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COMPUTER MODELING AND SIMULATION OF NEW JERSEY SIGNALIZED HIGHWAYS

(Volume II – Cost and Benefit Analysis)

Final report
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16. Abstract

This study developed a practical method to quantify costs and benefits associated with optimizing traffic signal timing plans. A benefit Analysis Tool (BAT) was developed for calculating the differences between existing and optimized traffic signal timing plans by interfacing the SYNCHRO results. A corridor for which data was recently collected and available is used as a case study to demonstrate the application of BAT. Results showed substantial benefit in reducing signal delay, fuel consumption, and vehicular emission.

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SUMMARY

While the nature of traffic flow is highly dynamic and continually changes, particularly in developing communities, many transportation agencies lack a programmatic approach to ease congestion through the optimization of traffic signal timing plans. Prior research initiatives have demonstrated the benefits of signal timing improvement. However, funding for the associated administrative, engineering and implementation costs must compete with other traffic safety and operational enhancements.

The New Jersey Department of Transportation is in the process of implementing optimal signal timing plans as a temporary installation for managing traffic flows associated with Route 23 and Route 42/322 in New Jersey. To help understanding the value of such a system, a cost benefit (C/B) analysis has been requested and conducted in this project.

The conducted C/B analysis was based on accepted procedures and evaluation frameworks for optimal signal timing plans. Outputs from SYNCHRO based on optimal signal timings were used to estimate the benefits for compared to that under existing conditions. Many variables were applied to develop models and estimate the system impacts before and after implementing the optimal signal timings on Route 23 and Route 42/322.

Results indicated that the benefit of the optimized signal timings on Route 23 and Route 42/322 outweighs the total cost by a ratio of 1 to 24 and 1 to 20, respectively. The total cost includes engineering and network modeling costs, of approximately $101,388 for on Route 23 and Route 42/322, which achieves the net benefit of more than 3.8 million dollars per year. The benefit was estimated from the reduction of travel time, fuel consumption, and environmental impacts. Additional benefits in terms of reduced accident cost reduction, customer satisfaction, productivity, and others were not quantified because of unavailable data. The calculation of benefits was based on a developed the Microsoft Excel based Benefit Analysis Tool (BAT), which can be easily revised for signal optimization projects to be conducted in other arterials.

The application of optimized signal timing plans for Route 23 and Route 42/322 was economically justified. Further evaluation of the studied corridors, while the optimized timings are in operation, to validate the results of the C/B analysis was recommended.

INTRODUCTION

Due to continuous traffic growth and financial difficulties in constructing new highway facilities, the optimization of traffic signal control has been recognized as an effective way to improve the efficiency of existing surface transportation systems. Synchronizing optimal signal timings along an arterial or in a network results in smoother traffic flow that increases roadway capacity. A number of previous studies summarized the benefit of optimal signal control including the reduction in travel times, number of vehicle stops, vehicle emissions, and fuel consumption. However, most of the cited benefits were based on limited data, and not related to geometric, traffic, and control conditions of the studied areas. In this project, we focused on quantifying the major measures of effectiveness (MOEs), such as travel times, fuel consumption, and vehicular emissions, before and after the implementation of the optimal signal control were evaluated.

The cost of a transportation investment in an economic term is the value of the resource that must be consumed to achieve expected benefits. It is important noting that the C/B analysis in this project aimed not only to define the cost and benefit components but also to formulate these components for similar projects to be conducted in the future. In general, as shown in Figure 1, the cost can be classified into three major components: engineering service, hardware, and administrative. Since no hardware and administrative costs were proposed only the cost of engineering service was considered. The cost of engineering service was further classified into the cost of (1) Network modeling and signal optimization (2) Data collection and processing, and (3) Signal timing adjustment.

The benefit achieved by a transportation investment can be generally defined as the positive intended effects. In a C/B analysis, shown in Figure 2, should be quanitified and converted into monetized values. Thus, the benefit can be estimated by conducting a before and after analysis on travel times, vehicle miles traveled and possibly the expected number of accidents/crashes if data are available.

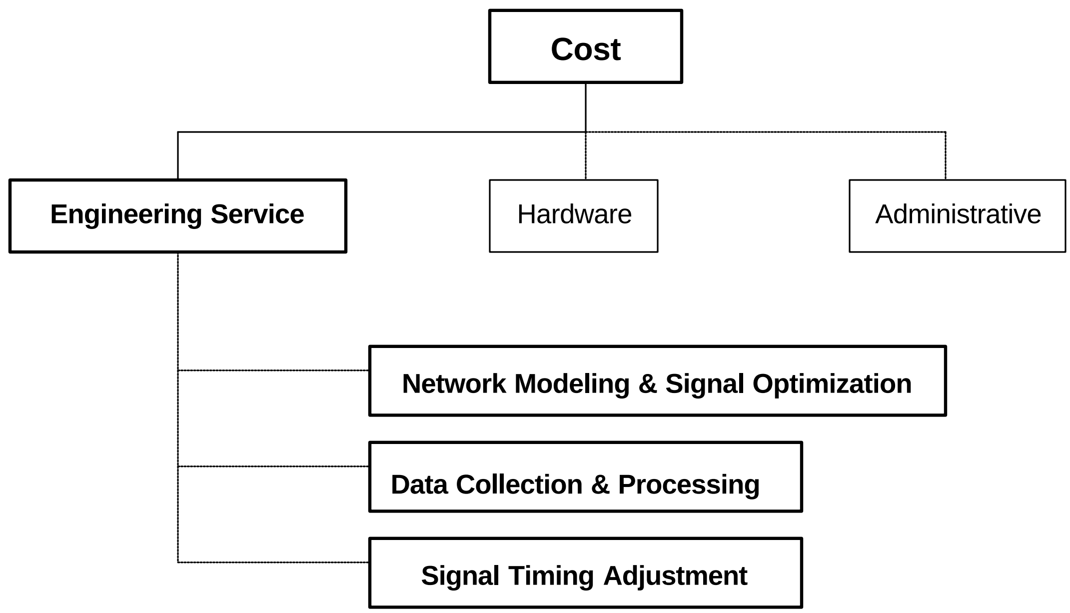


Figure 1. Cost Components

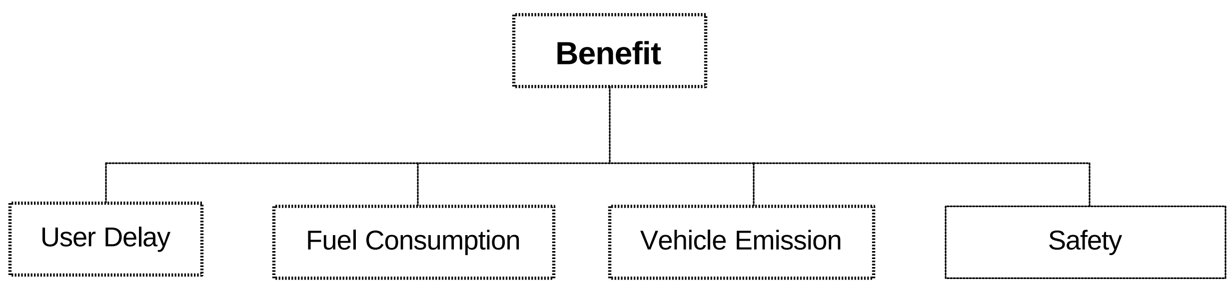


Figure 2. Benefit Components

RESEARCH APPROACH

The cost of a transportation investment in economic terms is the value of the resources that must be consumed to bring expected projects. It is important noting that the C/B analysis aims not only to define what incurs the cost but also to formulate all costs that are involved. The research approach tasks are listed below, and itemized tasks are illustrated in Figure 3.

- Task 1. Obtain SYNCHRO output.
- Task 2. Develop Cost and Benefit Model.
- Task 3. Compute Benefits.
- Task 4. Perform Sensitivity Analysis.

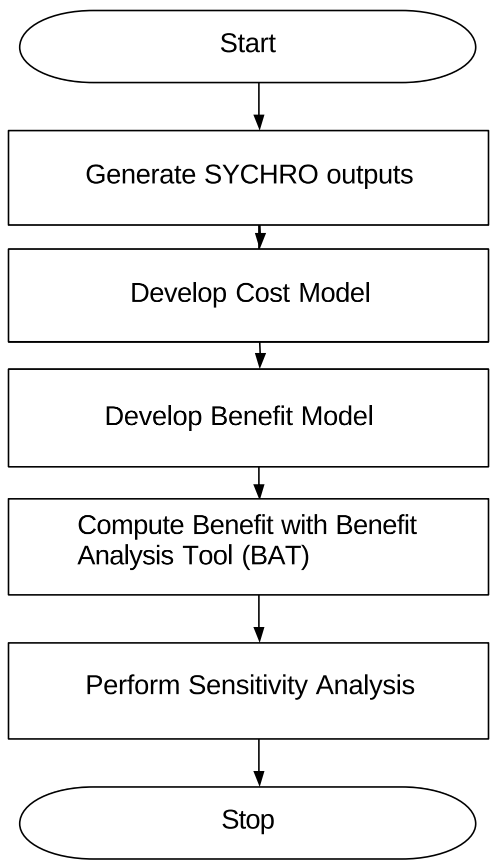


Figure 3. Research Approach

In general, the cost of signal timing optimization can be classified into three major components:

(1) Engineering service cost
(2) Hardware cost
(3) Administrative cost

In a C/B analysis, benefits (e.g., savings in travel times, reduction on fuel consumption, and vehicular emission, etc.) should be estimated quantitatively and then converted into a monetary value.

In general, costs and benefits of a signal optimization project consist of the savings of delay time, user cost, improved safety, throughput, customer satisfaction, and environmental impact, all of which are highly correlated. For example, An improvement in signal timing reduces delay which leads to more satisfied travelers, less wasted user cost, and less pollutants outputted by the vehicles.

