in Figure 2.

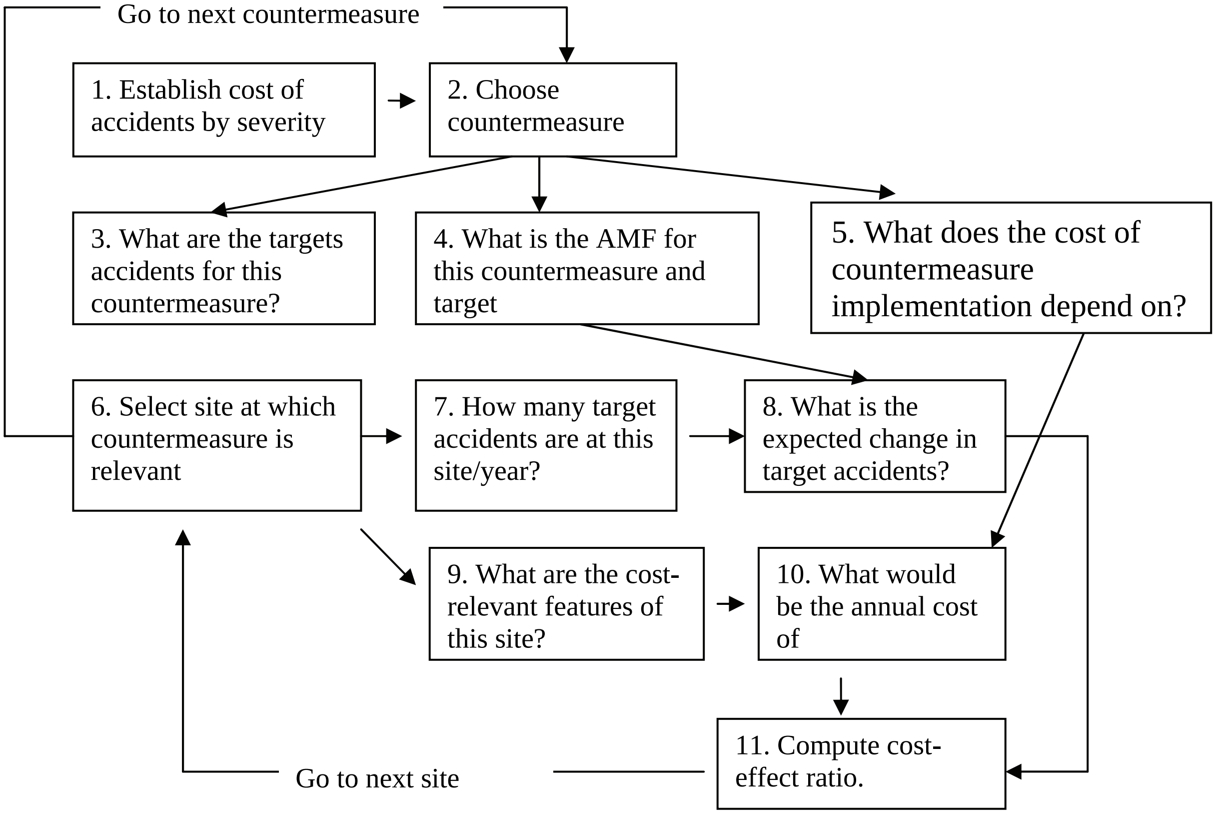

Figure 2

1. The cost of accidents, by severity will be that currently in use by CDOT.
2. Three countermeasures will be selected by CDOT staff for pilot implementation.
3. After reviewing the extant published literature on the selected countermeasures, and in consultation with CDOT staff, the determination will be made about what are the target accidents for the countermeasures selected in 2.
4. Also based on the review of the extant published literature provisional AMFs for the target accidents will be selected. To the extent that there is documented CDOT experience with the

countermeasure, special purpose before-after studies will be conducted and the AMFs amended accordingly.

5. For each selected countermeasure a study will be performed to determine it's 'implementation cost model'. This may entail consultation with CDOT staff; examination of project records etc. The purpose is to determine the manner in which the cost of countermeasure implementation depends on the characteristics of the site where the countermeasure is implemented.

6. Each countermeasure applies to sites of a certain kind. Thus, e.g., signal dilemma-zone pre-emotion applies to signalized detector-actuated intersections, while centerline rumble strips apply to undivided road segments. Thus, a list has to be compiled matching each countermeasure to the relevant site characteristics. Using this list all sites matching the characteristics will be selected for screening.

7. For each site to be selected, the number of expected target accidents will be determined using that sites historical accident records. To the extent that a corresponding Safety Performance Function is (or can be) available, an Empirical Bayes estimate of the expected number will be prepared. The amount of detail needed cannot be well envisioned at this time. Thus, e.g., if the target accidents of dilemma-zone pre-emotion are rear-end accidents on an intersection approach, then screening must be approach-by-approach. That means that accident record and the SPF must also be by approach. If also right-angle accidents are the target, right-angle accidents and their SPFs need to be available. Issues of this kind will become clearer in the course of the work.

8. This item is a straightforward product of 7 and 4.

9. Having determined what features of a site affect the countermeasure cost, a record of the corresponding feature has to be retrieved from an existing data-base. It may be expected that from the practical point of view this item may prove difficult in view of the incomplete information in the existing inventories.

10. This item is also a straightforward product of 5 and 9.

Even though the idea is simple and its attraction obvious, one can only assess its practicality through a pilot implementation. To test the process the Colorado DOT and FHWA decided to examine the attraction of the CWiP idea in practice. The countermeasure chosen for examination was that of changing left-turn phasing at signalized intersection to protected phasing.

Referring to the general CWiP schema in Figure 2, for Step 1 costs of \$6,500, \$35,000 and \$1,000,000 for PDO, Injury and Fatal accidents were used. The countermeasure selected in Step 2 is 'Change Left-Turn Protection'. Step 3 in the schema is the identification of target accidents. In principle, a change in left-turn protection will involve a change in signal timing for several, perhaps all, intersection traffic streams. Therefore, it may affect not only accidents involving the left-turning vehicles for which protection was changed but all other intersections accidents. However, our review of past research shows that what empirical evidence exists does not permit one to speculate about the magnitude (or even the direction) of such a change. Therefore, for the purpose of this project it is suggested that only accidents involving left-turning vehicles from the approach for which a change in left-turn protection is considered be considered target accidents. Step 4 in the schema is the determination of Accident Modification Factors. In the review of past research the following summary results were suggested:

Table 1. Accident Modification Factors

From phasing	To phasing	Accidents	AMF[1]
Permissive	Protected	Left-turn	0.3[2]
		Other	1[3]
Permissive	Protected/Permissive or Permissive/Protected	Left-turn	1[3]
		Other	1[3]
Protected/Permissive or Permissive/Protected	Protected	Left-turn	0.3
		Other	1[3]
Lagging	Leading	Left-turn	1

[1] Accident Modification Factor; Multiplies expected accidents in the ‘From’ phasing to obtain expected accidents with the ‘To’ phasing.

[2] Most likely depends on number of opposing lanes.

[3] Insufficient and contradictory evidence

That is, the only change in left-turn phasing deemed to have a clear safety benefit is from ‘Permissive’ or ‘Protected/Permissive’ to ‘Protected’ phasing. Both changes are estimated to have an AMF of 0.3. To illustrate, suppose that for a certain approach with ‘Permissive’ phasing one expects 5.1 accidents/year involving left turning vehicles. The benefit of changing the phasing to ‘Protected’ is a reduction by 5.1×(1-0.3)=3.6 accidents per year. Step 5 is the determination of what the cost of a change to left-turn phasing depends on. The review of the literature shows that there are some costs to hardware as well as operational costs; the latter that entail change in delay, stops, emissions and the like. The cost of added delay seems to dominate all other cost elements. Step 6 is the determination of relevant sites. For this countermeasure a ‘Site’ is an approach of a signalized intersection at which the left-turn phasing is either ‘Permissive’ or ‘Permissive/Protected’. Step 7 is the determination how many target accidents (PDO, Injury and Fatal) are expected at a site in a year. This step requires the knowledge of:

a. The history of the counts of accidents involving left turning vehicles at all sites (approaches of signalized intersections with ‘Permissive’ or Permissive/Protected’ phasing) and

b. A model to compute the expected number of such accidents based on the traits (Main road ADT, speed limit, current left-turn protection) of a site.

The information from ‘a’ and ‘b’ will be combined by the Empirical Bayes method to give the required estimates. The result of step 7 is an estimate of the expected number of accidents for the most recent year involving left-turning vehicles for all sites in a form such as.

Table 2. Estimates of Expected Target Accidents.

Intersection	Approach	Last Year		
		PDO	Injury	Fatal
1	1	2.12	0.34	0.07
	2	…	…	…
	3			
	4			
2	1			
	2			
	3			
	4			
3	1			
	…	…	…	…

Step 8 is to compute the expected annual change in target accidents. That PDO, Injury and Fatal accidents carry differing weights can be reflected by will be using the notion of ‘Equivalent Property Damage Only’ (EPDO) accidents. Step 9 is the determination of the cost-relevant features of a site. As established in Step 5, the change in delay that results from a change in left-turn protection dominates cost. Because the change of left-turn protection on one approach results in changes to the signal timing for several approaches, the change in delay is not confined to this the ‘site’ (approach) but extends several (perhaps all) intersection approaches. It follows that the ‘cost-relevant features’ of a site (approach) are all the features that affect the delay at all the affected intersection approaches. In principle the cost-relevant features are many. Here one must remember that we are dealing with a screening process for which the central idea is that it makes use only of readily available information. That is, we are not dealing with a detailed engineering study for which additional custom information may be prepared or collected in the field. What one may hope for in this case is to have information about ADT on the principal approaches, the number of lanes on all approaches, the presence of turning lanes, type of control (i.e., fixed time, semi-actuated, actuated) and perhaps number of phases. From this information one has to produce and estimate of cost in step 10. Step 10 is the determination of the annual cost of implementation. Since the main element of this cost is delay, the task is to obtain an estimate of the change in delay that is the result of the change in overall signal timing due to the change in left-turn protection on an approach. Since accident savings (Step 8) are on a yearly basis, the change in delay also has to be on the same (yearly) basis. This can be done by using the product:

ΔD_{year} = (Average Change in Delay/Vehicle)×(Vehicles/Year)

When one speaks of a change in Average Delay/Vehicle, averaging is over vehicles, traffic streams and times of day. Inherent in this kind of averaging is the very questionable assumption that the cost of delaying a hundred vehicles for one second is the same as the cost of delaying one vehicle for hundred seconds. Similarly, when one multiplies a change in average delay by the number of vehicles delayed, the same questionable assumption means that 3600 vehicles delayed for one second amounts to a delay of one hour to which, later one assigns an some $ cost for losing one hour of time. Nevertheless, since these kinds of assumptions are commonly made, there is no reason to depart from what is usual practice. To emphasize the fact that seconds of time lost are being accumulated, the dimension of ΔD_{year} will be ‘Seconds/Year’. Thus, the main problem is how to estimate the change in average delay on the basis of the limited information discussed in step 9. Step 11 was the computation of a cost-benefit ratio. Each site (approach) will yield a pair of numbers: a. Reduction in target accidents measured in EPDO/Year, b. Change in delay measured in Seconds/Year. Thus, if there are 1000 relevant sites (Step 6), we can have a graph with 1000 points such as the three points in Figure 3.

Line A represents all where 2 PDO accidents are saved at the expense of 10^6 seconds of delay, line B represent the lesser benefit of 1 PDO accident saved for 10^6 seconds of delay. Thus, the slope of a line through the origin represents a certain benefit/cost ratio. Clearly approach 1 should be considered before approach 2 and approach 3 is to be ranked last. If a certain limiting benefit/cost ratio can be selected, all approaches represent by point above that line should be considered.

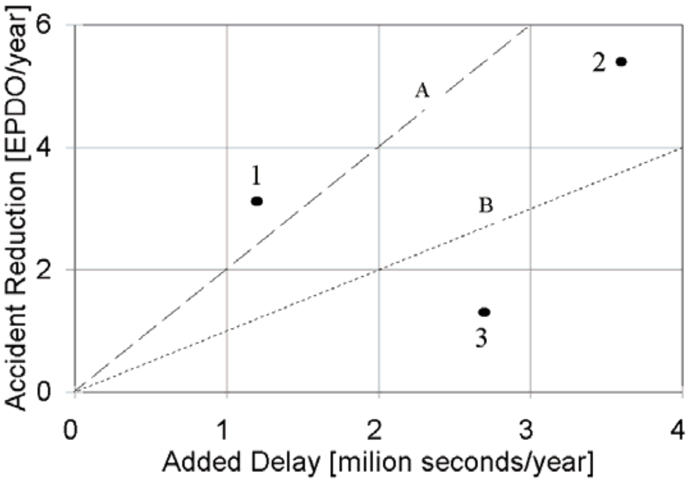

Figure 3

2. Data Requested and Obtained.

Data was requested in the format of Table 3 with explanations 1-7.

Table 3. Data Requested

Inters[1]	Appr[2].	1990[3]				1991				..	Protection Type[7]	No. of Approach Lanes	Speed Limit
		PDO[4]	Inj[4]	Fat[4]	ADT[5,6]	PDO	Inj	Fat	ADT				
1	1												
	2									..			
	3									..			
	4									..			
2	1									..			
	2									..			
	3									..			
	4									..			
3	1									..			
	…	…	…	…	…		…	…	…	..		…	…
										..			
										..			

1. We want to include all <u>signalized</u> intersections. In addition to the consecutive numbering please add a column or columns needed to identify the intersection in the way in which you and your regional engineers usually do.
2. Note that each intersection has data in several rows, each row corresponding to an approach. ‘T’ intersections will have three rows; ‘X’ intersections will have four rows etc. It will make my programming a bit simpler if between the ‘Inters’ and ‘Appr’ columns you could add a column with ‘No. of Approaches’.
3. Next are a set of four columns, one set for each year for which you have accident data; the more years, the better. If for some intersection and/or years the data is missing, put in some text (e.g. N).
4. For the accident counts (PDO, Non-Fatal Injury and Fatal Injury) the following conventions will apply:

a) Only accidents involving a left-turning vehicle will be counted.

b) The accident will be added to the count of that approach from which the left turning vehicle came. I hope that this can be done by combining your ‘Direction of Travel’ and ‘Vehicle Movement’ data about each accident. Please let me know whether this is a problem and whether there are many cases in which one or both data elements are not known.

5. I expect that in most cases you will only have ADT for the main road approaches (make them Approach 1 and 2). In these cases we will have to assume what the minor road ADT might be. There surely exist manual counts for some of your signalized intersections. If feasible[1], it would be good if the ADTs from such intersections could be placed in the data. This would allow me to make intelligent guesses about the minor road ADTs when such data does not exist.

6. Should it prove feasible to include in the data also of Table 4 the ADTs for those intersections and approaches where manual counts exist, I suggest that we add a column to the right of each ADT column in Table 4 to contain the Left-turn ADT. I will then use this information to add guesses about the left-turn ADT for all the approaches where this information is missing.

7. Ideally we should include in the ranking only approaches of signalized intersections that do not already have protected left-turn phasing. However, for the added delay calculation it may prove important to include in Table 4 all approaches, even those where left-turns already have a protected phase. I expect that the left-turn protection type (Permissive, Permissive-Protected, Protected) by approach is not known. Nevertheless, if for some reason it is known, adopt a code (1,2 3) and add the information.

Initially data was obtained for 1705 intersections. An extract is in Table 4.

Table 4. Data Obtained

Intersec-tion No.	Ap-proach[1]	1990					1991	...	2002	2003						
		Pdo	Inj	Fat	All[4]	Adt[2]	Pdo	...	Adt[2]	Pdo	Inj	Fat	All	Adt	Legs	Lanes[3]
...	...	...	...	...	...	...	...		...	...	...	...	...	...	...	...
51	1	0	0	0	2	11105	0		14777	0	0	0	0	0	3	2
0	2	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0	3	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0	4	0	0	0	0	0	0		0	0	0	0	0	0	0	0
52	1	0	0	0	1	12838	0		17212	0	0	0	6	15533	3	2
0	2	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0	3	0	0	0	0	0	0		0	1	0	0	0	0	0	0
0	4	0	0	0	0	0	0		0	0	0	0	0	0	0	0
53	1	0	0	0	0	0	0		0	0	0	0	17	22460	3	2
0	2	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0	3	0	0	0	0	0	0		0	0	0	0	0	0	0	0
0	4	0	0	0	0	0	0		0	0	0	0	0	0	0	0
54	1	0	0	0	6	24540	0		23518	0	0	0	3	22288	3	2
0	2	...	...	...	...	...	...	...								

[1] All intersections, even those with three legs, were given four rows. Rows labelled ‘Approach 1’ and ‘Approach 3’ are the main road approaches. Approach 1 is in the increasing mile-post

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[1] If manual counts for some signalized intersections are available in electronic form, but it is difficult to add the information to the data in Table 4, please forward it separately and I will attempt to use it.

direction, Approach 3 in the decreasing mile-post direction. Rows labelled ‘Approach 2’ and ‘Approach 4’ are the minor road approaches. If the intersection has three legs, a row with no recorded accidents is the non-existent approach.

[2] The ADT given in the ‘Approach 1’ row is the ‘Total through Volume’. Thus for approaches 1 and 3 of intersection No. 52 the ADT is 12838/2=6419. The ADT for approaches 2 and 4 are not known.

[3] The ‘Lanes’ given in the ‘Approach 1’ row is the total number of mainline lanes. The intersections 51 -54 shown have one lane in each direction of the main road.

[4] The accident counts in the ‘All’ column of approach 1 is the total number of all accidents occurring in a year, not only the number of accidents involving left-turning vehicles.

3. Data Preparation.

Several modifications were made to the original data.

1. Each ‘ADT’ was split in half and the result assigned to approaches 1 and 3. Thus, e.g., in year 2001 intersection 1 had a total through ADT of 6455. In the modified data for 2001 approach 1 was given 3227.5 and the same ADT to approach 3.

2. In preparation to step 3, a column with the sum of left-turn accidents over all 14 years (SumLt) was added. Thus, e.g., intersection 1 has one PDO and one injury left-turn accidents in 2001 (and not other left-turn accidents) for a SumLt=2.

3. When ‘Lanes’ (number of mainline lanes) was an even number it was divided by 2 and the result assigned to approaches 1 and 3. Thus, e.g., for intersection 1 ‘Lanes’ was 2 and in the modified data approaches 1 and 3 of that intersection have 1 lane each. When ‘Lanes’ was an odd number Lanes/2-0.5 was given to the approach which had more left-turn accidents over all years. The belief is that the approach has more left-turn accidents because its vehicles are turning across more lanes on the opposing approach. Thus, e.g., intersection number 83 in the original data shows 3 mainline lanes. Vehicles from approach 1 had 13 left-turn accidents and vehicles from approach 3 had 52. The assumption is that vehicles from approach 3 turned to cross more lanes than vehicles of approach 1. Therefore 2 lanes were assigned to approach 1 and 1 to approach 3. (File ADT&SumLt&Lanes mod).

4. In the original data all intersections have either 3 of 4 legs. For intersections with three legs, one of approaches 2 or 4 that have a 0 as entry for all accidents was designated as approach 5.

5. Occasions when a three-leg intersection had non-zero accidents on both approaches 2 and approach 4 were identified. Similarly identified were three-legged intersections that had non-zero left-turn accidents on both approaches 1 and 3. Some such intersections were identified as unusual and deleted, other intersections proved to be really four-legged and the data was modified accordingly. 1537 intersections remained in the data.

6. Intersections originally numbered 595 and 880 had a single ADT count coded as 999999. These intersections were removed from the data so that 1535 intersections remain.

After these changes the data in Table 4 looks as shown in Table 5.

Table 5. Modified Data

Inter-section	App-roach	1990						1991	...	2003	Legs	Lanes	ΣLt	ΣAll
		PDO	Inj	Fat	Lt	All	ADT	PDO		ADT				
51	1	0	0	0	0	2	5552.5	0		0	3	1	0	65
51	5	0	0	0	0	0	0	0		0	3	0	0	0
51	3	0	0	0	0	0	5552.5	0		0	3	1	0	0
51	4	0	0	0	0	0	0	0		0	3	0	0	0
52	1	0	0	0	0	1	6419	0		7766.5	3	1	0	37
52	5	0	0	0	0	0	0	0		0	3	0	0	0
52	3	0	0	0	0	0	6419	0		7766.5	3	1	7	0
52	4	0	0	0	0	0	0	0		0	3	0	0	0
53	1	0	0	0	0	0	0	0		11230	3	1	0	17
53	5	0	0	0	0	0	0	0		0	3	0	0	0
53	3	0	0	0	0	0	0	0		11230	3	1	0	0
53	4	0	0	0	0	0	0	0		0	3	0	0	0
54	1	0	0	0	0	6	12270	0		11144	3	1	2	101

This matrix is stored in the "Final Modified File".

The relationship between the ΣAll and the sum of ΣLt of all four row of an intersection is in Figure 4. Overall, about 17.4% of all accidents are of the 'approach-turn' type and deemed to be the target accidents.

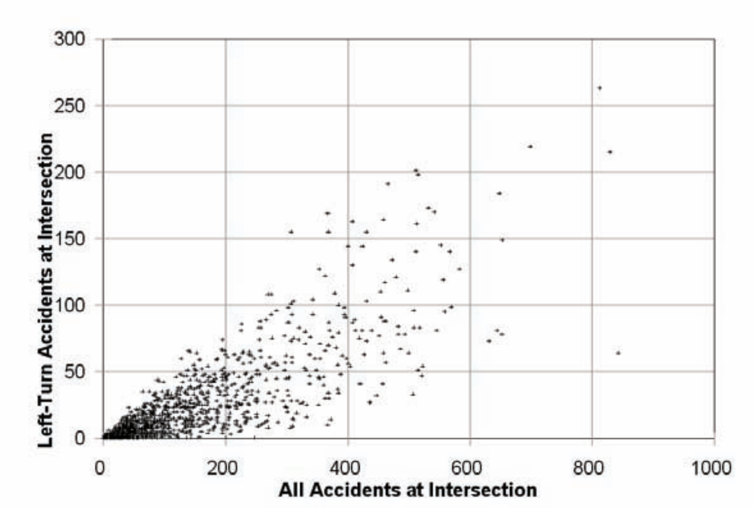

Figure 4

4. Filling in the ADT Table.

ADT data for the first seven of 1705 intersections is in Table 6.

Table 6. Original ADT Data

Intersection	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1												3228		
2									4840	4746	4564	3633		
3										4358				
4	4678	4728	4919	4725	6444	5139	6502	5464	5633	5714	6395	6187	7876	7603
5										2046				
6										1449	1451	1450		
7									5751	7385	4857	5482		

The cell entries - the data - are derived from manual or automatic counts. These are based on counts performed during a few days and factored-up for the entire year by using various empirical constants. As such that ADT data are subject estimation errors. The data for intersections 2, 4 and 5 are shown in Figure 5.

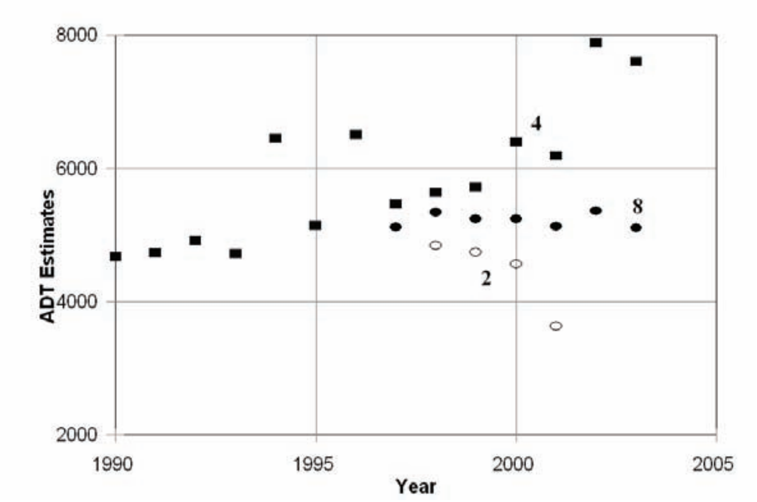

Figure 5. ADT data for a few intersections

Because the data are subject to some error it is perhaps reasonable to estimate the underlying ADT by fitting a smooth function to the available data points. T. Such a function would enable us smooth out the randomness in the ADT data and to fill in the empty cells for the years for which counts are not available. The choice of the linear function is supported by ADT for intersections that all had fourteen years of counts. Data for the first five such intersections are shown in Figure 6.

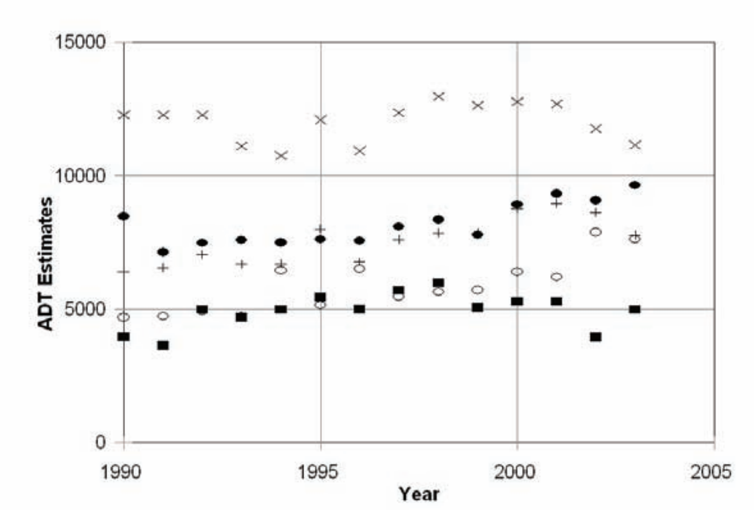

Figure 6. First five intersections at which 14 years of count data were available

The estimation equation is:

$$\text{Estimated ADT for year } Y = A + B \times I, I = 1 \text{ for } 1990, 2 \text{ for } 1991 \text{ etc.} \qquad \textbf{Eqn. 1}$$

The estimation of the regression parameters A and B proceeded in two stages. In the first stage ordinary least squares estimates $\hat{A}$ of A, $\hat{B}$ of B and of $VAR\{\hat{A}\}$ and $VAR\{\hat{B}\}$ were obtained for each of the 1537 intersections. If $|\hat{B}|/(\sqrt{VAR\{\hat{B}\}}<1$, i.e. when the slope is so inaccurately estimated that the estimate is not more than one $VAR\{\hat{B}\}$ standard error away from 0, I used $\hat{B}=0$. To diminish the problem of extreme estimates of B Empirical Bayes (shrinkage) estimates of B were produced as follow:

$$EB\hat{B} = \alpha_B \times \hat{B} + (1-\alpha_B) \times Avg(\hat{B})$$

$$\alpha_B = \frac{180828}{180828 + VAR\{\hat{B}\}}; \quad Avg(\hat{B}) = 207.7 \qquad \textbf{Eqn. 2}$$

When three or more ADT counts were available and $|\hat{B}|/VAR\{\hat{B}\}<1$, the Empirical Bayes estimates from Eqn. **2** were used in Eqn. 1. In this case A was computed so that the line goes through the center of gravity of the data. When one or two ADT counts were available, their average was used. The resulting estimates for the intersections in Table 6 are in Table 7.

Table 7. Estimated ADT Data

Intersection	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228	3228
2	7510	7187	6865	6542	6220	5897	5575	5252	4930	4607	4284	3962	3639	3317
3	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358	4358
4	4535	4738	4942	5145	5349	5552	5756	5959	6163	6366	6569	6773	6976	7180
5	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046	2046
6	1442	1443	1444	1444	1445	1446	1447	1447	1448	1449	1450	1450	1451	1452
7	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868	5868

The matrix is in text file “Filled ADT data for 1535 Intersections” and in the modeling spreadsheet.

5 Preparing Data for Modeling

The purpose of modeling is provide the information needed to eventually estimate the expected number of target accidents (PDO, Injury and Fatal) by the EB method for each approach of all 1535 intersections. The following categorization will be attempted:

1. Mainline approaches and Non-mainline approaches.
2. .PDO and Fatal & Injury. (The latter will be split into Injury and Fatal by a constant proportion)
3. Three and Four legged intersections.

Eight text files corresponding to the conditions in Table 8 were stored in the text files folder and on the modeling spreadsheet.

Table 8

Intersection	Approach	Accidents	Number
3 Legged	Mainline 1 and 3	PDO	537
3 Legged	Mainline 1 and 3	Inj&Fatal	370
3 Legged	Not-mainline 2 or 4	PDO	36
3 Legged	Not-mainline 2 or 4	Inj&Fatal	30
4 Legged	Mainline	PDO	12502
4 Legged	Mainline	Inj&Fatal	9070
4 Legged	Not-mainline 2 and 4	PDO	4238
4 Legged	Not-mainline 2 and 4	Inj&Fatal	2332

6 Exploratory Modeling.

6.1 Three Legged Intersections, Mainline Approaches 1 and 3, PDO Accidents.

How the number of PDO accidents/approach in 14 years depends on PDO is shown by the 21-approach moving average in Figure 7.

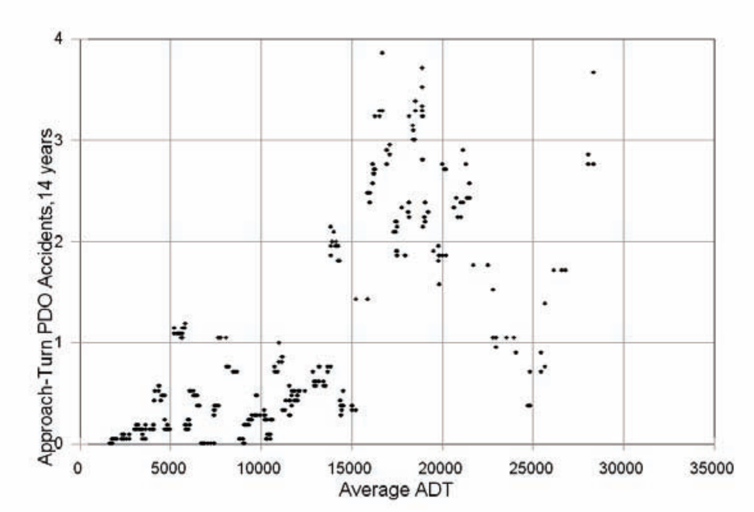

Figure 7. Moving averages (over 21 approaches) for 3-legged, mainline, PDO accidents

For the same data the Integrate-Differentiate (I-D) method[1] resulted in Figure 8. Since the I-D method offers a much cleaner picture, it was used for all other data.

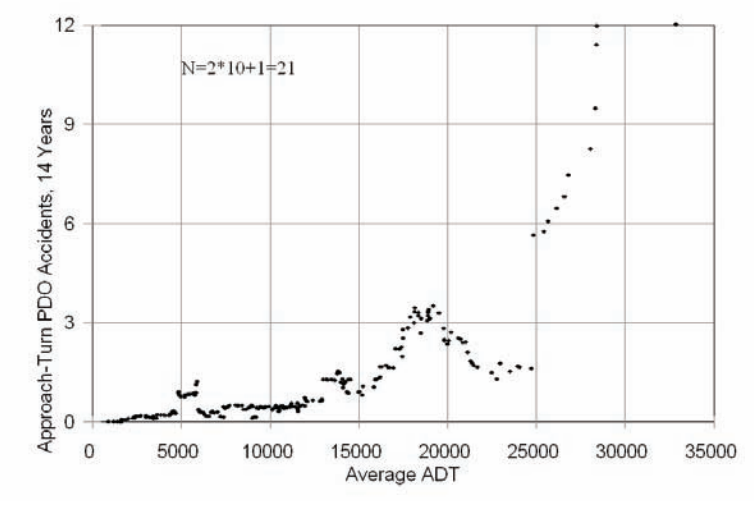

Figure 8. I-D (N=21) 3-legged, mainline, PDO accidents

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[1] The VB code "The Integrate Differentiate Method' store in the 'Programs' folder was used. The data for this program is store in the text folder with a name such as "ID 3Leg Mainline PDO.txt".

The functions $\beta_0 X^{\beta_1}$ and $\beta_0 X^{\beta_1} e^{\beta_2 X}$ in which X=ADT/10,000 are indicated by Figure 8.

6.2. Three Legged Intersections, Mainline Approaches 1 and 3, Injury and Fatal Accidents.

The I-D plot is in Figure 9.

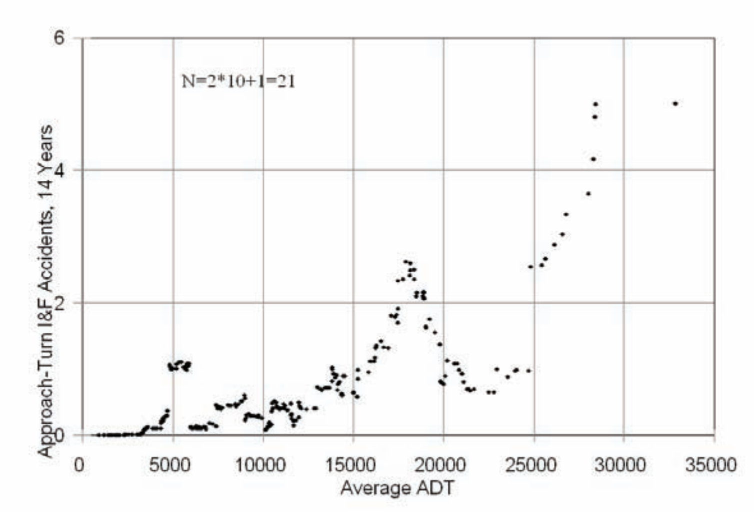

Figure 9. I-D (N=21) 3-legged, mainline, Injury and Fatal accidents

6.3. Three Legged Intersections, Non-Mainline Approaches 2 or 4, PDO Accidents.

Given that left-turn accidents on mainline approaches show a clear relationship with the average mainline ADT and assuming that there is a positive correlation between mainline ADTs and non-mainline ADTs, I expected to see a relationship between left-turn accidents on non-mainline approaches and the average mainline ADT. However, as is evident from Figure 10, for three-legged intersections, no clear relationship is indicated, perhaps because the number of accidents is so small (see Table 8).

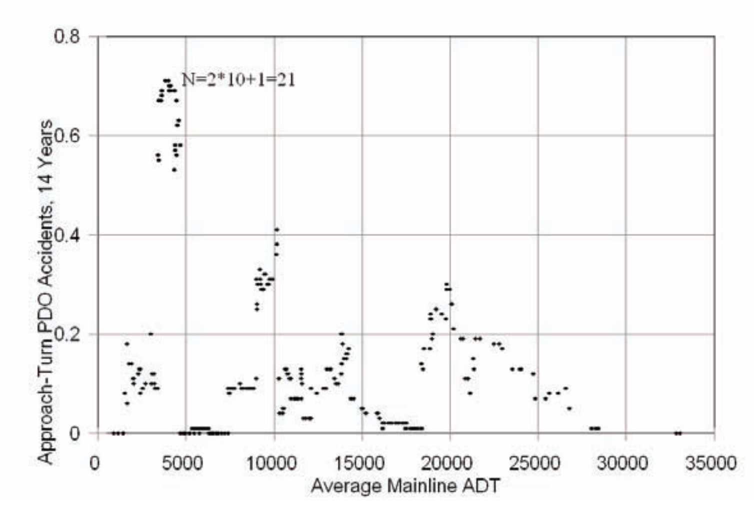

Figure 10. I-D (N=21) 3-legged, non-mainline, PDO accidents.