To avoid redundancy, this study will use three benefits categories, which are developed and formulated as:

(1) Road Users' Time Savings
(2) Fuel Consumption
(3) Vehicle Emissions

Cost Model

While conducting a C/B analysis, it is essential that the analyst carefully classify cost components. The literature review and simulation based results of existing and optimized signal timing plans from SYNCHRO suggested various cost and benefit components associated with arterial signal timing optimization. Cost estimation is generally straightforward and in most cases, consists of hardware installation, engineering service and administrative costs. These costs can be detailed further and may vary depending on site conditions.

Equation (1) is used to determine the cost associated with signal optimization for an intersection.

$$C_i = C_{E_i} + C_{H_i} + C_{A_i} \qquad (1)$$

where C_i : Cost for intersection i, ($)
C_{E_i} : Engineering service cost at intersection i, ($)
C_{H_i} : Hardware cost at intersection i, ($)
C_{A_i} : Administrative cost at intersection i, ($)

Thus, the total cost for optimizing signal timing at all intersections on the studied segment can be formulated as

$$C_T = \sum_{i=1}^{N} C_i \qquad (2)$$

where C_T : Total cost ($)
N: the number of intersections on the studied segment.

Where engineering and administrative costs are determined for an entire studied arterial, the cost per intersection would equal the total engineering and administrative costs divided by N.

Benefit Model

To develop the benefit model, required data (e.g., traffic volume and vehicle splits, speeds and travel times, value of time, vehicle occupancy rate, and signal delay, etc.) must be collected. The analysis of the SYNCHRO outputs on the basis of these field data were then integrated into the benefits model. To estimate signal timing optimization benefits, the benefit calculation for this study followed the comparison of measures of effectiveness (MOEs) ‘before’ and ‘after’ implementing optimized signal timing within the SYNCHRO model.

User cost saving

The estimation of user travel time savings resulting from the signal timing optimization is a primary interest in this study and is defined by total user time savings at all intersections. The user cost savings is the total travel time savings multiplied by the users' value of time. Travel time savings are based on the difference in delays before and after optimization, which can be obtained from the SYNCHRO output.

User cost saving is affected by the intersection delay per vehicle, road users' value of time, vehicle split, and vehicle occupancy. The vehicle occupancy weighting factors are computed as

$$WF \quad AV_{OC} \times \left(\frac{S}{100} \right) \left(\frac{\quad}{\quad} \right) \qquad (3)$$

where WF : Vehicle occupancy weighting factor (person/veh)

OC : Average Vehicle occupancy (persons/veh)

S : Vehicle split ratio (%)

Thus, road users' travel time cost saving is

$$RU = T \times WF \times S \qquad (4)$$

where RU : Road users' travel time saving ($)

T : Value of time ($/person-hr)

S : Travel Time saving (veh-hr)

Fuel Consumption

An estimate of fuel consumption before and after signal optimization is achieved by quantifying the relationship between vehicle stops and queue delays. Fuel consumption estimating used in this study is based on formula embedded in SYNCHRO and is the same as the default equation that is applied in TRANSYT-7F.

The reduction in fuel use is the difference between the total consumed fuel before optimization and after optimization, which is obtained directly from SYNCHRO outputs. The value of fuel savings is calculated using equation (5):

$$= \times {}_{1} + \times {}_{2} + \times {}_{3} \qquad (5)$$

where : Fuel Consumption (gallons)

: Total Travel (VMT)

: Total Delay (veh-hr)

: Stops (vph)

Note that ${}_{1}$, ${}_{2}$ and ${}_{3}$ are parameters and can be estimated from Eqs. (6), (7), and (8), respectively.

$${}_{1} := 0.075283 - 0.0015892 \times + 0.000015066 \times {}^{2} \qquad (6)$$

$${}_{2} := 0.7329 \qquad (7)$$

$${}_{3} := 0.0000061411 \times {}^{2} \qquad (8)$$

where : Speed (mph)

Fuel cost saving is then estimated by the total fuel consumption multiplied by the unit price of gasoline.

$${}_{s} = \Delta \times {}_{f} \qquad (9)$$

where ${}_{s}$: Fuel consumption saving ($)

Δ : Fuel consumption (gallon)

${}_{f}$: Unit price of gasoline ($/gallon)

<u>Vehicle Emission</u>

Total vehicle emission reductions are estimated from fuel consumption multiplied by emission production factors. Pollutants considered in this study include Carbon Monoxide (CO), Oxides of Nitrogen (NOx), and Hydrocarbons (HC). Hydrocarbons (HC) are a group of chemical compound composed of carbon and hydrogen. When in a gaseous form, HC are also called Volatile Organic Compounds (VOC).

This study used emission production rates obtained directly from SYNCHRO output, are estimated by Eq. 10.

$$ {}_{m} = \Delta \quad \times {}_{m} \qquad (10)$$

where ${}_{m}$: Emission rate (grams)

${}_{m}$: Emission production factor (grams/gallon)

: Index of CO, NOx, VOC

Note that 69.9, 13.6 and 16.2 represent emission production factors (${}_{CO}$, ${}_{NOx}$, and , ${}_{VOC}$) for estimating emission rates of CO, NOx and VOC, respectively.

Daily and Annual Benefit Calculation

Estimates of benefit in this study are based on one hour SYNCHRO output in the AM, Noon, and PM peak periods. Using only one-hour results for benefit calculation, the daily benefit defined here is the sum of benefits of the three periods. Thus, the total daily benefit (${}_{day}$) is

$$ {}_{day} = {}_{AM} + {}_{NOON} + {}_{PM} \qquad (11)$$

where ${}_{AM}$, ${}_{NOON}$, and ${}_{PM}$ represent benefits in the AM, Noon, and PM peak periods respectively.

The total annual benefit can be measured directly from the number of weekdays multiplied by the daily benefit. Thus, the annual benefit ($_{year}$) can be obtained from Eq.11:

$$ {}_{year} = {}_{day} \times \qquad (12) $$

Note that the number of weekdays per year is assumed 261 [365(days/year)-52(weeks/year) $\times$2].

Benefit Analysis Tool (BAT)

In order to estimate benefit with a robust way, a Benefit Analysis Tool (BAT, Figure 4) was developed, which is a Microsoft Excel based software package, and calculates the differences of SYNCHRO output for existing and optimized signal timing condition. BAT was designed to automatically compute benefits by inputting delay, fuel consumption, amounts of pollutants, and model variables (e.g., value of time, vehicle occupancy, vehicle split, gasoline unit price, pollutants unit price, etc.). A step procedure for operating BAT is summarized below:

Step 1: Generate existing and optimized signal timing SYNCHRO output in forms of a text file.

Step 2: Import the SYNCHRO output from Step 1 to BAT.

Step 3: Run macro named ‘Sort_Route_23’ to sort input. (for Rout 42/322, run macro named ‘Sort_Route_42)

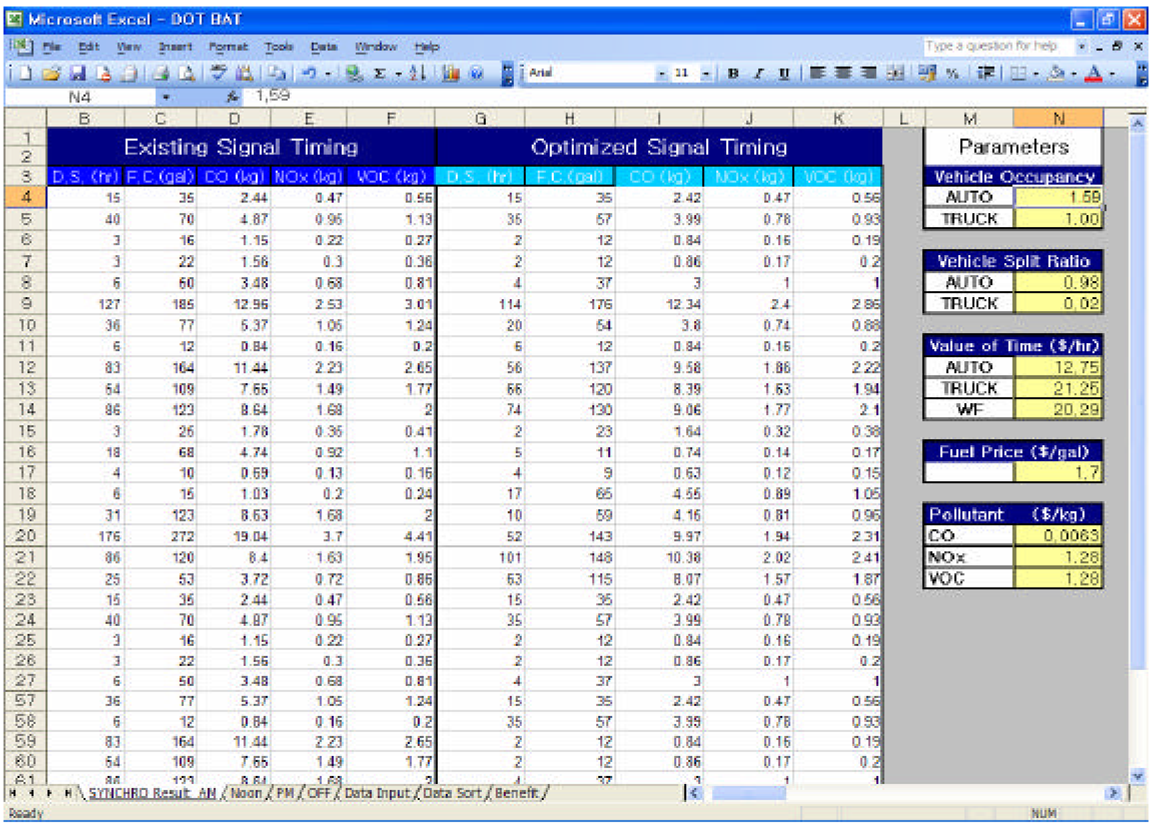
Step 4: Run one of the following listed macros considering time period and signal timing.