6.4. Three Legged Intersections, Non-Mainline Approaches 2 or 4, Injury and Fatal Accidents.

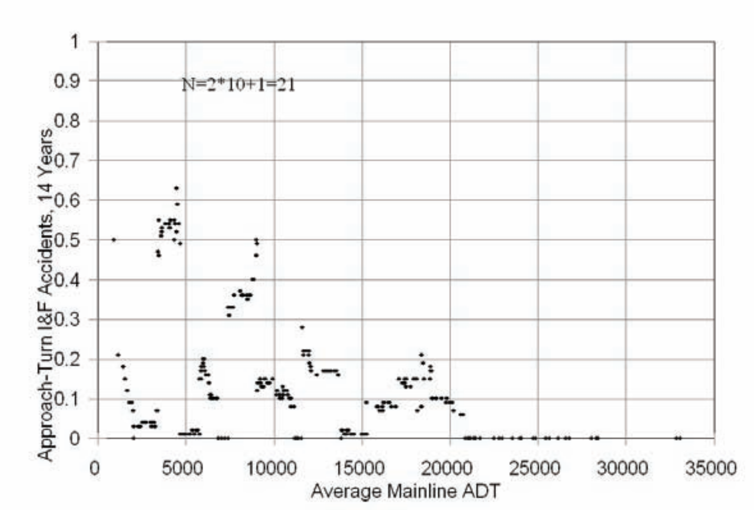

Figure 11. I-D (N=21) 3-legged, non-mainline, Injury and Fatal accidents.

The indication in Figure 10 and Figure 11 is the on the non-mainline approaches of three-legged intersections left-turn accidents are few and that their expected number is either not associated with the mainline ADT or is a decreasing function thereof.

6.5. Four Legged Intersections, Mainline Approaches 1 and 3, PDO Accidents.

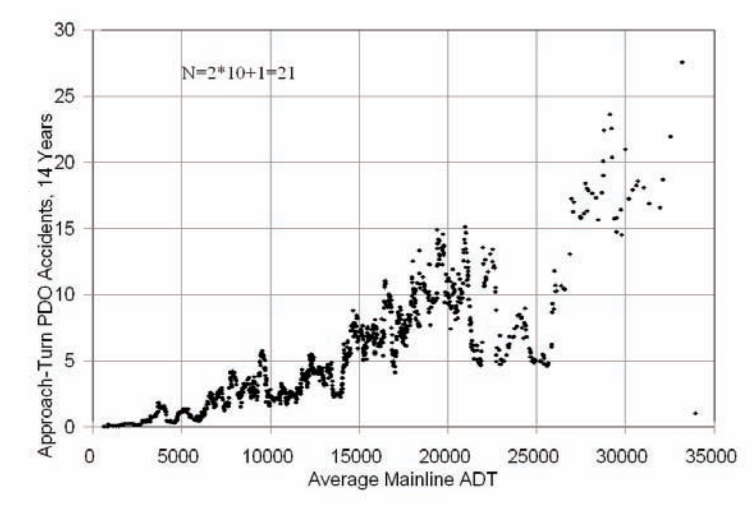

Figure 12. I-D (N=21) 4-legged, mainline, PDO accidents

6.6. Four Legged, Mainline Approaches 1 and 3, Injury and Fatal Accidents.

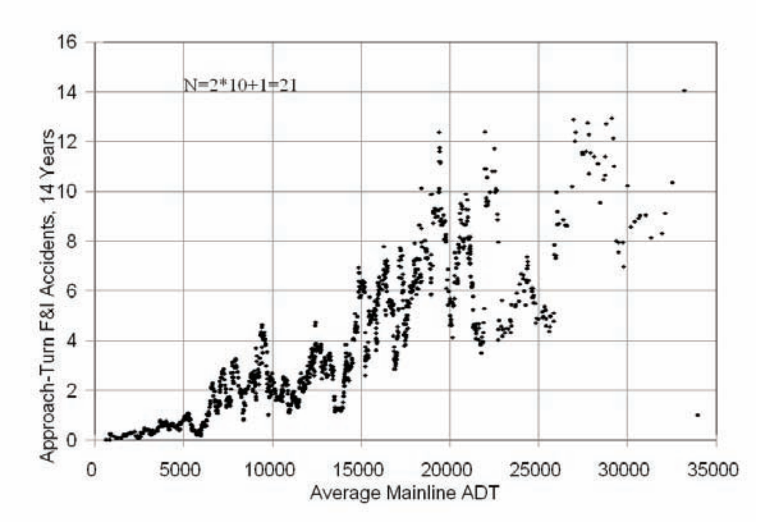

Figure 13. I-D (N=21) 4-legged, mainline, Injury & Fatal accidents

6.7. Four Legged, Non-Mainline Approaches 2 and 4, PDO Accidents.

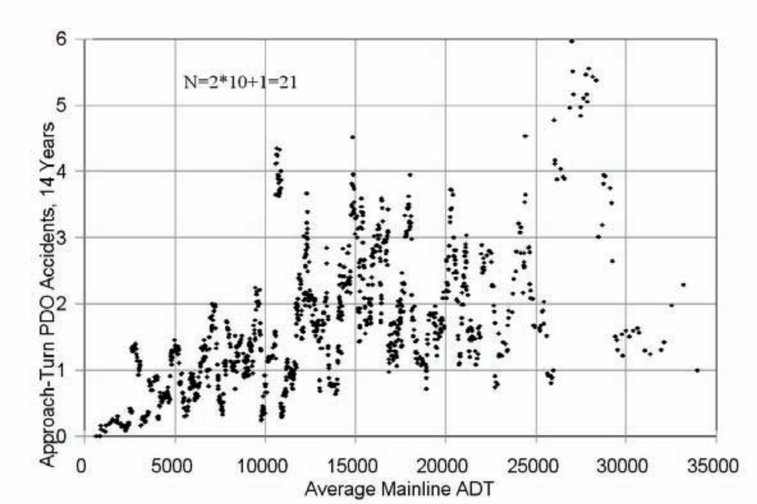

Figure 14. I-D (N=21) 4-legged, Non-mainline, PDO accidents

Unlike the non-mainline approaches at three-legged intersections, here there is a fairly clear relationship between the mainline ADT and left-turn accidents on the non-mainline approaches. Also unlike the three-legged intersections (where there were perhaps 0.2 accidents/approach in 14 years), on the non-mainline approaches of four legged intersections the number of left-turn accidents is substantial (perhaps ¼ of the left-turn accidents on the mainline approaches).

6.8. Four Legged, Non-Mainline Approaches 2 and 4, Injury and Fatal Accidents.

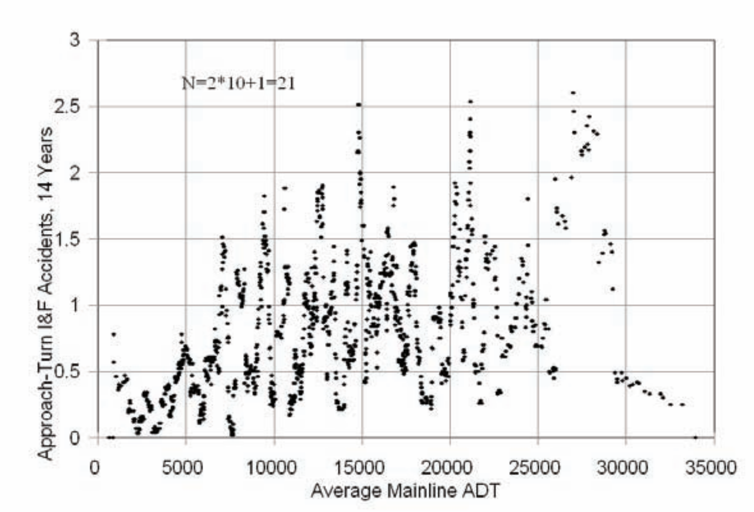

Figure 15. I-D (N=21) 4-legged, Non-mainline, Injury & Fatal accidents.

The relatively noisy relationships in Figure 14 and Figure 15 is probably due to the fact that the correlation between mainline a non-mainline ADTs is weak. Still, even the weak relationship can be used for modeling.

7. Models

Negative binomial models were estimated for the six intersection types and two alternative functional forms:

$$\text{Expected yearly left-turn accidents per approach} = \boldsymbol{\alpha}_y \mathbf{X}^{\beta_1}$$

Eqn. 3

$$\text{Expected yearly left-turn accidents per approach} = \boldsymbol{\alpha}_y \mathbf{X}^{\beta_1} \mathbf{e}^{\beta_2 \mathbf{X}}$$

Eqn. 4

where α_y is the multiplier for year y (=1,2,....,14), X is the mainline ADT for one approach, and β_1, β_2 are estimates of parameters. The estimated overdispersion parameter is φ.

Table 9. Estimated Model Parameters

	One β						Two βs					
	3Legs Mainline PDO	3Legs Mainline I&F	4 Legs Mainline PDO	4 Legs Mainline I&F	4 Legs Non-Mainline PDO	4 Legs Non-Mainline I&F	3Legs Mainline PDO	3Legs Mainline I&F	4 Legs Mainline PDO	4 Legs Mainline I&F	4 Legs Non-Mainline PDO	4 Legs Non-Mainline I&F
φ (overdispersion)	0.110	0.109	0.569	0.563	0.272	0.215	0.106	0.107	0.556	0.560	0.271	0.214
Average α	0.051	0.037	0.227	0.162	0.100	0.057	0.189	0.101	0.942	0.552	0.216	0.150
β_1	1.46	1.36	1.31	1.35	0.71	0.62	2.65	2.31	2.74	2.59	1.41	1.48
β_2							-1.084	-0.841	-1.217	-1.048	-0.643	-0.810
Log-likelihood	-1042	-932	-16609	-15340	-9364	-6605	-1040	-922	-16552	-15305	-9354	-6594
α_1	0.022	0.024	0.159	0.130	0.060	0.038	0.079	0.065	0.640	0.432	0.127	0.099
α_2	0.032	0.023	0.170	0.126	0.072	0.032	0.115	0.061	0.687	0.420	0.152	0.084
α_3	0.036	0.025	0.182	0.151	0.068	0.041	0.130	0.068	0.739	0.502	0.144	0.106
α_4	0.040	0.027	0.207	0.163	0.093	0.044	0.144	0.072	0.842	0.543	0.198	0.114
α_5	0.036	0.022	0.235	0.175	0.093	0.063	0.132	0.059	0.960	0.585	0.199	0.164
α_6	0.033	0.020	0.233	0.193	0.095	0.051	0.121	0.055	0.956	0.650	0.203	0.132
α_7	0.023	0.030	0.216	0.150	0.086	0.054	0.085	0.081	0.890	0.507	0.185	0.142
α_8	0.049	0.027	0.228	0.143	0.093	0.054	0.179	0.073	0.942	0.485	0.200	0.143
α_9	0.056	0.049	0.270	0.187	0.135	0.073	0.207	0.133	1.123	0.637	0.291	0.192
α_{10}	0.084	0.069	0.265	0.192	0.136	0.082	0.313	0.188	1.113	0.659	0.296	0.217
α_{11}	0.105	0.059	0.282	0.195	0.142	0.073	0.393	0.161	1.190	0.672	0.308	0.195
α_{12}	0.096	0.070	0.284	0.183	0.135	0.080	0.361	0.193	1.207	0.637	0.294	0.213
α_{13}	0.071	0.045	0.234	0.152	0.099	0.062	0.267	0.125	1.005	0.530	0.217	0.166
α_{14}	0.033	0.028	0.207	0.133	0.096	0.050	0.123	0.077	0.896	0.469	0.211	0.135

The two-β model have a somewhat larger log-likelihood and consistently exhibit a maximum as is illustrated in Figure 16. However, the two-β models also have consistently poorer cumulative residual (CURE) plots and illogical predictions in the high-ADT range where data is sparse. Therefore, for the six approach types in Table 9 the one-β models will be used.

For the non-mainline approaches of three-legged intersections the values in Table 10 will be used.

Table 10. Predictions and Overdispersion for Three-Legged Non-Mainline Approaches

	Prediction (accidents/year)	Φ
PDO	36/(14×273)=0.0094	0.155
Fatal & Injury	30/(14×273)=0.0078	0.077

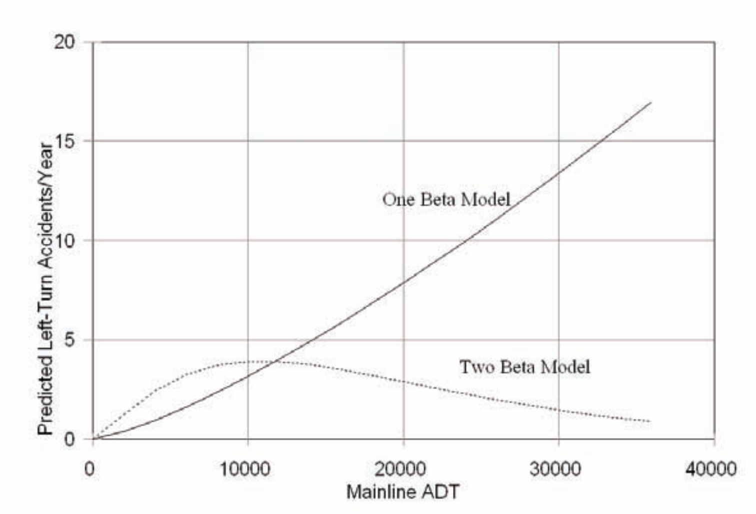

Figure 16. The difference between one and two β models for 4-legged, mainline approach PDO accidents.

Since it is not practical to estimate a separate model for fatal accidents, it will be assumed that the expected number of fatal accidents can be predicted by multiplying the expected number of fatal + injury accidents by a proportion. The proportions in the data are in Table 11.

Table 11

	Fatal	Injury	Ratios	Proportion Fatal	Proportion Injury
3 leg mainline	5	365	0.0137	0.0135	0.9865
4 leg mainline	81	8989	0.0090	0.0089	0.9911
Mainline	**86**	**9354**	**0.0092**	**0.0091**	**0.9909**
3 leg non-mainline	0	30	0.0000	0.0000	1.0000
4 leg non-mainline	8	2324	0.0034	0.0034	0.9966
Non-Mainline	**8**	**2354**	**0.0034**	**0.0034**	**0.9966**

It seems that the proportion of fatal accidents on mainline approaches is about three times that for non-mainline approaches. Therefore the following will be used:

Table 12

Model prediction for fatal accidents	Mainline Approaches	0.0091×Model Prediction for Injury & Fatal Accidents on Mainline Approaches
	Non-Mainline Approaches	0.0034×Model Prediction for Injury & Fatal Accidents on Non-Mainline Approaches
Model prediction for injury accidents	Mainline Approaches	0.9909×Model Prediction for Injury & Fatal Accidents on Mainline Approaches
	Non-Mainline Approaches	0.9966×Model Prediction for Injury & Fatal Accidents on Non-Mainline Approaches

8. Preparing EB Estimates of Expected PDO and Injury and Fatal Accident Frequencies.

The next task is to estimate the expected annual PDO, Injury and Fatal accident frequencies in 2003 (the last year of data) for each of the 1535 intersections. The method and notation in “Estimating Safety by the Empirical Bayes Method” (Hauer, Harwood, Council, Griffith in Transportation Research Record 1784, 126-131) will be used. The EB method specifies:

$$\begin{aligned}&\text{Estimate of Expected Accidents for an entity} =\\&\text{weight} \times \text{accidents expected on similar entities} +\\&(1 - \text{weight}) \times \text{count of accidents in this entity}\end{aligned}$$

Eqn. 5

and

$$weight = \frac{1}{1+\frac{\sum\limits_{year=First}^{year=Last}\mu_{year}}{\varphi}}$$

Eqn. 6

In these equations

μ_{year} is the number of accidents for expected on similar intersections in a certain year;
φ is the overdispersion parameter.

Numerical Example:

Intersection 91 (my numbering 90) is 4 legged. The example is for mainline approach 3.

Table 13. Computations

		1	**2**	**3**	**12**	**13**	**14**	*Sum*	Weight
1	ADT	8569	8709	8849	10114	10254	10395		
2	Prediction (I&F)	0.106	0.105	0.128	0.186	0.157	0.140		
3	Prediction Injury	0.105	0.104	0.127	0.184	0.155	0.139	*2.106*	0.211
4	Prediction Fatal	0.0010	0.0010	0.0012	0.0017	0.0014	0.0013	*0.0194*	0.967
5	Count Injury	1	1	0	2	3	0	*23*	
6	Count Fatal	0	0	0	0	0	0	*1*	
7	Expected Injury	0.93	0.92	1.12	1.63	1.37	**1.22**	*18.59*	
8	Expected Fatal	0.003	0.003	0.003	0.005	0.004	**0.0034**	*0.05*	

To compute the number of Injury + Fatal left-turn accidents predicted to occur in one year on a similar approach I used Eqn. 3 with $\varphi=0.535$, $\beta_1=1.35$, $\alpha_1=0.130$, $\alpha_2=0.126$, … from

Table 9. Thus, in year1, the predicted number is $0.130\times(8569/10{,}000)^{1.35}=0.106$ accidents/year. To compute the predicted number of injury and fatal accidents separately, the entries in row 2 were multiplied by 0.9909 and 0.0091 from Table 11. The accident counts at this site are in rows 5 and 6. The weights for injury and for fatal accidents (see Eqn. 6) are in the last column. Thus, for injury accidents, weight=1/(1+2.106/0.563)=0.211. Now, using Eqn. 5, the expected number of injury accidents in the 14 years is 2.106×0.211+23×(1-0.211)=18.59. The number expected in year 14 is 18.59×(0.139/2.106)=1.22 accidents.