- Existing_AM
- Existing_Noon
- Existing_PM
- Existing_Off-Peak
- Optimized_AM

- Optimized_Noon
- Optimized_PM
- Optimized_Off-Peak

Repeat step 1 to 4 for all time periods (e.g., AM, Noon, PM, and Off-Peak) of existing and optimized signal timing

Step 5: Input parameters for benefit model.



Microsoft Excel - DOT BAT

	Existing Signal Timing					Optimized Signal Timing				
	D.S. (hr)	F.C (gal)	CO (kg)	NOx (kg)	VOC (kg)	D.S. (hr)	F.C (gal)	CO (kg)	NOx (kg)	VOC (kg)
4	15	35	2.44	0.47	0.56	15	35	2.42	0.47	0.56
5	40	70	4.87	0.95	1.13	35	57	3.99	0.78	0.93
6	3	16	1.15	0.22	0.27	2	12	0.84	0.16	0.19
7	3	22	1.56	0.3	0.36	2	12	0.86	0.17	0.2
8	6	60	3.48	0.68	0.81	4	37	3	1	1
9	127	185	12.96	2.53	3.01	114	176	12.34	2.4	2.86
10	36	77	5.37	1.05	1.24	20	54	3.8	0.74	0.88
11	6	12	0.84	0.16	0.2	6	12	0.84	0.16	0.2
12	83	164	11.44	2.23	2.65	56	137	9.58	1.86	2.22
13	64	109	7.65	1.49	1.77	66	120	8.39	1.63	1.94
14	86	123	8.64	1.68	2	74	130	9.06	1.77	2.1
15	3	26	1.78	0.35	0.41	2	23	1.64	0.32	0.38
16	18	68	4.74	0.92	1.1	5	11	0.74	0.14	0.17
17	4	10	0.69	0.13	0.16	4	9	0.63	0.12	0.15
18	6	15	1.03	0.2	0.24	17	65	4.56	0.89	1.05
19	31	123	8.63	1.68	2	10	59	4.16	0.81	0.96
20	176	272	19.04	3.7	4.41	52	143	9.97	1.94	2.31
21	86	120	8.4	1.63	1.95	101	148	10.38	2.02	2.41
22	25	53	3.72	0.72	0.86	63	115	8.07	1.57	1.87
23	15	35	2.44	0.47	0.56	15	35	2.42	0.47	0.56
24	40	70	4.87	0.95	1.13	35	57	3.99	0.78	0.93
25	3	16	1.15	0.22	0.27	2	12	0.84	0.16	0.19
26	3	22	1.56	0.3	0.36	2	12	0.86	0.17	0.2
27	6	50	3.48	0.68	0.81	4	37	3	1	1
57	36	77	5.37	1.05	1.24	15	35	2.42	0.47	0.56
58	6	12	0.84	0.16	0.2	35	57	3.99	0.78	0.93
59	83	164	11.44	2.23	2.65	2	12	0.84	0.16	0.19
60	64	109	7.65	1.49	1.77	2	12	0.86	0.17	0.2

Parameters	
Vehicle Occupancy	
AUTO	1.59
TRUCK	1.00
Vehicle Split Ratio	
AUTO	0.98
TRUCK	0.02
Value of Time ($/hr)	
AUTO	12.75
TRUCK	21.25
WF	20.29
Fuel Price ($/gal)	
	1.7
Pollutant ($/kg)	
CO	0.0063
NOx	1.28
VOC	1.28

Figure 4. Benefit Analysis Tool (BAT)

RESULTS ANALYSIS

The New Jersey Department of Transportation is redesigning signal timing plans for a twelve-mile section of NJ Route 23 and a nine-mile section of NJ Route 42/322. Route 23 and Route 42/322 consist of 19 and 17 signalized intersections, respectively. Both pre-timed and adaptive signal controls are applied along the studied corridors. For the purpose of conducting a C/B analysis, available data, including intersection turning movements counts, roadway geometric condition and existing traffic signal timing were collected for developing SYNCHRO models, which were then used to optimize traffic signal timing plans during AM, Noon, and PM for the studied corridors.

Cost

Since the optimized timing plans can be implemented in the studied corridor with no new or additional signal equipment, the costs related to the case study consist only of engineering cost. Engineering costs include obtaining and summarizing traffic volume data, entering data, developing optimum timings, preparing new timing directives, and agency technical oversight and field implementation. A detailed breakdown of costs has been calculated and summarized in Table 1.

Table 1. Total Costs

Cost Component	**Cost ($)**
Network modeling and signal optimization	170,260
Data collection and processing	
Implementing signal timing	6,137
Hardware	0
Total	176,397

Benefit

As outlined in the methodology, three MOEs (total signal delay, fuel consumption, and vehicle emissions) were obtained from the SYNCHRO models that were used to estimate the benefit of the implementation of optimized signal timing plans. The input variables for the benefit model are shown in Table 2.

Table 2. Benefit Model Decision Variables

Parameters	**Value**	
Value of Time (V_T)	Cars	Trucks
	12.75 $/hr	21.25 $/hr
Vehicle Occupancy (V_{OC})	1.59	1.0
Vehicle Split (V_S)	98 %	2 %
Gas Unit Price	1.7 ($/gallon)	
Pollutant Unit Price		
CO	0.0063 ($/kg)	
NOx	1.28 ($/kg)	
HC	1.28 ($/kg)	

The decision variables in the road users' time saving model are value of time, vehicle occupancy, and vehicle split. Value of time refers to New Jersey Road User Cost Manual; 12.75 $/hr for passenger cars and 21.25 $/hr hour for trucks. Vehicle occupancy data was adopted from the 1995 Nationwide Personal Transportation Survey (NPTS); 1.59 for passenger cars, 1.0 for trucks. Vehicle splits were directly obtained from traffic volume data collected for the study corridor. Thus, value of time weighting factor can be computed as:

$$ _{T} \times _{WF} = (\times \times)_{Cars} + (\times \times)_{Truck} = ( ) \quad (13)$$

For the fuel consumption model, a value of 1.7$/gal was used.
(From http://www.newjerseygasprices.com)

The unit cost of pollutants was taken by Small and Kazimi (1995) as in Gillen et al., (1999) and is used for the vehicle emission model.

Road User Cost Saving

Outputs for the existing and optimized SYNCHRO models were inputted into the BAT. The estimates of total signal delay at each intersection for Route 23 and Route 42/322 are summarized in Tables 3 and 4, respectively.

For Route 23, total intersection delay at 19 signalized intersections dropped from 808 veh-hr, 106 veh-hr, and 447 veh-hr to 648 veh-hr, 89 veh-hr, and 335 veh-hr in the AM, Noon and PM peak hours, respectively. For Route 42/322, similar delay savings were obtained at 17 signalized intersections. As non-peak period was selected as it represents non-commuter condition, intersection delays for four time periods were calculated.

Table 3. Signal Delays at All Signalized Intersections (Route 23)

	Signal Delay (veh-hr)								
	Existing			Optimized			Saving		
Intersection	AM	Noon	PM	AM	Noon	PM	AM	Noon	PM
Vernon Stockholm(Rt.515)	15	3	4	15	4	4	0	-1	0
Canister Rd.	40	3	3	35	3	2	5	0	1
Reservior Rd.	3	2	19	2	2	4	1	0	15
Doremus Rd.	3	1	10	2	1	2	1	0	8
Paradise Rd.	6	3	5	4	2	3	2	1	2
OaK Ridge Rd.	127	18	48	114	11	24	13	7	24
Clinton Rd.	36	6	74	20	4	62	16	2	12
LaRue Rd. (NB)	6	2	19	6	3	17	0	-1	2
LaRue Rd. (SB)	83	1	2	56	2	1	27	-1	1
Kanouse (Old Route23)	54	5	20	66	2	14	-12	3	6
Echo Lake Rd.	86	4	55	74	4	32	12	0	23
Center Court	3	1	5	2	1	4	1	0	1
Kinnelon Rd. (Rt. 618)	18	13	41	5	12	32	13	1	9
Kiel Ave. & Ramp CC	4	3	11	4	3	10	0	0	1
Kakeout & Kinnelon Rd.	6	2	3	17	2	3	-11	0	0
Casecade Way	31	5	34	10	3	18	21	2	16
Boonton Ave.	176	8	34	52	10	65	124	-2	-31
Morse Ave.	86	7	12	101	6	8	-15	1	4
Cotluss Rd.	25	19	48	63	14	30	-38	5	18
Total	**808**	**106**	**447**	**648**	**89**	**335**	**160**	**17**	**112**

Total intersection delay at 17 signalized intersections dropped from 251 veh-hr, 272 veh-hr, 50 veh-hr, and 402 veh-hr to 140 veh-hr, 173 veh-hr, 36 veh-hr, and 274 veh-hr in the AM, Noon, Off peak, and PM peak periods, respectively. The total savings of 501 veh-hr and 574 veh-hr equivalent to $10,166 and $11,648 were obtained for Route 23 and 42/322 when a value of time weighting factor of $20.29 per veh-hr (Eq.13) is used. Delays and values of decision variables for users' cost saving (e.g., value of time, vehicle occupancy, vehicle split) are summarized in Table 5.