This procedure was coded in Visual Basic under the command button the caption of which is “Estimate Expected Accidents by EB” in the “Left Turn Data and Analysis” VB project. The output for the first five intersections and their approaches is in Table 14.

Table 14. EB Estimates and EPDO.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1	1	3	1	0.028409	0.030145	0.000054	0.198933
1	1	3	5	0.005089	0.003229	0.000027	0.026549
1	1	3	3	0.002815	0.002963	0.000054	0.027098
1	1	3	4	0.005089	0.003229	0.000027	0.026549
2	2	3	1	0.001938	0.002153	0.000056	0.022111
2	2	3	5	0.005089	0.003229	0.000027	0.026549
2	2	3	3	0.001938	0.002153	0.000056	0.022111
2	2	3	4	0.005089	0.003229	0.000027	0.026549
3	3	3	1	0.003343	0.003556	0.000081	0.034965
3	3	3	5	0.005089	0.003229	0.000027	0.026549
3	3	3	3	0.003343	0.003556	0.000081	0.034965
3	3	3	4	0.005089	0.003229	0.000027	0.026549
4	4	3	1	0.004844	0.005179	0.000159	0.057142
4	4	3	5	0.005089	0.003229	0.000027	0.026549
4	4	3	3	0.048879	0.052688	0.000159	0.356780
4	4	3	4	0.005089	0.003229	0.000027	0.026549
5	5	3	1	0.001982	0.002076	0.000029	0.017656
5	5	3	5	0.005089	0.003229	0.000027	0.026549
5	5	3	3	0.001982	0.002076	0.000029	0.017656
5	5	3	4	0.005089	0.003229	0.000027	0.026549

The EPDO accidents in the last column were computed using $6,500, $35,000 and $1,000,000 for PDO, Injury and Fatal accidents giving weights of 1, 5.38 and 153.84. The twenty approaches with the highest EPDO are in Table 15. The full table is in Spreadsheets\EB Estimates.wb3.

Table 15. Twenty Approaches with Largest EPDO in Last Year.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1071	1089	4	1	5.50	3.83	0.0028	26.52
1407	1425	4	1	4.46	3.78	0.0040	25.40
1403	1421	4	1	4.97	3.09	0.0047	22.32
1485	1503	4	1	5.25	2.86	0.0053	21.46
298	303	4	1	3.49	2.71	0.0025	18.48
297	302	4	3	3.62	2.56	0.0031	17.90
1534	1552	4	3	4.45	2.40	0.0030	17.84
1378	1396	4	1	4.49	2.32	0.0048	17.74
831	848	4	1	3.37	2.40	0.0032	16.80
1096	1114	4	3	4.95	1.96	0.0028	15.92
1503	1521	4	3	2.63	2.28	0.0043	15.54
1390	1408	4	3	3.33	2.12	0.0040	15.33
1466	1484	4	1	2.64	2.09	0.0094	15.32
1435	1453	4	1	4.29	1.94	0.0027	15.16
1434	1452	4	1	3.91	2.00	0.0031	15.16
358	374	4	3	2.83	2.18	0.0037	15.13
1531	1549	4	3	3.65	1.61	0.0150	14.63
1118	1136	4	3	2.29	2.07	0.0030	13.89
666	683	4	1	1.40	2.01	0.0098	13.72
1449	1467	4	1	1.83	2.10	0.0036	13.67

9. Estimating Added Delay.

The approach to the estimation of added delay using the Brondum-Martin equations was described in Working paper 1 (07/03/2005). The equation is:

$$D = \beta_1 (V_L + K)^1 + \beta_2 (V_L + K)^2 + \ldots + \beta_{n-1} (V_L + K)^{n-1} + \beta_n (V_L + K)^n + M$$

$$K = \alpha_0 + \alpha_1 V_T + \alpha_2 {V_T}^2 + \alpha_3 {V_T}^3$$

Eqn. 7

In this, D=Delay in seconds/vehicle, V_L=left-turn volume in vehicles/hour, M=vertical shift, K=horizontal shift as a function of the opposing volume V_T in vehicles/hour, n the degree of the polynomial, usually 4 and α_0 to α_3, β_0 to β_n and M are the estimated regression coefficients.

Table 16. Regression coefficients for 'Overall Delay' and 'Optimal Cycle Length'.

Phasing	M	α_0	α_1	α_2	α_3	β_1	β_2	β_3	β_4
One Opposing Lane									
Protected	5.970	-47.56	0.887	0	0	8.74E-03	8.26E-05	-2.71E-07	4.40E-10
Permitted	2.381	-169.20	2.009	-2.19E-03	9.49E-07	-1.60E-02	1.86E-04	-6.23E-07	9.23E-10
Two Opposing Lanes									
Protected	4.586	-180.10	1.874	-2.22E-03	9.35E-07	-5.58E-03	1.83E-04	-4.63E-07	5.78E-09

Permitted	2.754	-90.66	1.245	-1.08E-03	3.96E-07	-2.41E-02	2.41E-04	-7.53E-07	9.57E-10
Three Opposing Lanes									
Protected	4.586	-180.10	1.874	-2.22E-03	9.35E-07	-5.58E-03	1.63E-04	-4.63E-07	5.78E-10
Permitted	1.963	-83.00	1.159	-1.09E-03	4.62E-07	-1.83E-02	2.04E-04	-6.71E-07	9.11E-10

In developing the equation and its regression coefficients "*A standard geometry is* (was*) used for each of the modeled intersections. All modeled intersections are (*were) *symmetric with an equal number of through lanes, one left-turn lane, and one right-turn lane. By having individual left- and right-turn lanes, additional delay caused by share lanes is avoided. Delays are calculated for one, two, and three opposing through lanes."* (E. Brondum, P. T. Martin 1997). As a result the predicted D pertains directly only to such intersections.

Suppose now that one wishes to estimate the added delay due to conversion from unprotected to protected phasing on the mainline approaches at a three-legged intersection with two-lanes on the mainline approaches and one lane on the non-mainline approaches. The situation differs from that for which Brondum & Martin estimated D in several respects. First, the standard geometry was for a symmetric intersection which, I assume, had four legs. A three-leg intersection is likely to have a somewhat different (lesser) delay. Second, non-mainline approaches usually serve lesser volumes and often have fewer lanes than mainline approaches. It is not clear whether the volume-to-capacity ratio on non-mainline approaches is larger or lesser than that on the mainline approaches. However, since neither the ADT nor the number of non-mainline approaches is known, volume-to-capacity ratios on non-mainline approaches cannot be computed. Third, non-mainline approaches tend to have fewer and less severe left-turn accidents than mainline approaches[1]. As a result, the introduction of left-turn protection will be often justified on the mainline approaches and not justified on the non-mainline approaches of the same intersection. However, the Brondum-Martin D in is computed under the assumption the all approaches either do or do not have left-turn protection. Fourth, while the left-turn volume (V_L) is needed to compute D by Eqn. 7, it is not generally in electronically available databases; it will have to be assumed. For all these reasons the estimated values of D will be less than precise. Whether they are sufficiently precise for the purpose of developing a sensible list of ranked sites will be ascertained by a field study.

9.1 Assumptions

The following assumptions will be made:

1. The D for three and four legged intersections will be estimated by the same equation
2. Since the number of lanes for non-mainline approaches is not known it will be assumed to be the same as the smaller number of the lanes of the two mainline approaches.
3. Define:
   R_{LT}=Non-Mainline/Mainline EB estimated accidents per approach
   R_{ADT}=Non-mainline/Mainline ADT per approach
   N=EB estimated mainline left turn accidents in 14 years.
   To compute the non-mainline ADT the rules of Table 17 will be used.

Table 17. Values of R_{ADT} as a function of N and R_{LT}

if N	and	then R_{ADT}

---

[1] Of the 100 approaches with most expected left-turn accidents 92 are mainline.

<=10		0.7
>10	$R_{LT}<0.25$	0.25
	$0.25<R_{LT}<1.50$	R_{LT}
	$1.50<R_{LT}$	1.50

Typical results for ten intersections are in Table 18.

Table 18. Typical Non-Mainline ADT Estimates

Intersection Number		Number of Legs	Expected Accidents				Estimated ADT	
Consecutive	Original		Approach 1	Approach 3	Approach 2	Approach 4	Mainline	Non-Mainline
1	1	3	0.059	0.006		0.008	3227.5	2259.3
2	2	3	0.004	0.004		0.008	3316.9	2321.8
3	3	3	0.007	0.007		0.008	4358.0	3050.6
4	4	3	0.010	0.102		0.008	7179.8	5025.9
5	5	3	0.004	0.004		0.008	2045.5	1431.9
893	911	4	0.258	0.068	0.195	0.028	10992.1	7694.5
894	912	4	0.252	0.190	0.028	0.089	11897.2	8328.0
895	913	4	0.477	0.188	0.141	0.028	12506.7	8754.7
896	914	4	0.907	0.114	0.401	0.078	11145.4	5235.0
897	915	4	0.058	0.058	0.026	0.026	9156.5	6409.6

Examples:

a. At the three-legged intersection #1 the mainline ADT is 3227.5. For this intersection we estimated for the last year 0.059 and 0.006 left-turn accidents on the mainline approaches 1 and 3 and 0.008 on the non-mainline approach 4. N is approximately 14×(0.059+0.006)=0.91. Since this is less than 10, R_{ADT}=0.7 and Non-mainline ADT =0.7×3227.5=2259.3.

b. At the four-legged intersection #914 the mainline ADT is 11,145.4. For this intersection we estimated for the last year 0.907 and 0.114 left-turn accidents on the mainline approaches 1 and 3 and 0.401 and 0.078 on the non-mainline approaches 2 and 4. N is approximately 14×(0.907+0.114)=14.29 which is larger than 10. R_{LT}=(0.401+0.078)/ (0.907+0.114)=0.4697. Because 0.25<0.4697<1.5, R_{ADT}=0.4697. Now Non-mainline ADT =0.4697×11,145.4=5235.

4. Since approaches are considered one by one the amount of added delay due to changing the phasing from permitted to protected on one of the approaches (instead of all four as in the Brondum-Martin equation) will be D where phasing was changed and 0 on other approaches. (This is equivalent to assuming that the protection could be accommodated without changes in cycle and green time.)
5. Left turn volumes are 15% of the approach volumes.

6. The added delay due to changing the phasing from permitted to protected for the non-mainline approach of a three-legged intersection is that for one opposing lane when V_T=0. Selected values are in Table 19.

Table 19

V_L in vph	$D_{Protected}$ in sec../vehicle	$D_{Permitted}$ in sec./vehicle	Difference sec./vehicle
100	7.4	2.1	5.3

200	9.6	3.1	6.4
300	12.3	5.0	7.3
400	16.6	9.5	7.1
500	24.6	20.7	3.9

7. The approximation embodied by the estimation equation and its regression coefficients should not be used for either very small or very large volumes. At very small volumes D is sometimes larger than at larger volumes. Therefore, for $V_T<100$ vph I use the D computed at $V_T=100$ vph and $V_L=15$ vph. At the other extreme, when $D_{Protected}$ as calculated by Eqn. 7 >60 sec. and $D_{Permitted}$ as calculated by Eqn. 7>70 sec. then $D_{Protected}=$ 60 sec. and $D_{Permitted}=70$.

9.2 Hourly Volumes

The data contain information about average daily (24-hour) traffic volumes. The estimation of D requires hourly volumes. Based on data from 20 urban and 54 rural count station obtained on Wednesday, August 7, 2002, the average proportions in Table 20 were obtained. Since the urban and rural hourly profiles are similar (Figure 17), their average (last column in Table 20) will be used.

Table 20. Typical Hourly Proportions of ADT

Hour	Urban	Rural	Average
1	0.0089	0.0074	0.0081
2	0.0060	0.0056	0.0058
3	0.0048	0.0051	0.0050
4	0.0039	0.0047	0.0043
5	0.0069	0.0074	0.0072
6	0.0222	0.0159	0.0190
7	0.0490	0.0348	0.0419
8	0.0643	0.0518	0.0580
9	0.0595	0.0550	0.0573
10	0.0563	0.0617	0.0590
11	0.0538	0.0644	0.0591
12	0.0560	0.0653	0.0607
13	0.0560	0.0658	0.0609
14	0.0590	0.0678	0.0634
15	0.0620	0.0710	0.0665
16	0.0708	0.0742	0.0725
17	0.0761	0.0779	0.0770
18	0.0760	0.0751	0.0755
19	0.0615	0.0565	0.0590
20	0.0439	0.0418	0.0429
21	0.0340	0.0329	0.0335
22	0.0307	0.0273	0.0290
23	0.0236	0.0187	0.0211
24	0.0149	0.0119	0.0134

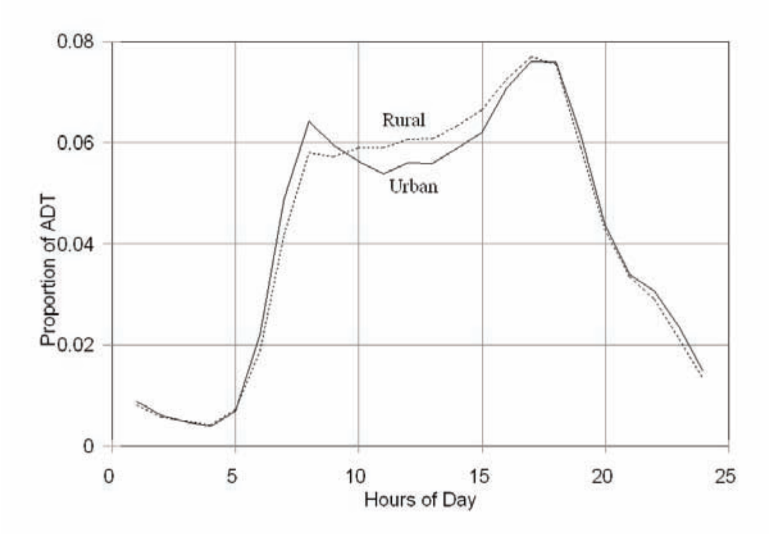

Figure 17. Proportions from Table 20.

9.3 The Code.

The code is in a Visual Basic program file saved as “Left Turn Data and Analysis” and placed under CmdDelay (Command button 9).

All required data are in comma-delimited text files which are opened in response to requests by message boxes. The Brondum-Martin regression constants[1] are in 'Brondum Regression Constants for Computation' text file[2]. The hourly proportions[3] are in the 'Hourly Proportions' text file[4]. After these are read and stored in memory, the loop over the 1535 intersections begins.

For intersection after intersection a record is read from the ADT file (the ‘Filled ADT Data for 1535 Intersections' text file’)[5]. Similarly for intersection after intersection and every approach the EB estimates of expected accidents in the 14-th year[6] are read from the 'EB Estimates' text file’[7]

The next step in the code (Step 6) is to compute the non-mainline ADT for intersection after intersection in accord with the assumptions and rules described earlier[8]. Delay for each of four approaches of intersection after intersection is computed in Step 7 of the code. This is done

---

[1] See Table 16.

[2] First a line of text and then six lines with: Phasing, OppLanes, M(I), Alpha(I, 0), Alpha(I, 1), Alpha(I, 2), Alpha(I, 3), Beta(I, 1), Beta(I, 2), Beta(I, 3), Beta(I, 4).

[3] See Table 20

[4] First a line of text and then 24 lines: Hr, HourlyProportion(I).

[5] There are 1535 records, each record consisting of: Inter, Intersection1, EstAdt(1), EstAdt(2), EstAdt(3), EstAdt(4), EstAdt(5), EstAdt(6), EstAdt(7), EstAdt(8), EstAdt(9), EstAdt(10), EstAdt(11), EstAdt(12), EstAdt(13), EstAdt(14).

[6] Table 14.

[7] I, Intersection2, Legs, Approach(J), Lanes(J), EstPDO(J), EstInj(J), EstFat(J), EPDO

[8] See Table 17.

separately for the mainline approaches (1 and 3), non-mainline approaches 2 and 4 for four legged intersections, and 2 or 4 for three legged intersections. Delay is computed for each of 24 hours of a day. The summed result for each approach is written into a comma-separated text file as the record:

> Approach Number, Number of Approach Lanes, Mainline Adt, Non-Mainline Adt, Expected Approach Accidents 14-th, Daily Delay [in seconds] if phasing=Protected in 14-th year, Daily delay if phasing='Permitted', Added Daily Delay in 14-th year [in seconds].

10. Results.

Sample results are in Table 21. The full table is on the first page of : "…Spreadsheets\ Results.wb3" and consists of 6140 approaches.