Table 4. Signal Delay at All Signalized Intersections (Route 42/322)

	Signal Delay (veh-hr)											
	Existing				Optimized				Savings			
Intersection	AM	Noon	Off *	PM	AM	Noon	Off *	PM	AM	Noon	Off *	PM
Greentree Rd.	61	55	11	72	24	20	3	55	37	35	8	17
Shopping Center Dr.	7	11	2	25	6	11	2	19	1	0	0	6
Whitman Dr.	9	13	2	19	6	10	2	15	3	3	0	4
Johnson Rd.(NB)	10	46	5	22	9	20	3	14	1	26	2	8
Fries Mill Rd.(SB)	15	13	3	15	7	10	3	9	8	3	0	6
Tuckahoe Rd.	15	24	4	24	11	19	4	14	4	5	0	10
Berlin Cross Keys Rd.	15	19	5	35	14	18	4	28	1	1	1	7
Kennedy Dr. (SB)	2	3	1	7	2	3	1	8	0	0	0	-1
Watson Dr.	14	13	2	23	9	9	2	13	5	4	0	10
Gantown Rd.	40	33	6	82	12	15	4	43	28	18	2	39
Lake Ave.	3	4	1	5	3	5	1	6	0	-1	0	-1
Sicklerville Rd.	38	18	4	47	16	13	3	23	22	5	1	24
Main St. (Rt.322)	2	2	0	4	1	2	0	2	1	0	0	2
Poplar St.	10	12	3	12	7	10	2	11	3	2	1	1
Corkery Ln.	5	3	1	4	6	4	1	6	-1	-1	0	-2
Malaga Rd.	3	2	0	3	4	2	1	5	-1	0	-1	-2
White Hall Rd.	2	1	0	3	3	2	0	3	-1	-1	0	0
Total	**251**	**272**	**50**	**402**	**140**	**173**	**36**	**274**	**111**	**99**	**14**	**128**

*****Off Peak Period

Table 5. Road Users' Cost Savings at All Signalized Intersections

Study Location	Time Period	Delay Saved (veh-hr)	Value of Time ($/hr)		Vehicle Occupancy		Vehicle Split		**User Cost Saving ($)**
			Auto	Truck	Auto	Truck	Auto	Truck	
Route 23	AM	160	12.75	21.25	1.59	1.0	0.98	0.02	3,247
	Noon	17	12.75	21.25	1.59	1.0	0.98	0.02	345
	PM	112	12.75	21.25	1.59	1.0	0.98	0.02	2,273
	Total								**5,864**
Route 42/322	AM	111	12.75	21.25	1.59	1.0	0.98	0.02	2,252
	Noon	99	12.75	21.25	1.59	1.0	0.98	0.02	2,009
	Off Peak	14	12.75	21.25	1.59	1.0	0.98	0.02	284
	PM	128	12.75	21.25	1.59	1.0	0.98	0.02	2,597
	Total								**7,143**

Fuel Consumption

The reduction in fuel consumption was computed at intersections in Route 23. Estimates of fuel consumption amounts are based on SYNCHRO outputs and the unit gasoline cost taken from http://www.newjerseygasprices.com. As shown in Figure 5, for existing signal timing, fuel consumption at signalized intersections was 1,461, 474, and 1,263 gallons for AM, Noon, and PM peak hours, respectively. After applying optimized signal timing, consumption dropped to 985, 418, and 1,050 gallons in the AM, Noon, and PM peak hours, respectively. Therefore, a total 745 gallons were saved, an equivalent at a $1,267savings.

Similarly, fuel consumption for Route 42/322 was decreased as shown in Figure 6. Consumption for existing signal timing was 567, 685, and 867 gallons in the AM, Noon, and PM period, respectively, and dropped to 433, 558,147, and 713 gallons in the AM, Noon, Off Peak, and PM period, respectively after applying optimized signal timing. A total 953 gallons were saved, an equivalent at a $1,620.

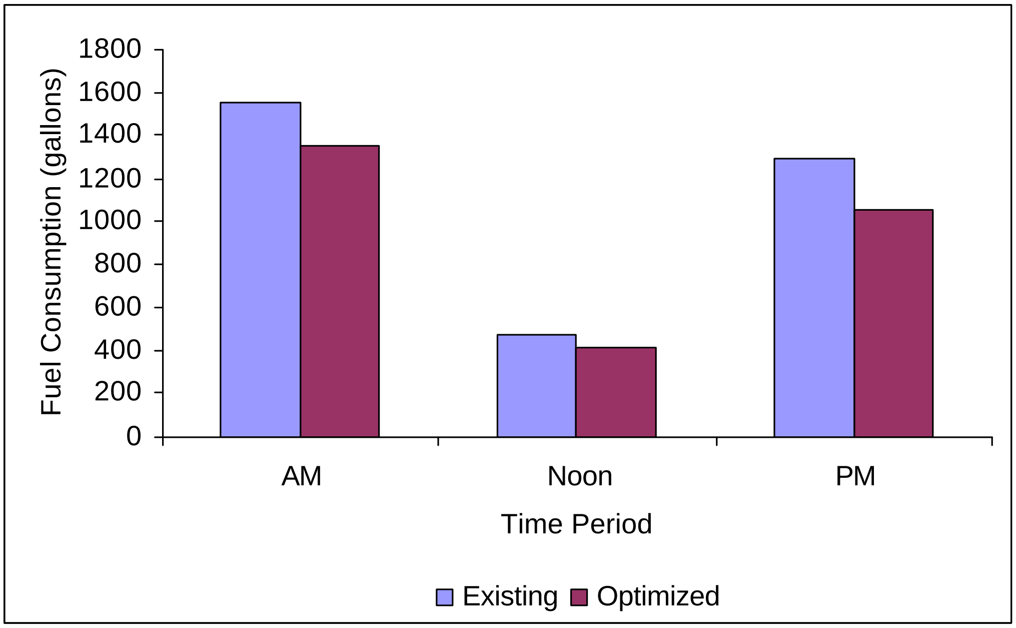


Figure 5. Fuel Consumption at All Signalized Intersections (Route 23)

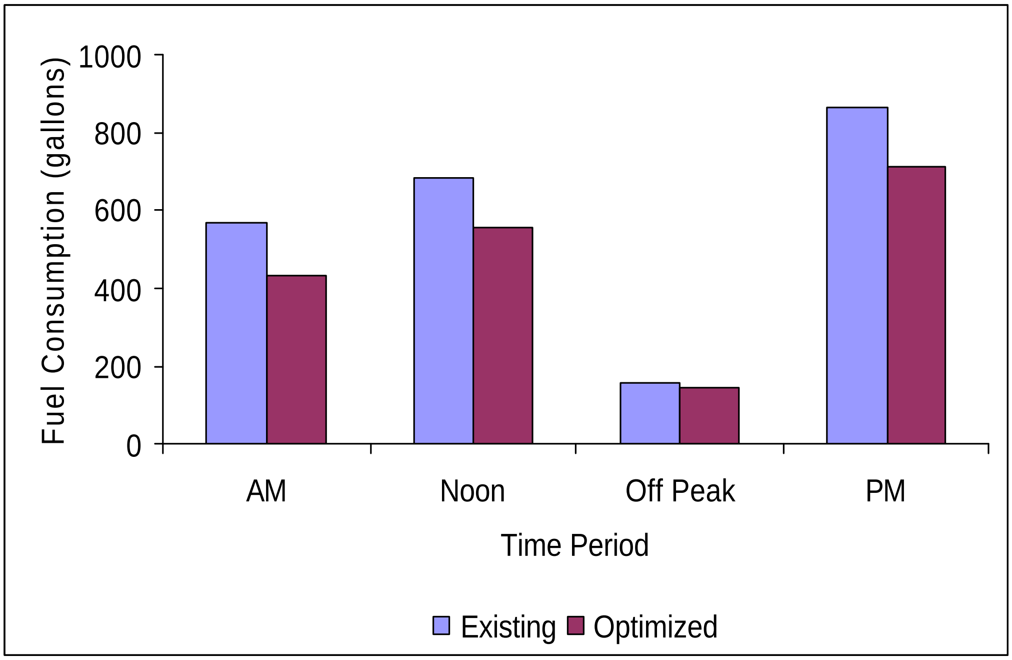


Figure 6. Fuel Consumption at All Signalized Intersections (Route 42/322)

Vehicle Emission

Emission amounts were taken from the SYNCHRO outputs for the existing and optimized signal timing plans for the study corridor. The adjusted signal timing plans resulted in a reduction in vehicle emissions. The costs of reduced pollutant amounts were computed from the emission amounts multiplied by the unit cost of a pollutant suggested previously (Table 2). The amount of emissions for the existing and optimized signal timing plans are summarized in Tables 6 and 7 for Routes 23 and 42/322, respectively.

Table 6. Vehicle Emissions at All Signalized Intersections (Route 23)

Time Period	Total Emission Rate (kg)								
	Existing			Optimized			Change		
	CO	NOx	VOC	CO	NOx	VOC	CO	NOx	VOC
AM	108.43	21.09	25.13	94.81	18.45	21.97	-13.62	-2.64	-3.16
Noon	33.43	6.53	7.73	29.63	5.76	6.87	-3.8	-0.77	-0.86
PM	90.01	17.51	20.86	74.06	14.44	17.17	-15.95	-3.07	-3.69
Total	231.87	45.13	53.72	198.5	38.65	46.01	-33.37	-6.48	-7.71

Table 7. Vehicle Emissions at All Signalized Intersections (Route 42/322)

Time Period	Total Emission Rate (kg)								
	Existing			Optimized			Change		
	CO	NOx	VOC	CO	NOx	VOC	CO	NOx	VOC
AM	39.53	7.68	9.16	30.23	5.88	7.00	-9.3	-1.8	-2.16
Noon	47.89	9.32	11.12	38.96	7.58	9.05	-8.93	-1.74	-2.07
Off Peak	10.9	2.12	2.52	10.17	1.98	2.34	-0.73	-0.14	-0.18
PM	60.69	11.81	14.07	49.82	9.71	11.55	-10.87	-2.10	-2.52
Total	196.00	38.13	45.47	129.18	25.15	29.94	-66.82	-12.98	-15.53

Based on the above analysis, total benefits obtained from optimized signal timing plan for Route 23 are 6,694 $/day and 1,747,049 $/year, and for Route 42/322 are 7,883 $/day and 2,057,463 $/year. Thus, one year B/C ratio from the results of C/B analysis is 1 to 24 and 20 for Route 23 and Route 42/322, respectively. For Route 23, as expected, most benefits are obtained from users' cost saving which is contributing 88.7% of the total benefits. Fuel consumption and vehicle emission occupy 11.05 % and 0.25% of the total benefit, respectively. For Route 42/322, significant benefits are obtained from AM and PM peak hour that represents commuter travel. Users' cost saving, fuel consumption, and vehicle emission benefits account for 90.6%, 9.18%, and 0.22% of the total benefits, respectively.

Table 8. Benefits and Costs

Study Corridor	**Time Period**	**Daily Benefits**	**Yearly Benefits**	**Cost***	**B/C ratio****
Route 23	AM	3,584	935,434		
	Noon	442	115,434		
	PM	2,667	696,182		
	Total	**6,694**	**1,747,049**	**73,494**	**1:24**
Route 42/322	AM	2,485	648,585		
	Noon	2,230	582,030		
	Off Peak	303	79,083		
	PM	2,865	747,765		
	Total	**7,883**	**2,057,463**	**102,903**	**1:20**
TOTAL		**14,577**	**3,804,512**	**176,397**	**1:21**

*:Total cost

**: Based on yearly benefit

Sensitivity Analysis

Since the C/B analysis was performed based on the current traffic volume, sensitivity analyses were performed for the cases in which traffic volume increased, and decision variables were assumed to remain unchanged. To perform the traffic volume increased sensitivity analysis, SYNCHRO was rerun with increased traffic volumes from one to five percent in all time periods for both the existing and optimized signal timing plans. A procedure for creating SYNCHRO file with an increased volume to obtain SYNCHRO output is summarized in the steps below:

1. Open SYNCHRO file.
2. Save current volume data as CSV file by using ‘Data Access’ function in SYNCHRO.
3. Open the saved CSV file in Microsoft Excel.
4. Increase traffic volume data with Excel function and save.
5. Open CSV file with the increased volume in SYNCHRO.
6. Generate output.

Sensitivity analysis with volume increase was performed with five different growth scenarios in next five future years. For example, the one percent volume scenario was increased by one percent in each year, and the two percent volume scenario was increased by two percent in each year for five years.

Figures 7 and 8 show the accumulated benefits over five years for the five growth rate scenarios for Routes 23 and 42/322, respectively. As shown in Figure 4, increasing volume from one percent to five percent resulted in gaining more accumulated benefits. While accumulated benefits with one percent volume increase per year was $16,169,841 for five years, the five percent volume increase per year more drastically increased the benefit to $23,783,826. Given the sensitivity analysis results, the increase of traffic volume would generate more benefits. Figures 9 and 10 present the two percent volume sensitivity curves applied with one, three, and five percent interest rates per year for Routes 23 and 42/322, respectively.

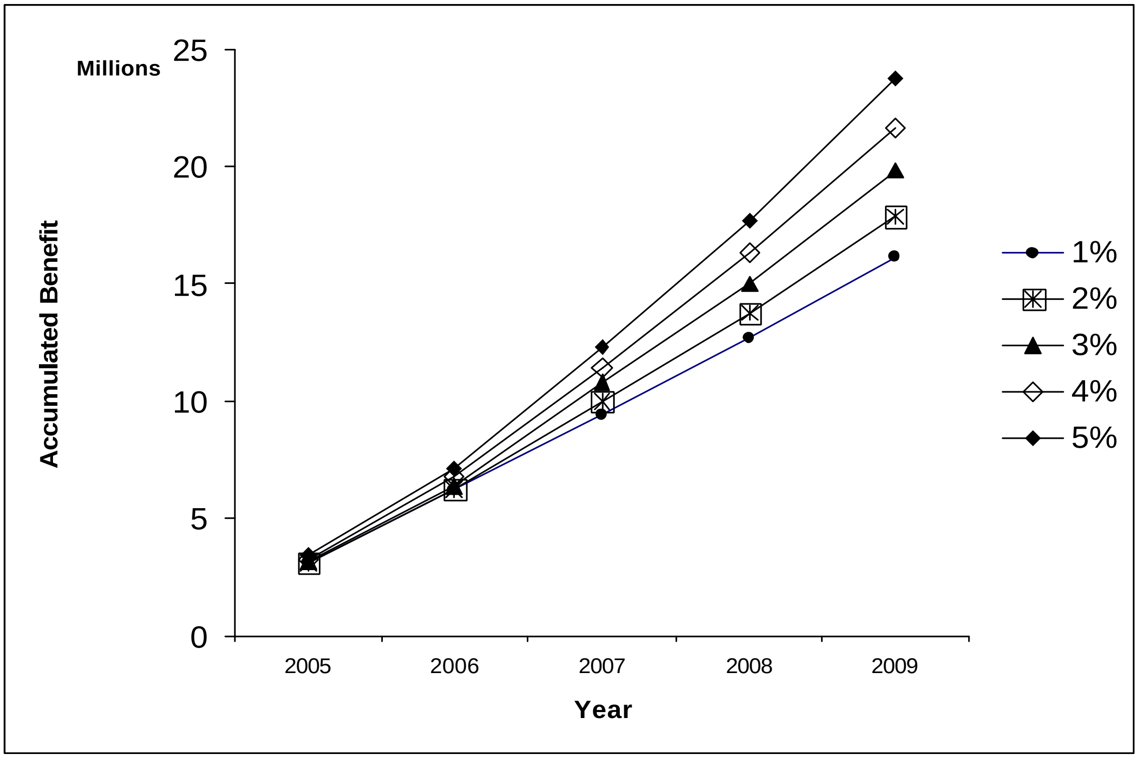


Figure 7. Benefit vs Time for Various Traffic Growth Rates (Route 23)

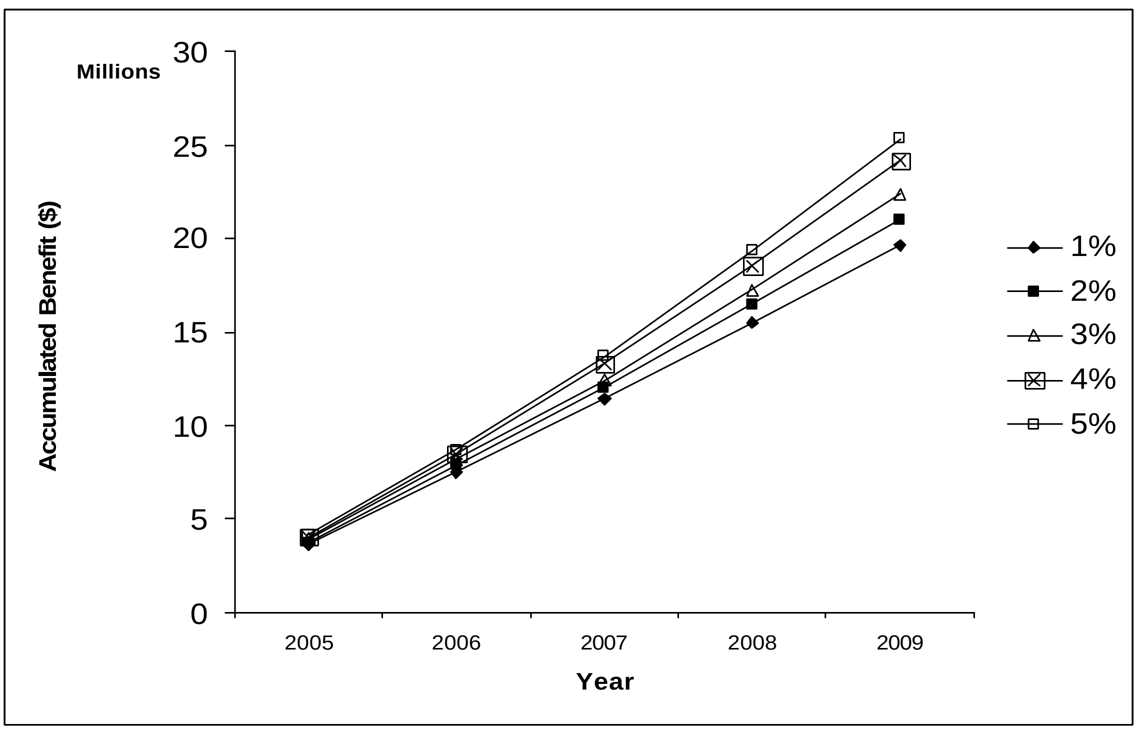


Figure 8. Benefit vs Time for Various Traffic Growth Rates (Route 42/322)