Table 21. Results for all 1535 intersections

Intersection (Consecutive Numbering)	Original Numbering	Approach Number	Approach Lanes	Mainline ADT	Non-Mainline ADT	Expected Accidents in 14-th year	Daily Delay in 14-th year [seconds]		
							Protected	Permitted	Added= Protected-Permitted
1	1	1	1	3228	2259	0.059	27204.8	9121.8	18083
1	1	5	0	3228	2259	0	0	0	0
1	1	3	1	3228	2259	0.006	27204.8	9121.8	18083
1	1	4	0	3228	2259	0.008	16570	4774.5	11795.5
2	2	1	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	5	0	3317	2322	0	0	0	0
2	2	3	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	4	0	3317	2322	0.008	17173.3	4980.9	12192.3
3	3	1	1	4358	3051	0.007	43451.1	18196.8	25254.2
3	3	5	0	4358	3051	0	0	0	0
3	3	3	1	4358	3051	0.007	43451.1	18196.8	25254.2
3	3	4	0	4358	3051	0.008	25057.3	8144.5	16912.8
4	4	1	1	7180	5026	0.01	123099.4	89364.9	33734.4
4	4	5	0	7180	5026	0	0	0	0
…	…	…	…	…	…	…	…	…	…

I noted in Working Paper 1 that the Brondum-Martin delay estimation equations predict that for high left-turn volumes the protected phasing is associated with lesser delay than the permitted phasing. If this is so then, when and where this is true, protected phasing is beneficial to both delay and to safety. For this reason, I produced separate tables for the approaches where the Added Delay (Last column of the table) is positive (i.e., approaches where conversion from permitted to protected phasing increases delay) and where it is negative (i.e. where conversion from permitted to protected phasing promises to decrease delay. There are 974 such approaches). Sample results are in Table 22 and Table 23. The full tables are on pages 2 and 3 of "…Spreadsheets\Results.wb3".

Table 22. Results for approaches where conversion from permitted to protected phasing is expected to increase delay.

Intersection (Consecutive Numbering)	Original Numbering	Approach Number	Approach Lanes	Mainline ADT	Non-Mainline ADT	Expected Accidents in 14-th year	Daily Delay in 14-th year [seconds]		
							Protected	Permitted	Added= Protected-Permitted
1	1	1	1	3228	2259	0.059	27204.8	9121.8	18083
1	1	3	1	3228	2259	0.006	27204.8	9121.8	18083
1	1	4	0	3228	2259	0.008	16570	4774.5	11795.5
2	2	1	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	3	1	3317	2322	0.004	28325.3	9652.3	18673.1
2	2	4	0	3317	2322	0.008	17173.3	4980.9	12192.3
3	3	1	1	4358	3051	0.007	43451.1	18196.8	25254.2
3	3	3	1	4358	3051	0.007	43451.1	18196.8	25254.2
3	3	4	0	4358	3051	0.008	25057.3	8144.5	16912.8
4	4	1	1	7180	5026	0.01	123099.4	89364.9	33734.4
…	…	…	…	…	…	…	…	…	…

Table 23. Results for approached where conversion from permitted to protected phasing is expected to decrease delay.

Intersection (Consecutive Numbering)	Original Numbering	Approach Number	Approach Lanes	Mainline ADT	Non-Mainline ADT	Expected Accidents in 14-th year	Daily Delay in 14-th year [seconds]		
							Protected	Permitted	Added= Protected-Permitted
63	63	1	1	24226	16958	0.193	1360959.2	1549482.7	-188523.4
63	63	3	1	24226	16958	0.014	1360959.2	1549482.7	-188523.4
63	63	4	0	24226	16958	0.008	910029.3	1008042.3	-98013
121	124	1	2	23027	16119	0.379	1335719.4	1350009.9	-14290.5
121	124	3	2	23027	16119	0.295	1335719.4	1350009.9	-14290.5
123	126	1	2	22985	16090	0.106	1333189.7	1346950.2	-13760.5
123	126	3	2	22985	16090	0.011	1333189.7	1346950.2	-13760.5
194	197	1	2	22062	15443	0.122	1278157.8	1281430.4	-3272.7
194	197	3	2	22062	15443	0.184	1278157.8	1281430.4	-3272.7
195	198	1	2	29564	20695	0.07	1728164.3	1847412.4	-119248.1
…	…	…	…	…	…	…	…	…	…

10.1 Ranking Approaches Where a Reduction in Delay May Be Expected.

Since protected phasing on approaches in Table 23 seems to benefit both safety and delay, they should perhaps be ranked separately. The expected accidents and the delay savings given in the file from which Table 22 was extracted are shown in Figure 18. In principle, all these approaches merit attention as long as the potential of delay savings + accident savings exceeds the cost of the engineering study + cost of controller changes + cost of signal head changes. However, in reality, one has to decide on a sensible order of priority.

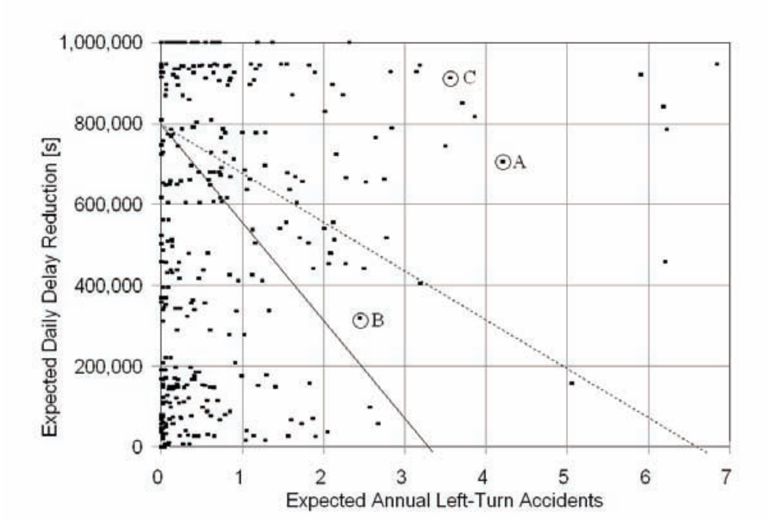

Figure 18. Left-turn accidents and savings in delay

I do not place much trust in the very large estimates of potential delay savings. These are usually associated with large ADTs and may be in error for a variety of reasons - the Brondum-Martin equations may not apply when the volume-to-capacity ratios are close to 1; the assumptions about the proportion of left-turning traffic may be out of whack etc. Still, I will assume that the estimated delay reductions are well correlated with what really happens. This assumption may have a large effect on ranking and therefore a part of the follow-up study should entail its examination.

It is clear that the approach shown as ‘A’ offers more benefits than the approach marked ‘B’ both delay and in accident reduction. Therefore A should receive attention before ‘B’. This kind of ‘dominance’ consideration does not allow us to decide whether A should be considered before C. To develop the necessary criterion for priority setting, consider an approach where 9.43 accidents are expected but no delay reduction. A 9.43 expected frequency of left-turn accidents and a 70% reduction in left-turn accidents due to conversion from permitted to protected phasing promises a reduction of 6.6 accidents per year. Consider also another approach with no expected left-turn accident savings but an accumulated delay reduction of 800,000 seconds due to conversion from ‘permitted’ to ‘protected’ phasing. If these two potential benefits are deemed equivalent then all outcomes on the dashed line joining these two points have the same potential benefit; all points above that line have a larger potential benefit and all point below that line have a smaller benefit. Imagine a line that is parallel the dashed line and going through A. Since C is above that line, its potential benefits are larger and should be considered before A.

The same principle can be described algebraically. Suppose that a delay reduction of 800,000 seconds/day is deemed equivalent to a reduction of 6.6 left-turn accidents/year (which obtains on approaches with 9.43 expected left-turn accidents/year.) If so, (Equivalency Constant)×800,000=6.6. Thus, if the X and Y coordinates in Figure 18 correspond to the “expected left-turn accidents/year” and “estimated delay reduction/day”, the benefit associated with some X and Y is Benefit=X+Y×6.6/800,000. The value of “Benefit” will serve to rank approaches. Naturally, the magnitude of the benefit depends on the Equivalency Constant (EC) used. I will examine below the sensitivity of the ranking to choice of the equivalency factor. Using EC=2/800,000, the 10 top ranked approaches (out of more than 900) are in Table 24.

Table 24. Top Ten Approaches at which both Accidents and Delay may Decrease

Rank	Intersection No.	Original Intersection No.	Approach	Mainline Adt	Non-Mainline Adt	Expected Approach Accidents/year	Added Seconds of Delay per Day	Benefit when EC=8.25E-06
1	1485	1503	1	33203	10223	8.121	-296960.9	10.57
2	1407	1425	1	26298	6574	8.239	-235582.7	10.18
3	1403	1421	1	30072	7518	8.063	-251206.5	10.14
4	1378	1396	1	31008	7752	6.823	-263691.4	9.00
5	1435	1453	1	19570	4893	6.232	-249080.3	8.29
6	1534	1552	3	20874	5218	6.853	-171787.7	8.27
7	1531	1549	3	34441	8610	5.279	-318187	7.90
8	298	303	1	17977	4494	6.211	-187982.6	7.76
9	1373	1391	3	30899	10570	5.579	-262183.5	7.74
10	1531	1549	1	34441	8610	5.08	-318187	7.71

How the ranking of approaches depends on the assumed EC can be gleaned from Table 25 in which both the double and the half of the EC in Table 24 was used to compute then benefit and then rank.

Table 25. Sensitivity of ranking to the assumed Equivalency Constant in top 25 approaches

Original Intersection No.		Rank	
	EC=6.6/800,000	EC=2×6.6/800,000	EC=0.5×6.6/800,000
1503	1	1	1
1425	2	3	2
1421	3	2	3
1396	4	4	4
1453	5	6	6
1552	6	9	5
1549	7	5	10
303	8	11	7
1391	9	8	9
1549	10	7	13
302	11	14	8
1408	12	10	12
1452	13	15	11
1521	14	13	14
374	15	16	15
1551	16	12	21
1385	17	23	17
1362	18	17	20
1484	19	31	18
1484	20	34	19
1393	21	19	22
1368	22	21	26
1425	23	22	25
848	24	98	16
1408	25	36	24

Thus, intersection #302 which ranked 11 when EC=6.6/800,000 would rank 14 if EC was twice as large and 8 if EC was 3.3/800,000.

10.2 Ranking Approaches Where an Increase in Delay May be Expected.

The expected accidents and the delay increases given in the file from which Table 23 was extracted are shown in Figure 19.

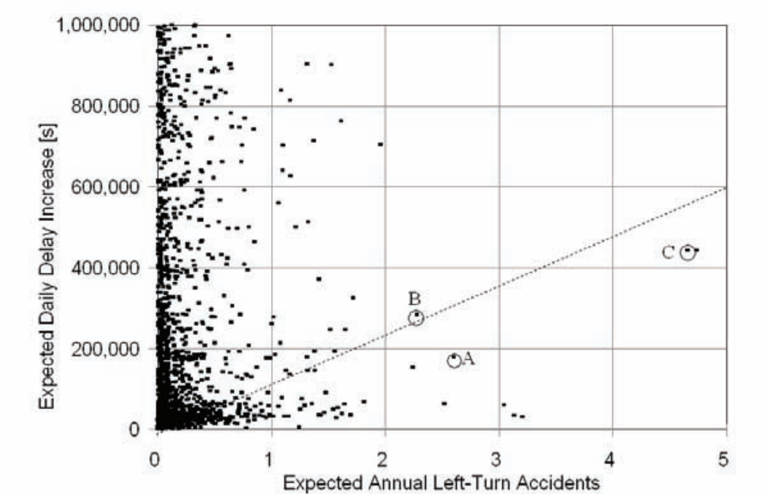

Figure 19. Left-turn accidents and increases in delay

It is clear that the approach shown as ‘A’ is more attractive than the approach marked ‘B’ since it promises a larger accident reduction and a lesser increase in delay. Therefore A should receive attention before ‘B’. This kind of ‘dominance’ consideration does not allow us to decide whether A should be considered before C. To allow the determination of priority in such cases, as before, I will use the notion of an Equivalency Constant. Consider, e.g., an Equivalency Constant of 6.6/800,000. This is the same as 4.95/600,000 shown by the slope of the dashed line in Figure 19. With this EC the approaches on the dashed line represent Benefit=0; those above the line amount to a net loss and those below the dashed line represent a positive benefit. Since a line of constant (positive) benefit from the origin to point C passes above point A, approach A should be considered before approach C.

As before, the same principle can be described algebraically. Suppose that a delay increase of 800,000 seconds/day is deemed equivalent to a reduction of two left-turn accidents/year (which obtains on approaches with 6.6 expected left-turn accidents/year.) If so, (Equivalency Constant)×800,000=6.6. Thus, if the X and Y coordinates in Figure 19 correspond the “expected left-turn accidents/year” and “estimated delay increase/day”, the benefit associated with some X and Y is Benefit=X-Y×6.6/800,000. The value of “Benefit” will serve to rank approaches. Naturally, the magnitude of the benefit depends on the EC used. I will examine below the sensitivity of the ranking to choice of the equivalency factor. Using EC=6.6/800,000, the 10 top ranked approaches are in Table 26. Out of 4915 approaches where the conversion to protected phasing is expected to increase delay, using EC=6.6/800,000, there are only about 500 approaches where a non-negative benefit may be expected.

Table 26. Top Ten Approaches at which Accidents are Expected to Diminish but Delay to Increase

Rank	Intersection No.	Original Intersection No.	Approach	Mainline Adt	Non-Mainline Adt	Expected Approach Accidents/year	Seconds of Added Delay per Day	Benefit when EC=8.25E-06
1	1071	1089	1	19887	4972	9.332	18199	9.18
2	1096	1114	3	19585	4896	6.915	28714.1	6.68
3	1118	1136	3	20766	5192	4.361	8411.7	4.29
4	1314	1332	1	20723	5181	3.712	8750.2	3.64
5	1249	1267	3	17154	4289	5.237	217911.3	3.44
6	938	956	1	19356	14392	3.742	44474	3.38
7	1118	1136	1	20766	5192	3.382	8411.7	3.31
8	934	952	3	16734	4183	5.028	247014.4	2.99
9	938	956	3	19356	14392	3.322	44474	2.96
10	604	621	4	10875	6748	3.209	32760.2	2.94

How the ranking of approaches depends on the assumed EC can be gleaned from Table 27. Sensitivity of ranking to the assumed Equivalency Constant in top 25 approaches in Table 27 in which both the double and the half of the EC in Table 26 was used to computed benefit and then rank.

Table 27. Sensitivity of ranking to the assumed Equivalency Constant in top 25 approaches

Original Intersection No.	Rank		
	EC=6.6/800,000	EC=2×6.6/800,000	EC=0.5×6.6/800,000
1089	1	1	1
1114	2	2	2
1136	3	3	4
1332	4	4	7
1267	5	31	3
956	6	6	8
1136	7	5	10
952	8	66	5
956	9	10	12
621	10	9	14
1227	11	8	17
1265	12	7	19
851	13	15	15
857	14	32	9
1133	15	11	21
833	16	139	6
1449	17	21	20
1231	18	13	24
302	19	12	25
858	20	38	18
1137	21	14	26
1370	22	20	28
1328	23	22	27
1047	24	16	32
1338	25	17	34

As expected, sites where conversion to protected phasing is expected to reduce delay tend to have a higher expected benefit (compare Table 24 and Table 26) and should usually be considered first.

10.3 Ranking of All Approaches

The notion of EC allows the joint ranking of all approaches by the expected benefit. Of the 5857 approaches considered (file ….\Spreadsheets\Results and Ranking) more than 1400 have non-negative benefit when EC=6.6/800,000. The top ten approaches are in Table 28.

Table 28. Top Ten Approaches with Most Benefit

Rank	Intersection No.	Original Intersection No.	Approach	Mainline Adt	Non-Mainline Adt	Expected Approach Accidents/year	Seconds of Added Delay per Day	Benefit when EC=8.25E-06
1	1485	1503	1	33203	10223	8.121	-296960.9	10.57
2	1407	1425	1	26298	6574	8.239	-235582.7	10.18
3	1403	1421	1	30072	7518	8.063	-251206.5	10.14
4	1071	1089	1	19887	4972	9.332	18199	9.18
5	1378	1396	1	31008	7752	6.823	-263691.4	9.00
6	1435	1453	1	19570	4893	6.232	-249080.3	8.29
7	1534	1552	3	20874	5218	6.853	-171787.7	8.27
8	1531	1549	3	34441	8610	5.279	-318187	7.90
9	298	303	1	17977	4494	6.211	-187982.6	7.76
10	1373	1391	3	30899	10570	5.579	-262183.5	7.74

Note that out of these ten top ranked approaches only one (approach 1 of intersection 1089) is where delay is expected to increase; at the other nine approaches conversion to protected phasing is predicted to decrease delay.

11. Summary and Suggestions for Field Validation.

The aim was to identify approaches to signalized intersections where conversion from permitted to protected left-turn phasing promises to be of benefit. The task had to be accomplished with the limitation that only electronically available information could be used. I based the ranking on two considerations. One was the expectation of a 70% reduction in left-turn accidents; the other was an estimate of the change in delay that would come from the retiming of the signal. While the expected accident reduction could be reasonably well estimated by the EB method on the basis of models and accident history, the change in delay is likely to be only a crude approximation. The reason is in that some important data are not available (e.g., number of approach lanes and traffic volume on non-mainline approaches), that use was made of approximating equations which produce bad estimates at low and at high volumes, and in that a the multitude of assumptions made to cover for the absence of information (e.g., that we do not know whether an approach does or does not have a protected left-turn phase). The question is whether the resulting ranking is good enough to lead engineers to sites where a change to protected phasing will be of benefit or whether the ranking provided here is so imperfect that a more effective screening method should be sought. This question can be answered by the conduct of a field study.

Our ranking may fail for a variety of reasons. First, the information on which the ranking is based (number of approaches, number of lanes, ADT, etc.) may be inaccurate. A field examination of these elements is in order. Second, the method used to estimate delay may produce such bad estimates as to impair the ranking instead of improving it. This too can be determined on the basis of data collected in the field and subjected to subsequent analysis. The yardstick by which to determine success or failure of the method is whether the ranking of sites would change substantially if correct information was used. That is, whether approached now near the top of the ranking would rank substantially lower if correct information and accurate delay estimation was used and conversely, if approaches now ranked low would show up near the top of the list.

In our preliminary discussions we spoke of conducting a field study at about 30 intersections. My suggestion is to take the 10 intersections listed in Table 24, the 10 intersections in Table 26 and the 10 intersections which ranked 101 to 110 when all approaches were ranked without regard to whether delay is expected increase or decrease (Table 29).

Table 29. Approaches Ranked 101-110

Rank	Intersection No.	Original Intersection No.	Approach	Mainline Adt	Non-Mainline Adt	Expected Approach Accidents/year	Seconds of Added Delay per Day	Benefit when EC=8.25E-06
101	313	324	3	29152	7288	1.866	-245427.3	3.89
102	1477	1495	3	18473	4618	2.124	-211629	3.87
103	351	366	3	27481	6870	1.745	-256956.8	3.86
104	1376	1394	1	26048	32036	1.959	-229568.5	3.85
105	559	575	3	23432	5858	2.324	-180191.3	3.81
106	1369	1387	1	33760	8440	1.27	-306451.5	3.80
107	1209	1227	2	20055	27733	2.952	-100822.5	3.78
108	1533	1551	3	36269	9067	1.077	-327745.7	3.78
109	1375	1393	3	29696	9621	1.702	-246429.1	3.74
110	1346	1364	3	32745	8186	1.335	-289493.9	3.72

Judgement can be exercised in order to substitute conveniently located intersections for remote ones.

The first task is to ascertain (either by phone or by field visit) whether the left-turn phasing of the ranked approach is indeed ‘Permitted’. If the phasing is ‘Protected’ or ‘Protected-Permissive’ this should be noted, no field study should be conducted at this intersection, and then next ranked intersection should be added to the list. The second task is to produce a sketch of the intersection showing the approximate geometry (number of approaches, number of through and turning lanes on each approach, special features such s skew). The third task is to obtain all the information necessary to run the simulation to determine total intersection delay for each hour of day and night with ‘Permitted’ phasing and with ‘Protected phasing’. I will want to compare this estimate to what the Brondum-Martin equations produced. I expect that to run the simulation you will need to obtain for each approach the through, left and right turn hourly volumes. I will want to compare those to what I estimated using the mainline ADTs, the hourly proportions and the many assumptions that I had to make.

12. Field Validation.

The purpose of the field validation was to determine to what extent the delay estimated by the Brondum-Martin estimation that uses electronically available data and an assortment of assumptions resembles the delay estimated by using data collected in the field in the SimTraffic simulation software (that also requires a series of assumptions to be made).

12.1 Simulation Results With and Without Full Left-turn Protection.

The comparison of simulation results for mainline approaches under either Protected or Permissive-Protected phasing is in Figure 20.

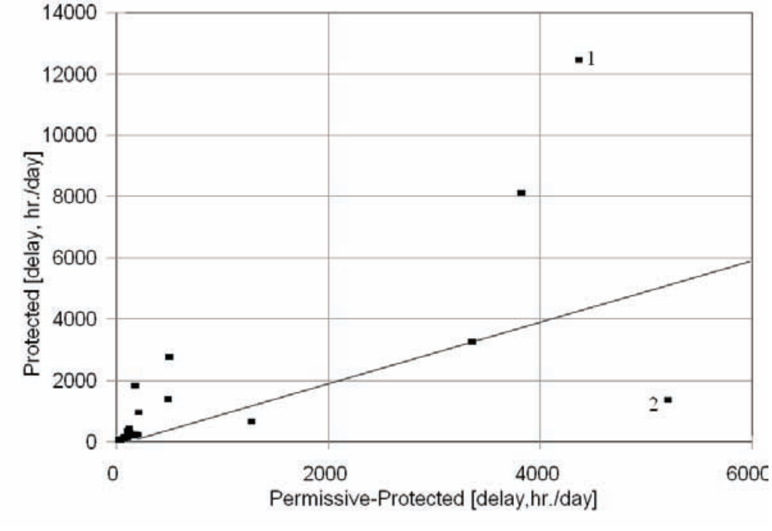

Figure 20. Simulated delay for mainline approaches, with differing left-turn protection.

Point 1 is the Colfax-Potomac intersection (22-4, ID=302). For the simulated condition (which is different from the one now prevailing) *"Extremely lengthy queues were observed in the westbound left-turn lane. Insufficient left-turn green time is the likely cause but no manual adjustments were made."* The condition now prevailing provides for protected left turns, presumably without such lengthy queues. Thus, the devil seems to be in the details; it is apparently possible to operate this intersection without "extremely long queues" while providing full protection for left turns even though simulation seems to indicate the contrary. At this intersection, the simulation results might not have been a good indication of what can be done.

Point 2 is University-Arapahoe (22-13, ID=1231). It shows a much lesser delay with full protection than with permissive-protected phasing. In the field study it turned out that: "*The current left-turn phasing for the east and west approach is protected-only. The information available to me indicates that the intersection has been phased in this manner for quite some time. Modifying this to protected-permissive phasing would likely conflict with the conditions as they existed for the accident analysis."*

These two points (intersections) lead to several conclusions:

a. Both intersections already operate with protected phasing. Both would have been ranked fairly highly for consideration to be converted to protected phasing. It follows that when a ranked list is prepared, an accompanying note should make it clear to the recipients that the list was prepared without knowledge of what left-turn phasing and protection are present. It is up to the engineers in the region to ascertain what left turn protection exists, and to delete from the list those sites where full left-turn protection has already been provided.

b. Headquarters should aim to assemble electronic information on left-turn protection so that future lists can be limited to sites where such full protection does not exist.

c. At least at high-volume intersections, the amount of delay is difficult to predict even with sophisticated software. (In the present case the software predicted long queues with protected phasing while the intersection actually operated in this mode, presumably without very long queues). It would seem reasonable to regard such intersections that have many left-turn accidents and are presently without full left-turn protection as sites deserving detailed traffic engineering. The purpose of such an examination would be to determine what would be the delay with optimal control strategies.

Figure 21 is a detail of the previous figure and shows the points near the origin. In most cases the simulations show only a small increase in delay. There are three (six?) mainline approaches where conversion to full protection would result in a large increase in delay and one approach where it seems to diminish delay. Whether the distinction between sites where full protection increases delay and sites where it decreases delay can be made using the Brondum-Martin equations remains to be examined.

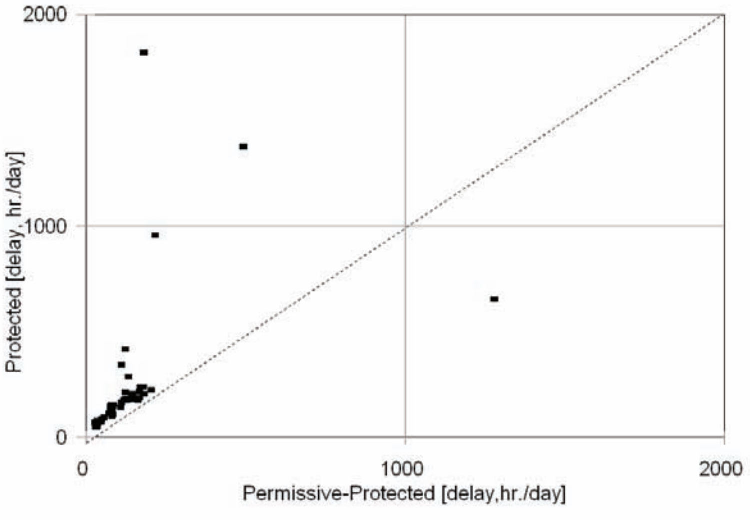

Figure 21. Detail from Figure 20

In principle, there are some points where conversion to full protection makes for a large increase in delay, some points where the opposite would be the result, and many points where the change in delay is small.

For non-mainline approached the situation is similar as shown in Figure 22. Some intersections are below the 'equality line' indicating that the intersection would operate with less delay if left-turns were fully protected; some points give unreliable delay estimates because of over-saturation and very long simulated queues; and for most points near the origin the difference in delay is small.

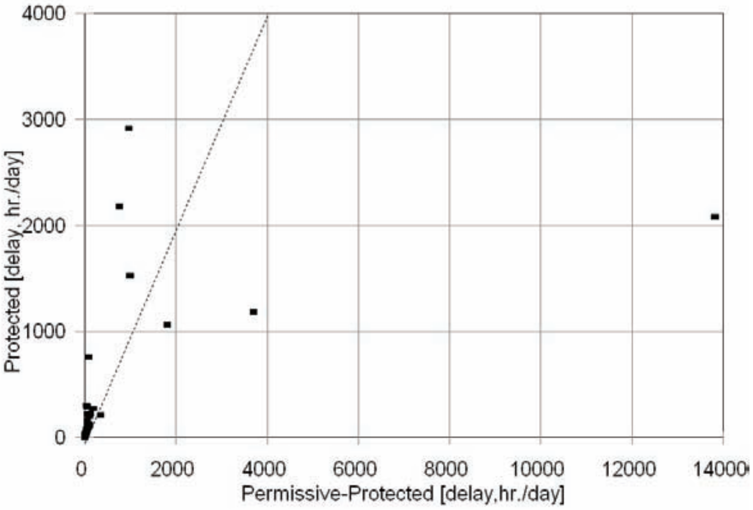

Figure 22. Simulated delay for non-mainline approaches, with differing left-turn protection.

12.2 Comparing Simulated Delay with Brondum-Martin Delay Estimates

Figure 23 shows the relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations for Protected phasing on Mainline Approaches. The scale was selected so as to shown only points where there is no danger of incorrect estimates due to over-saturation. The Brondum-Martin equation usually estimate a larger delay than the simulation and the correlation between the two estimates is minimal.

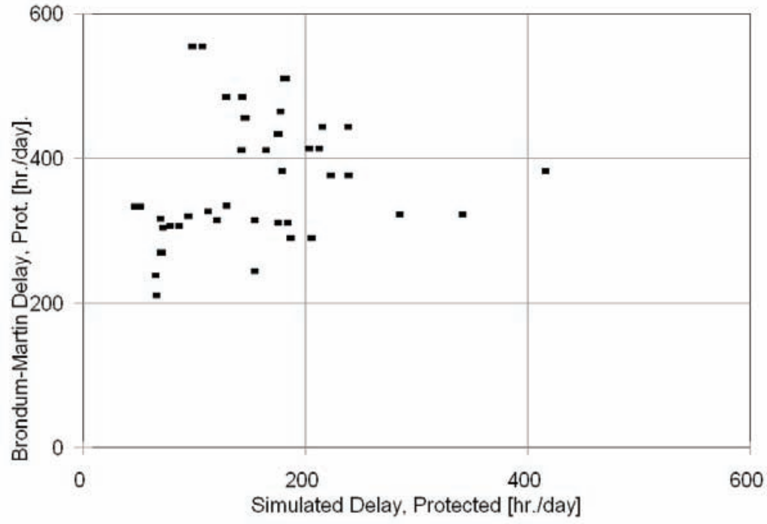

Figure 23. Relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected phasing for Mainline Approaches

Figure 24 shows the relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations for Mainline Approaches with Protected-Permissive phasing. The scale was selected so as to shown only points where there is no danger of incorrect estimates due to over-saturation. Here too the Brondum-Martin equations over-estimate delay and the correlation between the two estimates is minimal.

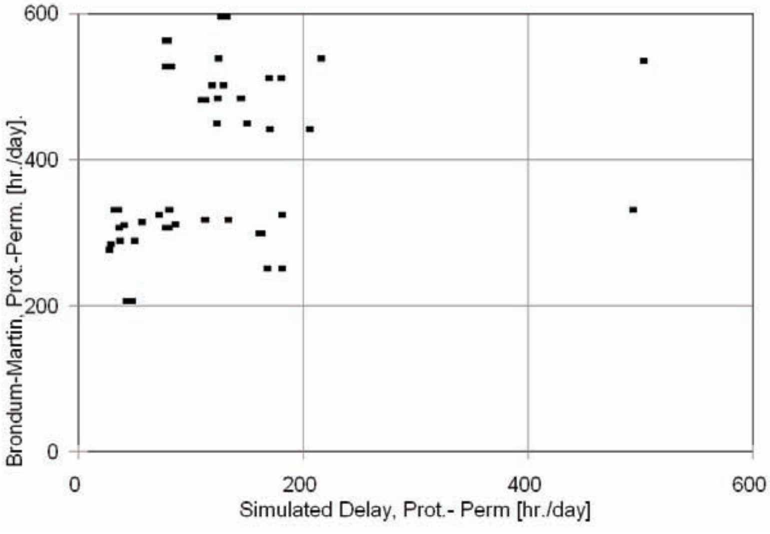

Figure 24. Relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected-Permissive phasing for Mainline Approaches

Similar comparisons for non-mainline approaches are in Figure 25 and Figure 26. As for mainline approaches, the association between the delay estimated by SimTraffic and that estimated by the Brondum-Martin equations is weak. Unlike on the mainline approaches, the delay estimated by the Brondum-Martin equations tends to be smaller than that estimated by simulation.

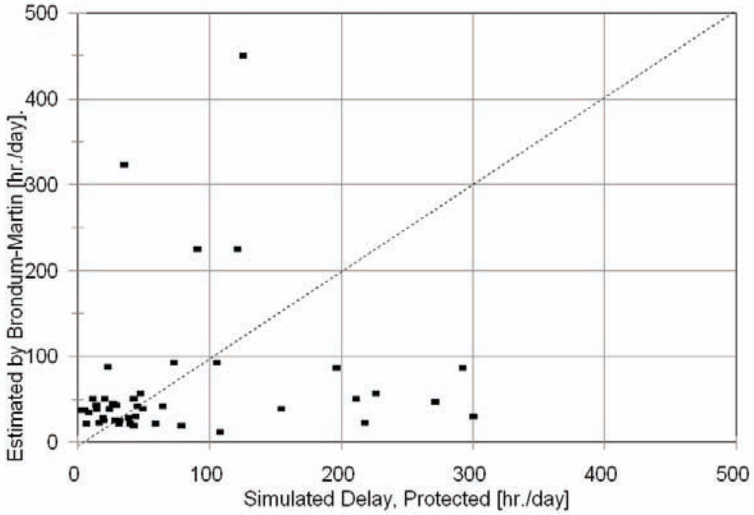

Figure 25. Relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected phasing for Non-Mainline Approaches

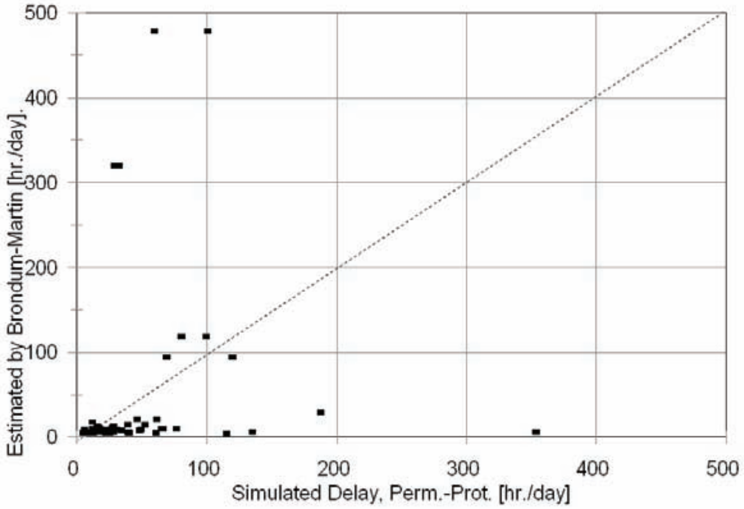

Figure 26. Relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Permissive-Protected phasing for Non-Mainline Approaches

As already noted, the reasons for the small correlation may be many. Some reasons may be due to discrepancies in input data (number of lanes, hourly ADTs etc.) some may be due to the many assumptions and approximations associated with the use of the Brondum-Martin equations, some may be caused by the differences between the HCM procedure (which is in the background of the Brondum-Martin equations) and the microscopic simulation in SimTraffic. The question is whether there are significant discrepancies in the input data which are perhaps correctible or whether the differences are due reasons that cannot be easily corrected.

12.3 Comparing the Input Data to Field Data

12.3.1 Approach lanes

The comparison of the number of lanes observed in the field and extracted from the electronic data bases for mainline approaches is in Table 30. Part of the discrepancy in delay estimation may be due to the fact that in many cases fewer approach lanes were assumed than actually exist in the field. For such approached the Brondum-Martin delay estimate would be larger than that from the simulation.

Table 30. Number of Mainline Approach Lanes

Observed in field and used in simulation	From electronic data based and used in Brondum-Martin			
	2	**3**	**4**	Total
2	10	1		11
3	12	27		39
4		1	1	2

Since the number of non-mainline lanes is not available in the electronic data base, to compute the Brondum-Martin delay the assumption was made that the number of lanes on the non-mainline approach is the same as the smaller of the number of lanes on the two mainline approaches. The comparison of the number of lanes observed in the field and those based on the above assumption for non-mainline approaches is in Table 31. The assumption turned out to be correct only on 21 of the 52 approaches (see shaded cells). On 30 approaches delay was calculated as if more lanes existed than is true. For such approached the Brondum-Martin delay estimate would tend to be smaller than that from the simulation. It appears therefore that a part of the discrepancy in Figure 25 and Figure 26 may be due to this inaccurate assumption.