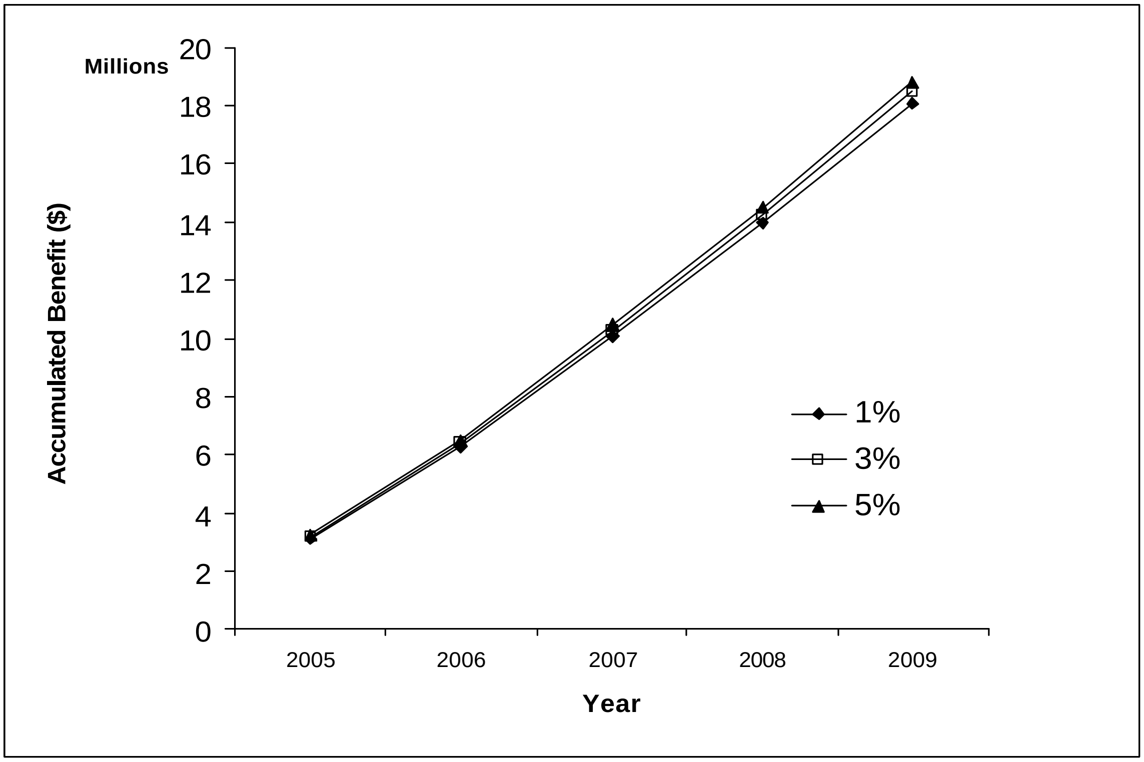


Figure 9. Benefit vs Time for Various Interest Rates (Route 23)

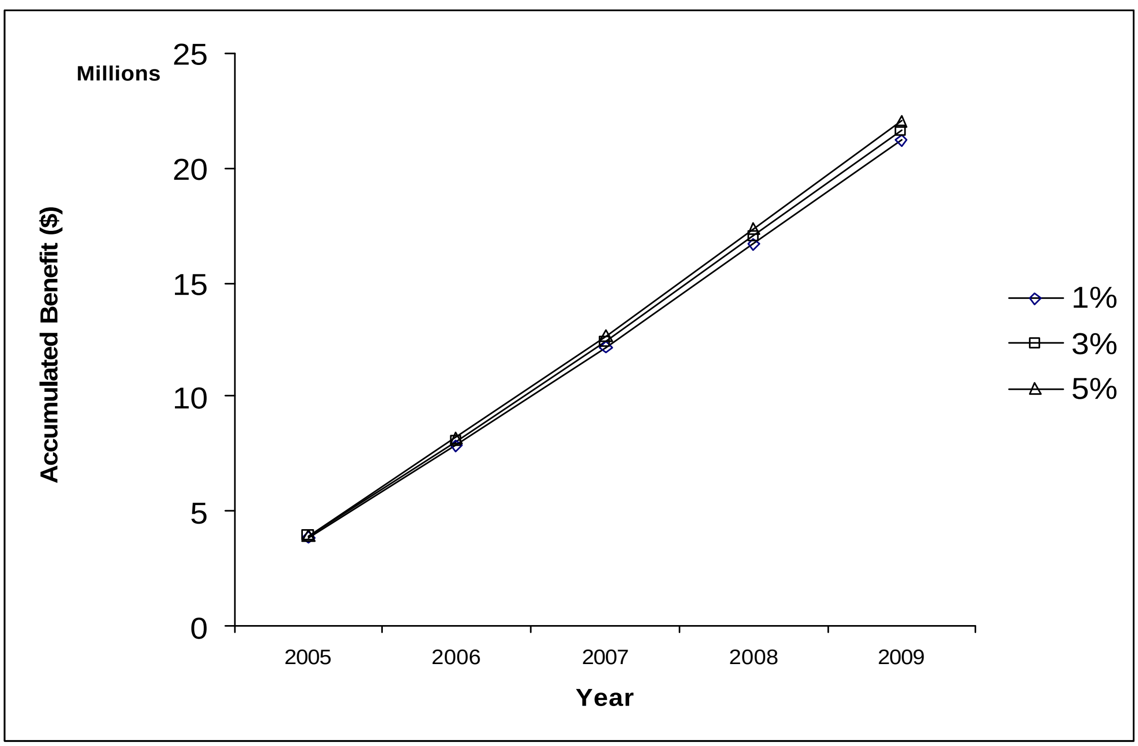


Figure 10. Benefit vs Time for Various Interest Rates (Route 42/322)

CONCLUSIONS

This study provides methodological analysis of signal timing optimization. The findings of this study indicate that three benefit categories were developed by applying optimized signal timing plans where the cost saving includes the saved travel time, fuel consumption, and vehicle emissions at the studied intersections. Among these benefits, travel time saving is the major benefit which was obtained with the optimal signal timing plans.

The optimal signal timing plans applied to this study were developed with SYNCHRO that has gained popularity as a signal timing optimization software for its simplicity of manipulation and flexibility of applications. SYNCHRO can simultaneously optimize lead-lag phase ordering in addition to cycle length, phase lengths, and coordination offsets. SYNCHRO use percentile delay estimation methodology which provides an alternative methodology that attempts to model the effects of actuation and coordination in a more realistic manner.

The initial results showed that benefits of the optimal signal timing were 6,694 $/day and 1,747,049 $/year for Route 23, and 7,883 $/day and 2,057,463 $/year for Route 42/322. The resulting B/C ratio based on yearly benefit was 1 to 24 and 1 to 20 for Route 23 and Route 42/322, respectively, and overall 1 to 21. In addition to the initial benefits, accumulative benefits indicate that yearly benefits will be drastically increased as costs are fixed.

When the optimized signal timing plans cannot operate efficiently with newer traffic patterns, signal timing should be fine-tuned to operate better. For traffic signals to operate efficiently, completly retiming of traffic signals is often necessary. It is recommended to review traffic signal and system performance continuously. Ideally, signal timing should be reviewed every year for its effectiveness and efficiency.

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APPENDIX A: LITERATURE REVIEW

The purpose of the literature review was to identify, review, and synthesize research in C/B analyses focusing on arterial signal optimization, considering both user and non-user benefits. Despite the fact that transportation planners and engineers developed many ways to evaluate traffic flows in signalized arterials, few C/B analysis reports were documented in a systematic way for optimization of signal timing projects. The review of literature followed the path of investigating existing C/B analysis models in general, then more specifically categorizing detailed cost and benefit components.

User Benefit Analysis for Highways (AASHTO Redbook)

The AASHTO Redbook (2003) has provided a comprehensive review and illustrated key methods for quantifying user benefit of highway projects through a number of practical examples. The suggested benefit analysis procedure has been summarized in Table A-1. Four modules (value of time, operating cost, accident cost, and project management) were suggested to quantify benefits, as summarized in Table A-2. The output from these modules can also be used to approximate the costs and benefits over the life of the project.

The monetary value of the road users' time was suggested to be computed by multiplying the total users' travel time and the value of time that is usually measured by dollars per hour. The value of travel time is influenced by many factors, including the income level of motorists, trip purpose, and productivity of alternative activities which time will otherwise be used for (Lee and Pickrell, 1997). While information on travelers' characteristics (e.g., income ,trip purpose, etc.) is available, they should be incorporated to determine of the value of time. Alternatively, one can adopt the value of time used in other sources as references, if there is a justification for the adoption.

Table A-1. The Basic Steps for User Benefit Analysis (AASHTO, 2003)

Step 1: Defining the project alternative and the base case • Clearly identify what improvement to the road system is being evaluated
Step 2: Determine level of detail needed • Determine analytical detail required
Step 3: Develop basic user cost factors • Develop basic user cost factors (e.g. the value of time and vehicle occupancy rates, and vehicle operating cost parameters to evaluate operational savings) • The value of time is related to the wage rate prevailing among the users of the facility, and the vehicle operating costs relate to the type of the vehicles involved
Step 4: Select economic factors • Select economic factors or parameters, such as the discount rate, the analysis period, evaluation date, inflation rates, and the value of life and injury to be used in accident analysis
Step 5: Obtain traffic data • Obtain traffic performance data. Usually the most time-consuming part of C/B analysis project. • Analyst must provide the traffic volume, speed/travel time, and other performance measurements for all of the affected road segments of both the project alternative and the base case
Step 6: Determine User Costs • Develop user cost data such as travel delay costs, vehicle operation costs, and operation costs associated with specific projects.
Step 7: Calculate User Benefits • Calculate user benefits of the project in terms of reductions in travel time costs, vehicle operation costs, and accident costs incurred by users of the project facility.
Step 8: Expand Benefits to All Project Years • Extrapolate either the traffic performance data, or to extrapolate/interpolate the user benefits calculated in selected years to other years of the project's life.
Step 9: Estimate Terminal Value • Determine the terminal value of the facility at the end of project life period used in the analysis.
Step 10: Determine Present Value of Costs and Benefits • Perform the present valuation of the stream of user benefits and capital and operating costs of the facility so as to reduce this complex stream to a single, tractable number.
Step 11: Make Project Selection Decision • Evaluate the merits of different project alternatives.

Source: User Benefit Analysis for Highways, AASHTO, 2003

Table A-2. AASHTO Benefit Analysis Module

Benefit Module	Description
Value of Time	Presents information on calculating value of travel times
Operating Cost	Presents operating costs affected by travel speed
Accident Cost	Presents accident costs calculation.
Project Management	Addresses how the user benefit components are impacted during construction period.

Source: User Benefit Analysis for Highways, AASHTO, 2003

A detailed procedure was illustrated in Table B-3 to estimate the value of time based on the average annual wage of travelers, compensation rate, and changes in travel speed and delay.

Highway Economic Requirements Systems (HERS)

Highway Economic Requirements Systems (HERS) is a computer model developed by FHWA (1999) for estimating the benefit of potential transportation improvement using incremental life-cycle C/B analysis. A key component of HERS is its ability to compare aggregated travel times for a base case and an improved case. Several computer algorithms were developed in HERS to estimate the benefits, while an economic value on travel time savings was applied to approximate the benefit in monetary value.

While using HERS, specific data listed below must be obtained to estimate travel time savings:

- The average wage rate;
- The average hourly wages for truck drivers;
- Fringe benefits for truck drivers;
- The average vehicle occupancy for on-the-clock trips (trips for one’s employer) and off-the-clock trips (personal travel) in automobiles;
- Average vehicle cost per year of heavy trucks;

Table A-3. Procedure for Value of Time Calculation

STEP 1: Data Collection

- Obtain value of time data based on mode and trip purpose.
- In addition to mode and purpose, determine compensation rate: the percentage of compensation rate for each transportation mode and purpose is shown in table A
- Obtain hourly wage data: average wages and total compensation by industry are shown in table B
- Determine average vehicle occupancy

STEP 2: Estimating Value of Travel Time Saved

(a) Value of time saved due to change in speed in roadway segment

$$\Delta_{c} = 100 \, O_{c} \left(\frac{1}{S_0} - \frac{1}{S_1} \right)$$

Equation 1: Value of travel time saved

where:

[illegible]$_c$ = the value of travel time savings enjoyed by user class *c* (cents per vehicle- mile)

[illegible]$_c$ = the value of time for user class *c* (dollars per hour)

[illegible]$_c$ = the occupancy rate of vehicles of user class *c*

S_0, S_1 = the speed without (S_0) and with (S_1) the improvement (miles per hour)

(b) Value of time saved due to change in intersection delay

H intersection, c = D / 3600 ((V 0c + V 1c) / 2) 100M O c [illegible]

Equation 2: value of time saved due to change in delay

where:

[illegible] intersection, c = change in the value of travel time through an intersection, user class *c*
= dollars per affected intersection motion

[illegible] = [illegible]$_0$ − [illegible]$_1$ = the change in intersection delay per vehicle, in seconds

[illegible]$_{0c}$, [illegible]$_{1c}$ = vehicle volumes without and with the intersection improvement

[illegible]$_c$ = the value of time for user class *c* (dollars per hour)

[illegible]$_c$ = vehicle occupancy, in persons per vehicle

Source: User Benefit Analysis for Highways, AASHTO, 2003

- The average value of commodities shipped by axle combination;
- The percentage of automobiles that are in commercial light trucks;
- Initial vehicle costs for automobiles in commercial motor pools and four-tire trucks;
- The percentage of vehicle-miles that were on-the-clock for four-tire trucks; and
- Indices to adjust 1995 dollars to those of the study year.

For on-the-clock trips (trips for one's employer), HERS values time savings based on wages, fringe benefits and for some types of trucks, vehicle cost and inventory costs. Off-the-clock (personal trips) time savings are estimated using choice situations that ask travelers to select between saving time versus saving money or having a safer roadway.

HERS applies estimates of the average value of travel time for each of seven vehicle types (Table A-4). Using the values presented in Table A-4, estimates are generated in year 2000 dollars. This value of time may be indexed from 1995 dollars to dollars of any other year using the Bureau of Labor Statistics (BLS) data on average hourly earning of civilian workers. For trucks, one can use BLS data on mean hourly earnings of truck drivers (by truck type).

HERS uses the following equation to estimate travel time costs:

$$TTCST_r \quad \frac{\quad}{AES_r} \times TVAL_r$$

where, $\;_r$ = average travel time cost ($/thousand vehicle-miles) for vehicles of type *r*

$\;_r$ = average effective speed of vehicle of type *r* on the highway section being analyzed.

$\;_r$ = average value time (in dollars) for occupants and cargo traveling In vehicles of type *r* (as shown on the bottom line of Table 4)

HERS is becoming one of the more commonly used tools for calculating travel time savings. Note that it values time savings for on-the-clock trips on the basis of the savings to the employer and off-the-clock time savings at 60 percent of the wage rate exclusive of benefits. The value of passengers' time is assumed to be 45 percent of the wage rate.

Table A-4. Value of Travel Time per Hour

Category	Vehicle Class						
	Small Automobile	Medium Automobile	4-tire truck	6-tire truck	3-or 4-axle truck	4-axle comb.	5-axle comb.
On-the-clock*							
Labor	$28.36	$28.36	$19.45	$23.62	$19.67	$23.69	$23.69
Vehicle	1.86	2.18	2.35	3.32	9.49	8.01	8.61
Inventory	0.00	0.00	0.00	0.00	0.00	1.78	1.78
Total	$30.22	$30.54	$21.80	$26.94	$29.16	$33.48	$34.08
Other Trips							
% of miles	90	90	69	0	0	0	0
Value	$13.79	$13.79	$13.79	NA	NA	NA	
Weighted Average	$15.44	$15.47	$16.28	$26.94	$29.17	$33.48	NA

*: On-the-clock trips (trips for one's employer), Off-the-clock (personal trip)

Source: Guidebook for Assessing the Social and Economic Effects of Transportation Projects (2001)

In addition to the average annual wage of travelers and detailed data mentioned above, detailed analysis procedures as discussed in Table A-5 will be performed in HERS.

With HERS, Gillen et al. (1999) performed a C/B analysis for an ITS project titled: Evaluated the Benefit of Electronic Toll Collection (ETC). An aggregated travel time saving model was developed by considering queuing delay, vehicle occupancy, value of time, and population of different vehicle modes. Results of travel time saving were obtained for passenger cars, buses and trucks. In that study, a cost of 12.75 $/hr for automobiles and buses, and 33.41 $/hr for trucks for estimating hourly travel time cost (dollars in 1988). To compute the average hourly wage rate, the employment cost index published by the U.S. Bureau of Labor Statistics was used.

Table A-5. Five-step Analysis Procedure for Travel Time Saving (HERS)

Step 1 • Measure the current travel time and average annual daily traffic (AADT) on the unimproved facility. • Estimate the change in travel time required to traverse a corridor, as well as change in AADT
Step 2 • Estimate the vehicle occupancy rate of current travelers along the corridor. • Estimate the vehicle mix between automobiles and trucks
Step 3 • Estimate the number of vehicle hour • Calculate the total number of automobile and truck person hours
Step 4 • Apply the HERS fraction of person hours saved calculated in Step 3 • Apply the current average wage rate plus fringe benefits for the area
Step 5 • Apply the average wage for employees of trucking companies plus the fringe benefit rate • Add an average figure of $7 per hour for truck operating costs and another $.80 for vehicle Inventory

Source: Guidebook for Assessing the Social and Economic Effects of Transportation Projects (2001)

Road User Cost Manual

Road user cost components are well defined in Road User Cost Manual, (NJDOT, 2001). This manual familiarizes the cost and benefit analyst with work zones and corresponding traffic characteristics, explains the potential work zone related road user cost components that can occur, and presents a detailed procedure through a number of examples to determine road user costs.

It was found that ten potential work zone related road user cost components. Three components [speed change VOC (vehicle operating cost), speed change delay, and work zone delay] are associated with a base case situation where traffic operates under “unrestricted flow” conditions. Four components [stopping VOC, stopping delay, queue delay, and queue idling VOC] are associated with a queue situation where traffic operates under “forced flow” conditions. Two components [circuity VOC and circuity delay] are associated with a "circuity" situation where traffic is forced to utilize a detour to avoid a highway work zone. The final component is associated with "crash costs". These user cost components are summarized in Table A-6.

Example problems, default hourly traffic percentages, and calculation worksheets are also provided to calculate the road users costs. In the section titled 'Road User Costs at a Signalized Intersection' (problem 6), New Jersey drivers' values of time of 12.75 $/hr for passenger cars and 21.75 $/hr for trucks are suggested. Both AASHTO and HERS models also provide procedures for calculating road users' hourly value of time,

Table A-6. Road User Cost Components

	Cost Components
Unrestricted Flow	• Speed Change VOC (Vehicle Operating Cost) • Speed Change Delay • Work Zone Delay
Forced Flow	• Stopping VOC • Stopping Delay • Queue Delay • Queue Idling VOC
Circuity	• Circuity VOC • Circuity Delay
Crash Costs	• Crash Cost

Source: Road User Cost Manual, NJDOT (2001)

however, these calculations require average road users' wage compensation data that is not available to be applied in this study. For this reason, the hourly road user travel time value suggested in Road Users Cost Manual is applied for conducting this C/B analysis to compute travel time savings. Table A-7 shows the differences of value of time among AASHTO Red book, HERS, and Road User Cost Manual.

Table A-7. Value of Hourly Travel Time

	Value of Time ($/hr)		
Vehicle Type	Road User Cost Manual (NJDOT), 2001	HERS (FHWA), 1999	Redbook (AASHTO), 2003
Auto	12.75	30.22* (15.44)**	13.92
Truck	21.25	29.16* (29.17)***	21.24

- indicates on-the-clock trip
- ( )** personal trip
- ( )*** 3 or 4 axle truck personal trip

Fuel-Efficient Traffic Signal Management (FETSIM)

Fuel efficiency benefit of signal timing optimization was discussed extensively in the FETSIM (1994) project. The objective of the FETSIM project was to evaluate retimed traffic signals. The FETSIM demonstrated that improving traffic signal timing is a cost-effective way to reduce vehicle stops, delays, and fuel consumption. Annual fuel savings alone outweighed the total program costs by more than 5:1 benefit-to-cost (B/C) ratio, based on the TRANSYT-7F model.