Table 31. Number of Non-Mainline Approach Lanes

Observed in field and used in simulation	By assuming to equal the smaller number of mainline lanes and used in Brondum-Martin			
	2	**3**	**4**	Total
1	7	12		19
2	19	10		29
3	1	2		3

It would have been better to assume that the number of non-mainline lanes is 2. This assumption would have been right in 29 of 52 cases. While this may remove some of the bias, without knowing the number of approach lanes one may not expect to get good delay estimates.

12.3.2 ADT

The comparison of ADT count data used in the simulation and that from electronic sources used in the Brondum-Martin equations for mainline approaches is in Figure 27. With few exceptions the correspondence is quite good. The ADT from electronic sources tends to be larger than that from field counts. This too may be part of the reason for which the Brondum-Martin delay tends to be larger than that produced by SimTraffic.

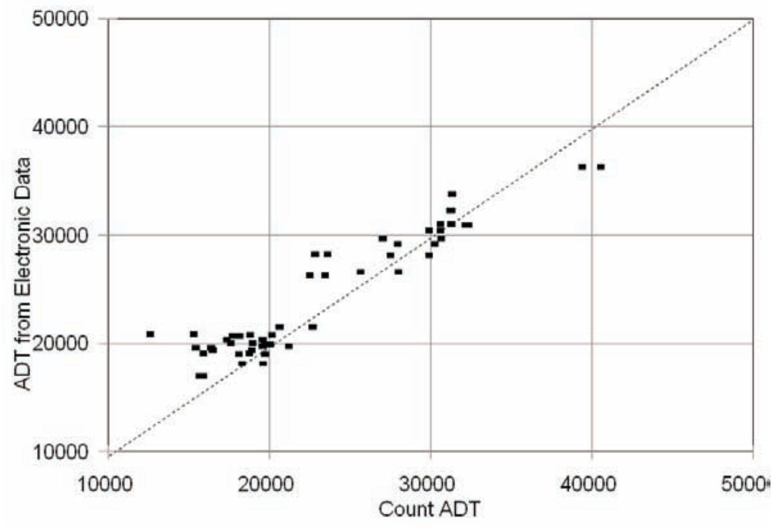

Figure 27. Comparison of ADT data from field counts and used in the simulation to that from the electronic data-base and used in the Brondum-Martin equations.

12.3.3 Left Turns

When computing delay by the Brondum-Martin equations the assumption was made that the left-turning traffic is 15% of the approach volume. The field data shows that on the 52 mainline approaches the average proportion of left-turning traffic was 7% with a standard error of ±6% while on non-mainline approaches the average proportion was 34% with a standard error of ±15%. This is a major discrepancy which could perhaps explain the disappointing association between the delay estimated by the Brondum-Martin and that by SimTraffic.

12.4 Lessons Learned and Modifications Needed

On the whole, the correspondence between the delay predicted by the Brondum-Martin equations using only electronically available data and that obtained by SimTraffic using data collected in the field is poor. This result is not entirely unexpected. It was clear at the outset that the Brondum-Martin equations were obtained for conditions that differ from those in the field and that the use of only such data as is available electronically requires many assumptions and guesses to be made that do not well match reality. The divergent results are best discussed for two separate conditions.

The first condition pertains to intersections working near capacity. Here the discrepant results reflect the fact that when long queues might be present the actual delay will depend on a large number of factors and the fine-tuning of geometry, turn restrictions and timing. Under such conditions one cannot hope to estimate delay well by some simple expression. Even microscopic simulation may not yield credible results. Originally I rigged the Brondum-Martin estimation so that with protected phasing the delay/vehicle could not excess 60 seconds and with permissive phasing it did not excess 70 seconds. The SimTraffic simulation using field data did not use similar limits and allows long queues to form. Therefore, under near capacity conditions, the two methods will produce discrepant results.

The second condition under which divergent results were noted pertains to intersections with small volume-to-capacity ratios. At such intersections the assumptions about number of lanes, traffic and proportion of left-turning vehicles are the main source of discrepancy. Therefore I rerun the Brondum Martin delay estimation using 7% left turns for mainline approaches and 34% left turns for non-mainline approaches.

12.5 Comparing SimTraffic Delay with Brondum-Martin Delay Estimates After Code Modification.

Figure 28.shows for ‘Protected’ phasing on ‘Mainline Approaches’ the corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations. The scale was selected so as to shown only points where there is no danger of incorrect estimates due to over-saturation. The relationship is somewhat stronger than that in Figure 23. The Brondum-Martin equations usually estimate a larger delay than the simulation and the correlation between the two estimates is minimal. Subtracting 200 hours/day from the Brondum Martin estimate would approximate the simulation delay.

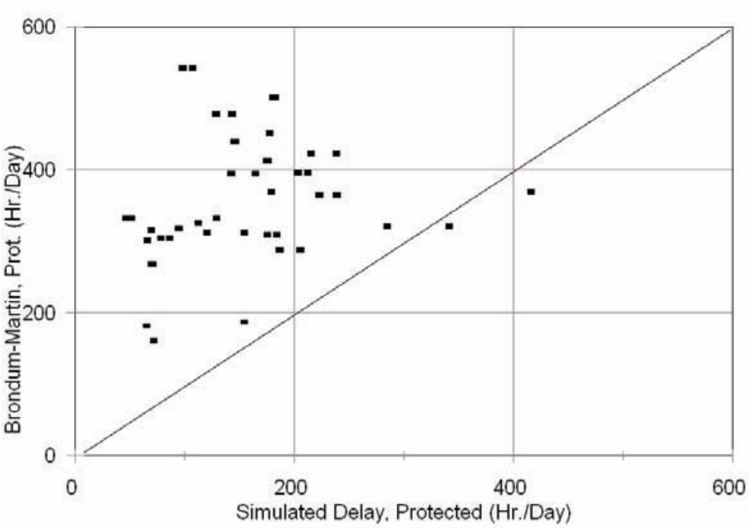

Figure 28. Corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected phasing for Mainline Approaches

Figure 29 shows for Mainline Approaches with Protected-Permissive phasing the corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations. The scale was selected so as to shown only points where there is no danger of incorrect estimates due to over-saturation. The corrected Figure 29 and the uncorrected Figure 24 are very similar. Here too the Brondum-Martin equations over-estimate delay and the correlation between the two estimates is minimal.

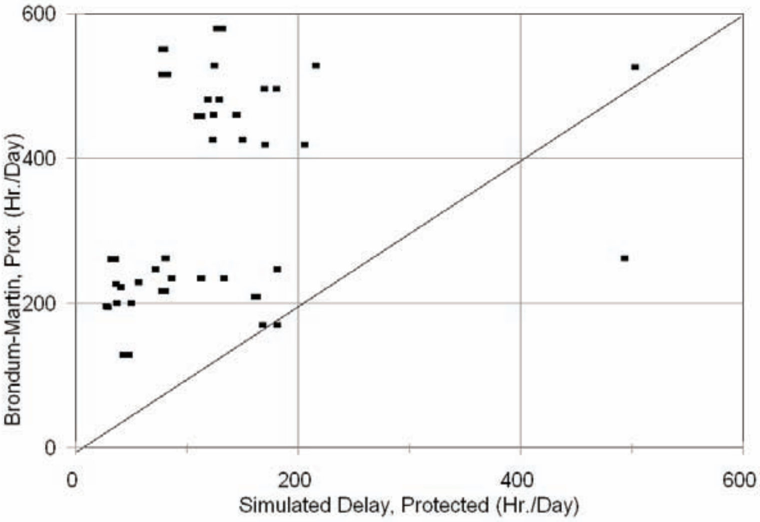

Figure 29. Corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected-Permissive phasing for Mainline Approaches

Similar comparisons for non-mainline approaches are in Figure 30 and Figure 26. As for mainline approaches, the association between the delay estimated by SimTraffic and that estimated by the Brondum-Martin equations is still weak. However, the corrected relationships (Figure 30 and Figure 31) are stronger than the uncorrected ones (Figure 25 and Figure 26).

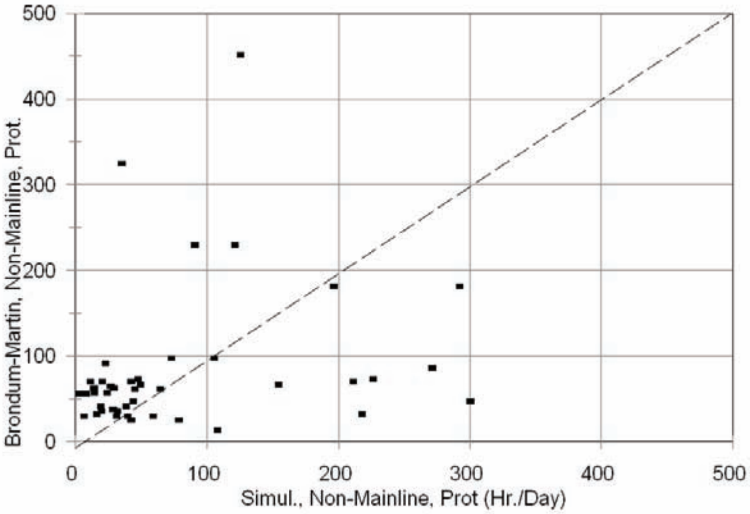

Figure 30. Corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Protected phasing for Non-Mainline Approaches

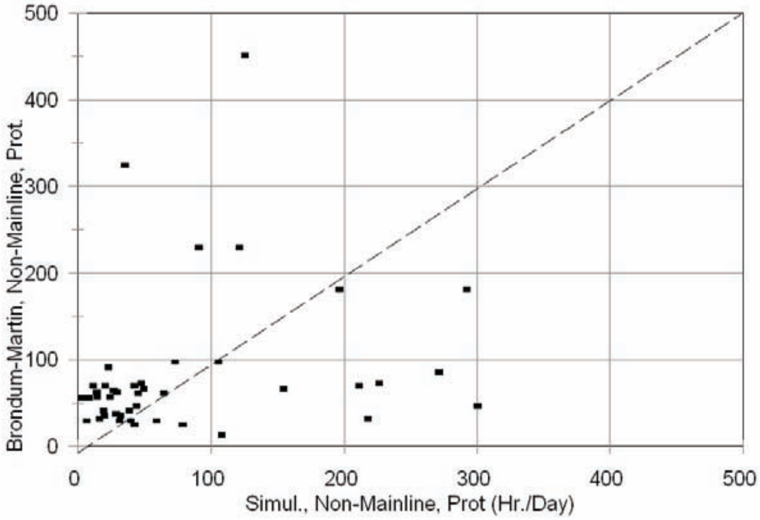

Figure 31. Corrected relationship between delay simulated by SimTraffic and delay estimated by the Brondum-Martin equations under Permissive-Protected phasing for Non-Mainline Approaches

12.6 Comparing Added Delay Estimates after Code Modification.

Because ranking is affected by the estimate of Added Delay, this is the most important comparison to be made. For non-mainline approaches the correspondence of the SimTraffic and the Brondum-Martin estimates is shown in Figure 32. The heavy line segments serve to point out the origin (0,0) and the four quadrants.

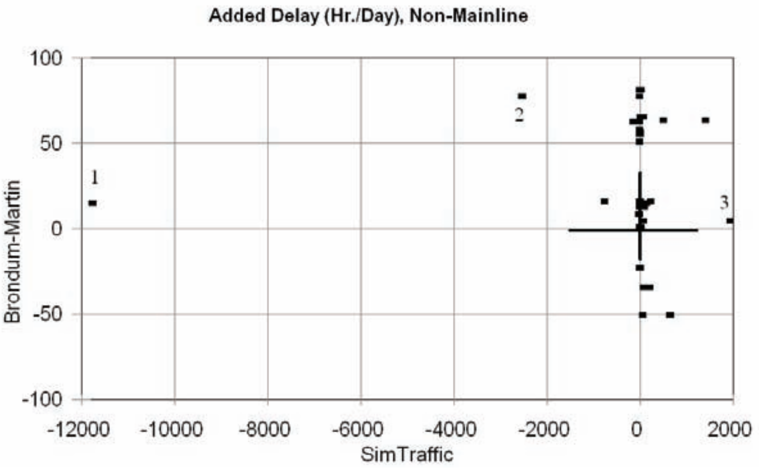

Figure 32. Comparison of Added Delay Estimated by SimTraffic from field data and by the Brondum-Martin equations using electronic data

Both SimTraffic and Brondum-Martin estimates indicate that there are a few approaches where conversion to Protected Phasing reduces delay. Alas, the two methods of added delay estimation identify entirely different approaches. Thus, the Brondum-Martin equations cannot be relied on to identify approaches where conversion to protected phasing is likely to reduce delay.

Points 1, 2 in quadrant IV and point 3 in quadrant 'I' are few of the approaches for which SimTraffic estimates large reductions or increases in added delay. That is, during parts of the day these approaches are oversaturated under at least one of the alternative left turn phasings. Noting the differences in horizontal and vertical scales, the Brondum-Martin estimates of added delay are small. The reason is that SimTraffic allows queues to grow without limit while in the Brondum-Martin estimation I restricted the average delay/vehicle not to exceed 60 and 70 seconds. Real intersections seldom operate under over-saturation for long periods. It is therefore not self-evident whether for approaches operating near capacity SimTraffic or Brondum-Martin produce more reasonable estimates. The correspondence of the two estimates near the origin is shown in Figure 33.

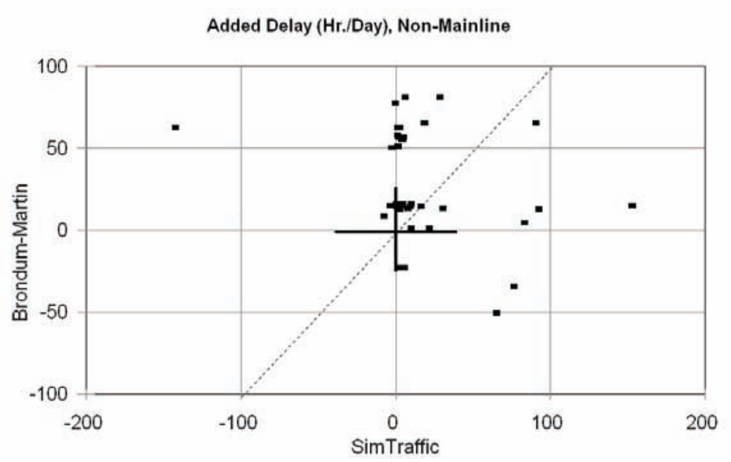

Figure 33. Comparison of Added Delay Estimated by SimTraffic from field data and by the Brondum-Martin equations using electronic data – Detail

The only positive observation that can be made is most estimates agree in sign; the correspondence in magnitude is slight to non-existent.

For mainline approaches the correspondence of the SimTraffic and the Brondum-Martin estimates is shown in Figure 34. The heavy line segments again serve to point out the origin (0,0) and the four quadrants. The discrepant results for points such as 1 and 2 are again due to the difference in how over-saturation was treated. Detail near the origin is shown in Figure 35. It seems that for mainline approaches even the minimal correspondence noted earlier vanishes; the number of points where the two estimates agree in sign (first quadrant) is roughly the same as the number of approaches where their signs differ (quadrant II).

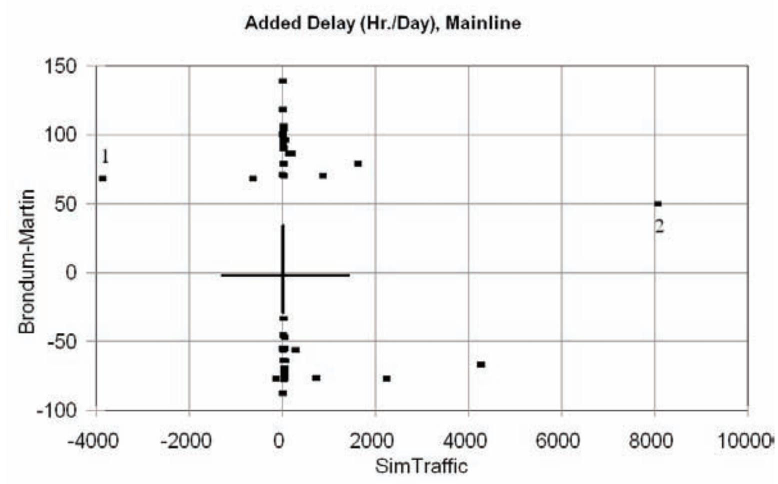

Figure 34. Comparison of Added Delay Estimated by SimTraffic from field data and by the Brondum-Martin equations using electronic data

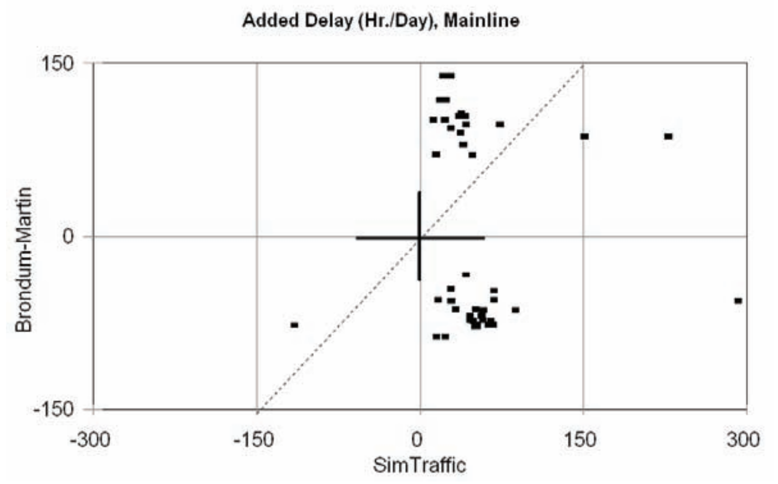

Figure 35. Comparison of Added Delay Estimated by SimTraffic from field data and by the Brondum-Martin equations using electronic data – Detail

12.7 Conclusions from the Field Validation.

The comparison of Delay and Added Delay estimates obtained by SimTraffic and by the Brondum-Martin equations shows that the two produced discrepant results. Therefore, the Brondum-Martin equations cannot be relied upon to give an indication of what change in delay should be expected from the change of left-turn phasing to full protection. The electronically available data when coupled with such equations that cannot be closely matched to the specific conditions in the field are unequal to the task. It follows that, at this time, the task of assessing what change in delay may result from a conversion to full left-turn protection at some intersection must be left to the expert traffic engineer.

It is possible that future research could produce a method of added delay prediction which would better match simulation results. However, inasmuch as such a method does not seem to be now available one must conclude that the ranking at this time should be solely on the basis of expected number of left turn accidents. This ranked list should be forwarded for detailed engineering examination. Such an examination is to consist of two steps. First, intersection approaches at which left-turns are already fully protected should be deleted from the list. Second, using the abridged list the engineer, using her/his familiarity with the sites, should examine in detail the delay consequences of a change in left-turn phasing.

13. Ranked Lists

As explained earlier (in the section on 'Preparing EB Estimates of Expected PDO and Injury and Fatal Accident Frequencies) the EB estimation procedure was coded in Visual Basic under the command button the caption of which is "Estimate Expected Accidents by EB" in the "Left Turn Data and Analysis" VB project. The output for the first five intersections and their approaches was shown in Table 14 repeated below as Table 32.

Table 32. EB Estimates and EPDO.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1	1	3	1	0.028409	0.030145	0.000054	0.198933
1	1	3	5	0	0	0	0
1	1	3	3	0.002815	0.002963	0.000054	0.027098
1	1	3	4	0.005089	0.003229	0.000027	0.026549
2	2	3	1	0.001938	0.002153	0.000056	0.022111
2	2	3	5	0	0	0	0
2	2	3	3	0.001938	0.002153	0.000056	0.022111
2	2	3	4	0.005089	0.003229	0.000027	0.026549
3	3	3	1	0.003343	0.003556	0.000081	0.034965
3	3	3	5	0	0	0	0
3	3	3	3	0.003343	0.003556	0.000081	0.034965
3	3	3	4	0.005089	0.003229	0.000027	0.026549
4	4	3	1	0.004844	0.005179	0.000159	0.057142
4	4	3	5	0	0	0	0
4	4	3	3	0.048879	0.052688	0.000159	0.356780
4	4	3	4	0.005089	0.003229	0.000027	0.026549
5	5	3	1	0.001982	0.002076	0.000029	0.017656
5	5	3	5	0	0	0	0
5	5	3	3	0.001982	0.002076	0.000029	0.017656
5	5	3	4	0.005089	0.003229	0.000027	0.026549

The EPDO accidents in the last column were computed using $6,500, $35,000 and $1,000,000 for PDO, Injury and Fatal accidents giving weights of 1, 5.38 and 153.84. The twenty approaches with the highest EPDO were shown in Table 15 repeated here as Table 33. The full table is in the first worksheet of: **'Ranking by EB.xls'**.

Table 33. Twenty Approaches with Largest EPDO in Last Year.

Consecutive numbering	Original Numbering	Number of Legs	Approach	Left-Turn Accidents Expected in Year 14			Equivalent PDO
				PDO	Injury	Fatal	
1071	1089	4	1	5.50	3.83	0.0028	26.52
1407	1425	4	1	4.46	3.78	0.0040	25.40
1403	1421	4	1	4.97	3.09	0.0047	22.32
1485	1503	4	1	5.25	2.86	0.0053	21.46
298	303	4	1	3.49	2.71	0.0025	18.48
297	302	4	3	3.62	2.56	0.0031	17.90
1534	1552	4	3	4.45	2.40	0.0030	17.84
1378	1396	4	1	4.49	2.32	0.0048	17.74
831	848	4	1	3.37	2.40	0.0032	16.80
1096	1114	4	3	4.95	1.96	0.0028	15.92
1503	1521	4	3	2.63	2.28	0.0043	15.54
1390	1408	4	3	3.33	2.12	0.0040	15.33
1466	1484	4	1	2.64	2.09	0.0094	15.32
1435	1453	4	1	4.29	1.94	0.0027	15.16
1434	1452	4	1	3.91	2.00	0.0031	15.16
358	374	4	3	2.83	2.18	0.0037	15.13
1531	1549	4	3	3.65	1.61	0.0150	14.63
1118	1136	4	3	2.29	2.07	0.0030	13.89
666	683	4	1	1.40	2.01	0.0098	13.72
1449	1467	4	1	1.83	2.10	0.0036	13.67

It might be of interest to rank sites by:
1. Sum of EPDO estimates for the two mainline approaches;
2. Sum of EPDO estimates for the two non-mainline approaches on four legged intersections;
3. The EPDO of the non-mainline approach on three legged intersections;
4. Sum of EPDO for all approaches for four legged intersections;
5. Sum of EPDO for all approaches for three legged intersections.

All rankings are given in the first worksheet of: **‘Ranking by EB.xls’**. The top twenty entries are in the tables below.

Table 34. Sum of EPDO/year for two mainline approaches.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of 2 Mainline Approach EPDOs/year
1	1407	1425	4	38.80
2	1403	1421	4	31.55
3	1071	1089	4	31.46
4	1485	1503	4	29.25
5	831	848	4	29.17
6	298	303	4	28.23
7	1466	1484	4	27.39
8	1531	1549	4	27.34
9	297	302	4	24.69
10	1118	1136	4	24.25
11	1249	1267	4	23.16
12	1534	1552	4	21.69
13	1096	1114	4	21.01
14	1378	1396	4	20.81
15	938	956	4	20.64
16	1385	1403	4	20.04
17	1416	1434	4	19.85
18	1431	1449	4	19.75
19	1390	1408	4	19.52
20	1503	1521	4	19.43

Table 35. Sum of EPDO/year for two non-mainline approaches of four legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of 2 Non-mainline Approach EPDOs/year
1	1209	1227	4	18.65
2	939	957	4	17.33
3	831	848	4	15.72
4	816	833	4	14.89
5	841	858	4	13.51
6	1385	1403	4	12.39
7	938	956	4	12.01
8	604	621	4	9.95
9	1455	1473	4	9.27
10	421	437	4	9.21
11	1115	1133	4	9.19
12	1535	1553	4	9.00
13	1452	1470	4	8.76
14	1431	1449	4	8.34
15	1454	1472	4	8.32
16	1390	1408	4	8.28
17	1411	1429	4	8.06
18	1376	1394	4	7.96
19	1238	1256	4	7.87
20	827	844	4	7.65

Table 36. EPDO/year for non-mainline approach of three legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Non-Mainline Approach EPDO/year
1	21	21	3	1.35
2	222	227	3	0.93
3	7	7	3	0.74
4	211	216	3	0.51
5	58	58	3	0.48
6	46	46	3	0.48
7	243	248	3	0.35
8	107	109	3	0.32
9	345	360	3	0.29
10	378	394	3	0.25
11	212	217	3	0.25
12	56	56	3	0.25
13	270	275	3	0.25
14	187	190	3	0.25
15	276	281	3	0.25
16	103	105	3	0.25
17	83	84	3	0.25
18	30	30	3	0.25
19	47	47	3	0.09
20	128	131	3	0.09

Table 37. EPDO/year for four legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of Approach EPDOs/year
1	831	848	4	44.88
2	1407	1425	4	43.64
3	1403	1421	4	38.74
4	1071	1089	4	38.37
5	1485	1503	4	36.44
6	1209	1227	4	34.43
7	939	957	4	33.47
8	938	956	4	32.65
9	1385	1403	4	32.43
10	298	303	4	29.99
11	1466	1484	4	29.67
12	1531	1549	4	28.61
13	1431	1449	4	28.09
14	604	621	4	28.08
15	1249	1267	4	27.95
16	1390	1408	4	27.80
17	297	302	4	27.73
18	1118	1136	4	26.30
19	841	858	4	25.82
20	833	850	4	25.77

Table 38. EPDO/year for three legged intersections.

Rank	Consecutive Numbering	Original Numbering	No. of Legs	Sum of Approach EPDOs/year
1	382	398	3	8.84
2	305	312	3	6.87
3	327	339	3	6.57
4	309	320	3	5.73
5	57	57	3	5.38
6	379	395	3	4.54
7	47	47	3	4.45
8	307	318	3	4.31
9	303	310	3	3.95
10	318	330	3	3.70
11	306	317	3	3.45
12	319	331	3	3.45
13	302	308	3	3.34
14	214	219	3	3.06
15	308	319	3	2.98
16	174	177	3	2.58
17	378	394	3	2.53
18	369	385	3	2.42
19	321	333	3	2.36
20	304	311	3	2.29

14. Summary and Conclusions

An important task in road safety management is to monitor where accidents occur on the road system and to assess whether at the high-accident sites safety can be cost-effectively improved. The weak point of the customary process is that the list of high-accident sites is prepared without considering what countermeasures, if any, could apply at the sites on the list. This weakness could be obviated by structuring the process in the reverse order. Instead of first selecting the sites and only later asking what countermeasures could be applied at these, one could begin by choosing countermeasures known to be effective and then seeking sites where these could be implemented to best effect. This alternative approach is the ‘Countermeasures With Promise’ (CWiP) process. The main weakness of the CWiP process is that it may require information that is currently not in electronic data bases. Its main promise is the ability to identify better sites; sites at which safety money will be spent to more effect. Even though the CWiP idea is simple and its attraction obvious, one can only assess practicality through pilot implementations.

The countermeasure chosen for examination was that of changing left-turn phasing at signalized intersection to ‘Protected’ phasing. The target accidents are those involving left-turning vehicles. Review of past research suggested that the change from ‘Permissive’ or ‘Protected/ Permissive’ to ‘Protected’ phasing has a clear benefit. Both phasing changes are estimated to have an AMF of 0.3 – a 70% reduction in target accidents. In the extant literature the effect of this change in left-turn phasing on non-target accidents is not clear and was therefore assumed to be about zero. To estimate the benefit of the conversion at a site one has to determine how many target accidents (PDO, Injury and Fatal) in a year are expected. To do so by the Empirical Bayes estimation method requires the knowledge of the history of accidents involving left turning vehicles at each site and also a model for predicting the expected number of such accidents based on the traits of each site. That PDO, Injury and Fatal accidents carry differing weights was accounted for by the notion of 'Equivalent Property Damage Only' (EPDO) accidents. Assuming accidents costs of $6,500, $35,000 and $1,000,000 for PDO, Injury and Fatal accidents respectively, one Injury accident was equivalent to about 5.4 PDO accidents and one fatal accident counts to about 154 PDO accidents. The cost of this countermeasure is mainly that of added delay. Thus, the main problem was how to estimate the change in average delay on the basis of the limited information available in electronic form.

Data to perform the tasks of estimating EPDO and of average delay estimation was requested, obtained, verified, and modified as necessary. Using the available ADT estimates a Visual Basic code was written to generate estimates for the years for which they are not available. **This code may be of interest to CDOT for other purposes as well.**

To generate the information needed for EPDO estimation by the Empirical Bayes (EB) method, Negative binomial models were estimated for six intersection types and two alternative functional forms. It is not practical to estimate a separate model for fatal accidents. Therefore the assumption was that the expected number of fatal accidents can be predicted by multiplying the expected number of fatal + injury accidents by a proportion. The procedure for EPDO estimation in which accident counts are combined with model predictions to obtain Empirical Bayes estimates was also coded in Visual Basic. EB estimates are deemed to be more accurate than estimates based on accident counts only and are not subject to regression-to-the-mean bias. **This procedure too may be of interest for wider implementation in CDOT.**

A change in left turn phasing at one or more intersection approaches entails a change in signal timing and thus a change in intersection delay. To properly estimate this change in intersection delay requires complex computations (or simulations) and detailed information about the intersection and its traffic. The challenge was to find a reasonable way for estimating this change in delay when only very the limited electronically available information was available (mainline ADT, number of intersection approaches and number of lanes on mainline approaches). In addition, the estimation procedure had to be such that it could be performed easily for a large number of intersections. The approach chosen was to estimate the added delay using the Brondum-Martin equation described in Working paper 1 (07/03/2005). This approach is far from ideal and, given the paucity of information available, its implementation required a large number of assumptions to be made. A Visual Basic code was written the estimate the added delay due to change in left-turn phasing.

With estimates of EPDO and of added delay in hand, it was possible to create a ranking of all intersection approaches considering both benefit (the 70% reduction in target EPDO) and cost (the estimated added delay). In this manner the aim was to identify approaches to signalized intersections where conversion to protected left-turn phasing promises to be most cost-effective. While the expected EPDO reduction could be reasonably well estimated by the EB method on the basis of models and accident history, the estimated change in delay was likely to be an approximation of unknown quality. The reason is in that some important data are not available (e.g., number of approach lanes and traffic volume on non-mainline approaches), that use was made of approximating equations which are known to produce bad estimates at low and at high volumes, and that a multitude of assumptions was made to cover for the absence of information.. The question was whether the resulting ranking is good enough to lead engineers to sites where a change to protected phasing will be cost-effective. To answer the question a field data collection and delay estimation study was conducted.

The field data collection and delay estimation study was conducted by Felsburg, Holt, Ullevig on 104 approaches of 26 intersections. The purpose was to determine to what extent the delay estimated by the Brondum-Martin equation that uses only electronically available data and an assortment of assumptions resembles the delay estimated produced by the SimTraffic simulation software that makes use of data collected in the field. The result was disappointing. The Brondum-Martin equation usually estimates a larger delay than the simulation and the correlation between the two estimates was minimal. As already noted, the reasons for the small correlation may be many. Some reasons may be due to discrepancies in input data (number of lanes, hourly ADTs etc.) some may be due to the many assumptions and approximations associated with the use of the Brondum-Martin equations, some may be caused by the differences between the HCM (Highway Capacity Manual) delay estimation procedure (which is in the background of the Brondum-Martin equations) and the microscopic simulation in SimTraffic. The question was whether there are significant discrepancies in the input data which are perhaps correctible or whether the differences are due reasons that cannot be easily corrected.

When computing delay by the Brondum-Martin equations the assumption was made that the left-turning traffic is 15% of the approach volume. The field data showed that on the 52 mainline approaches the average proportion of left-turning traffic was 7% with a standard error of ±6% while on non-mainline approaches the average proportion was 34% with a standard error of ±15%. This is a major discrepancy which could perhaps explain the disappointing association between the delay estimated by the Brondum-Martin and that by SimTraffic. Therefore the code was modified using 7% left turns for mainline approaches and 34% left turns for non-mainline approaches and the delay estimation repeated.

Unfortunately, even after the correction, the comparison of Delay and Added Delay estimates obtained by SimTraffic and by the Brondum-Martin equations shows that the two produce discrepant results. The conclusion is that the Brondum-Martin equations cannot be relied upon to give an indication of what change in delay should be expected from the change of left-turn phasing to full protection. The electronically available data when coupled with such equations that cannot be closely matched to the specific conditions in the field are unequal to the task. It follows that, at this time, the **task of assessing what change in delay may result from a conversion to full left-turn protection at some intersection must be left to the expert traffic engineer.**

Both the simulation when based on field data and the Brondum-Martin equation indicate that under some conditions delay is lesser with protected left-turn phasings. Unfortunately the two methods of estimation do not agree about the conditions (intersections) where this is the expected outcome. It would be important to know under what conditions full left-turn protection saves delay because at such intersection full left-turn protection is clearly beneficial. To the extent that the conditions have not yet been established, **research into this matter is likely to be of much benefit.**

It is possible that future research could produce a method of added delay prediction which would better match simulation results. However, inasmuch as such a method does not seem to be now available one must conclude that the **ranking at this time should be solely on the basis of the EPDO.** Such ranked lists should be forwarded for detailed engineering examination to consist of two steps. First, intersection approaches at which left-turns are already fully protected should be deleted from the list. Second, using the abridged list the engineer, using her/his familiarity with the sites, should examine in detail the delay consequences of a change in left-turn phasing. Several ranked lists were produced:

- All intersection approaches ranked by EPDO estimates.
- Two mainline approaches ranked by the sum of EPDO estimates;
- Two non-mainline approaches for the on four legged intersections ranked by the sum of EPDO estimates;
- The non-mainline approach of the on three legged intersections ranked by EPDO estimates;
- All approaches for four legged intersections ranked by the sum of EPDO estimates;
- All approaches three legged intersections ranked by the sum of EPDO estimates.

Complete rankings are provided in the spreadsheet ‘Ranking by EB.xls’.

After a review of this report, the next step should be to forward the ranked lists to the CDOT offices with jurisdiction over signalized intersections. Those intersections near the top of the lists which are presently without full left-turn protection should be considered for full protection implementation. Such consideration would entail an estimation of added detail due to a possible signal retiming. The results of this consideration should then be examined at headquarters with a view to whether and how the CWiP procedure for left-turn protection could be improved. Should the CWiPs identified here lead to changes in left-turn protection, the corresponding safety effect ought to be ascertained in a well conducted before-after study.

Reference List

1. Brondum, E., Martin, P. T. "A delay estimation model for signalized intersections using permitted, protected and permitted/protected phasing." *The University of Utah's Journal of Undergraduate Research*, 1997, *8* (1), 15-22.