FETSIM program used TRANSYT-7F as a simulation engine to approximate results, and the outcomes were compared with field data. Field tests were conducted using the floating car technique, in which a vehicle is driven on selected routes at the perceived average speed of traffic flow and a recorder makes manual entries of travel time, delay and stops. Based on TRANSYT-7F output, the retimed FETSIM project produced an average of 7.8 percent reduction in fuel consumption. Overall program benefit was 8.5 percent reduction in fuel consumption.

The Surface Transportation Efficiency Model (STEAM)

STEAM is a model developed by the Federal Highway Administration (FHWA) to estimate user benefits, costs, and externalities of transportation projects, based on trip tables (person trip tables for passenger travel and vehicle trip tables for truck travel) and networks from four-step travel demand models. Travel time and cost matrices are skimmed from transit networks and from highway networks.

STEAM was developed for estimating the impacts of multimodal transportation alternatives in a system-planning context. Cost-effectiveness evaluation of alternatives is a complex process requiring close interaction among planning professionals, decision makers, and citizens. Such assessments require an understanding, estimation, and comparison of the wide range of impacts transportation alternatives typically generate. A variety of economic, financial, social, and environmental impacts must be assessed and tradeoffs made to present decision makers with good information.

STEAM provides default analysis parameters for seven modes (auto, truck, carpool, local bus, express bus, light rail, and heavy rail) and allows the user to accommodate special circumstances or new modes by modifying these parameters. The software develops impact estimates for a wide range of transportation investments and policies, including major capital projects, pricing, and travel demand management (TDM). Impact measures are monetized to the extent feasible and quantitative estimates of natural resource usage (e.g., energy consumption) and environmental impacts (e.g., pollutant emissions) are also provided.

STEAM consists of four modules:

- A User Interface Module, which includes on-line help files.
- A Network Analysis Module, which reads a file containing highway link data and produces zone-to-zone travel times and distances based on minimum time paths.
- A Trip Table Analysis Module, which produces estimates of user benefits based on a comparison of Base Case and Improvement Case travel times and out-of-pocket costs for each zone-to-zone trip interchange for a given forecast year. It also produces estimates of pollutant emissions, noise costs, accident costs, energy consumption, and other external costs associated with highway use.
- An Evaluation Summary Module, which calculates net present worth and a B/C ratio for the improvement under consideration. It also provides summary information on individual benefit and cost items, and probability distributions of several performance measures based on a risk analysis.

ITS Development Analysis System (IDAS)

In order to integrate intelligent transportation systems (ITS) into the planning process, the Federal Highway Administration (1997) initiated a program to develop a tool to help planners address these transportation planning issues. IDAS is an ITS sketch-planning analysis tool that can be used to estimate the impacts, benefits and costs resulting from the deployment of ITS. IDAS operates as a post-processor to travel demand models, used by Metropolitan Planning Organizations (MPO), local agencies, and State

Departments of Transportation (DOT) for transportation planning purposes. IDAS implements the modal split and traffic assignment steps associated with a traditional planning model. These steps are key to estimating the changes in modal, route, and temporal decisions of travelers resulting from the application of ITS.

The set of impacts evaluated by IDAS include changes in user mobility, travel time/speed, travel time reliability (non-recurrent congestion), fuel costs, operating costs, accident costs, emissions, and noise. The performance of selected ITS options can be viewed by market sector (mode), facility type, and district. IDAS can produce a benefit/cost summary report and a performance summary report. Given the diverse types of performance measures that may be impacted by ITS, and the requirements to provide a comprehensive analysis tool, IDAS is comprised of five different analysis modules:

- An Input/Output Interface Module (I/O);
- An Alternatives Generator Module (AGM);
- A Benefits Module;
- A Cost Module; and
- An Alternatives Comparison Module (ACM).

The Benefits Module is further comprised of four submodules: Travel Time/Throughput, Environment, Safety, and Travel Time Reliability. Within each of these submodules, both traditional benefits of ITS deployment (e.g., improvement in average travel time) and non-traditional benefits (e.g., reduction in travel time variability) are estimated.

The IDAS Cost Module estimates the life-cycle expenditures by year and the average annual costs for ITS improvements. The cost estimates include public sector capital costs, public sector operating and maintenance costs, private sector capital costs, and private sector operating and maintenance costs. The Cost Module compiles costs based upon the inventory of ITS equipment associated with the ITS components deployed by the user. These costs were obtained from the National ITS Architecture and updated information, and are modifiable by the user.

Valuation of Emission Rate

Valuation of reduced vehicle emission rate has been discussed extensively in the transportation economic literature. There are a number of ways to determine value of pollution reduction. One is called direct damage costing method, which determines the value of pollution based on the amount of economic or health damages caused by pollution (Small and Kazimi, 1995; Ottinger,et al., 1990; and Fuller et al*.*,1983). According to Small and Kazimi, the unit costs of health damage are 0.0063 $/kilogram of CO, 1.22 ~ 1.33 $/kilogram of HC and NOx, respectively, in the 1995 dollars.

Another method to value the cost of removing pollutant is to determine the unit cost. Wang and Santini (1993) determined the removal unit cost for pollutants based on the cost of replacing typical gasoline powered cars with electric vehicles. The values provided by the Illinois EPA (1993) were based on the costs of buying older, high polluting cars and destroying them. The unit estimates of Bernard and Thorpe (1994) were taken from studies of railroad electrification for emission reduction. The pollutants unit cost applied in those studies are presented in Table A-8.

Table A-8. Cost Estimates of Air Pollution

Source	NOx ($/kg)	HC ($/kg)	CO ($/kg)
Bernard and Thorpe (1994)	8.21	6.7	1.1
Wang and Santini (1993)	27.84	22.69	0
Illinois EPA (1993)	24.16	3.81	N/A
Small & Kazimi (1995)	1.22~1.33	1.22~1.33	0.0063

Source: Assessing the benefits and costs of ITS projects (1999)

Small and Kazimi (1995) discussed the average cost of health damage to evaluate the impact of vehicle emission since the environmental effect of pollution on health is more tangible to daily life. In that study, a pollutant emitted into the atmosphere changed the spatial and temporal patterns of ambient concentrations of that pollutant and perhaps others. These patterns were determined by atmospheric conditions, topographical features and the presence of other natural or man-made chemicals in the air. The resulting ambient concentrations interacted with people, buildings, plants and animals in a way that depends on their locations and activity levels. The results included physical and/or psychological effects: coughing, erosion of stone, retarded plant growth, injury to young, loss of pleasurable views, and so forth. Most studies of direct air pollutant damages found that human health effects are the dominant component of air pollution costs.

Value of Time

Hensher (1978) conducted a comprehensive literature review and identified many key questions for future research. He discussed several approaches to valuing commuter travel time and outlines some of the advantages of adopting stated preference methods to collect survey data, based partly on a critique of revealed preference techniques. For example, the relationship between how travelers perceive attributes and how they are reported is unclear, as is the relationship to attribute measurement done by the researcher. More recent reviews have suggested a consensus that the value of time for work trips is about 50 percent of the wage rate on average and that it varies with income or wage rate, but not necessarily proportionally

APPENDIX B: BENEFIT ANALYSIS TOOL (BAT)

BAT is a Microsoft Excel based package developed by NJIT research team to calculate the benefit of signal timing optimization using results generated by SYNCHRO, including reduced delay, fuel consumption, and vehicle emission. The step procedure for using the BAT package is illustrated and discussed below.

Step 0. Activate BAT

Click BAT Microsoft Excel file.

Step 1. Import SYNCHRO Results

1. Select **Data Input** sheet by clicking "**Data Input**"
2. On the **Data** menu, point to **Import External Data**, and then click **Import Data**. (Figure B-1)

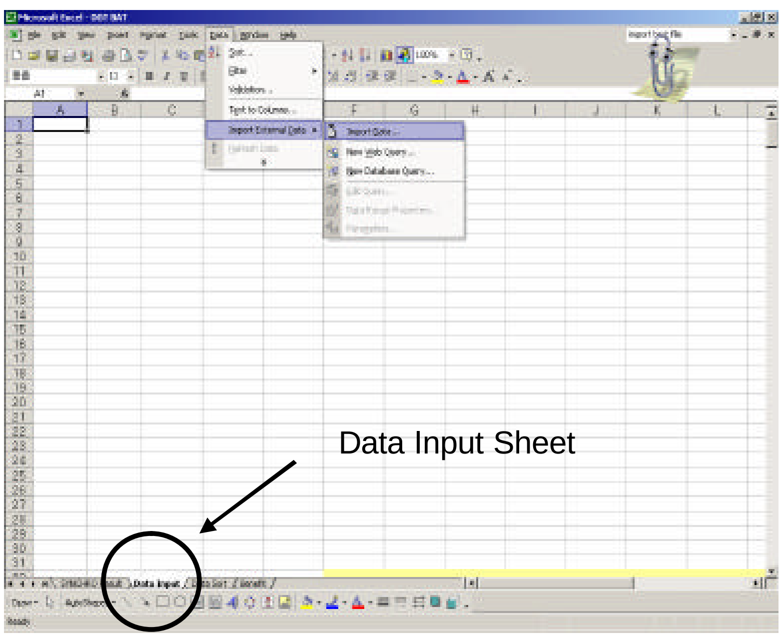


Figure B-1. Data Input sheet

3. In the **Files of type** box, click **Text Files** (Figure B-2)

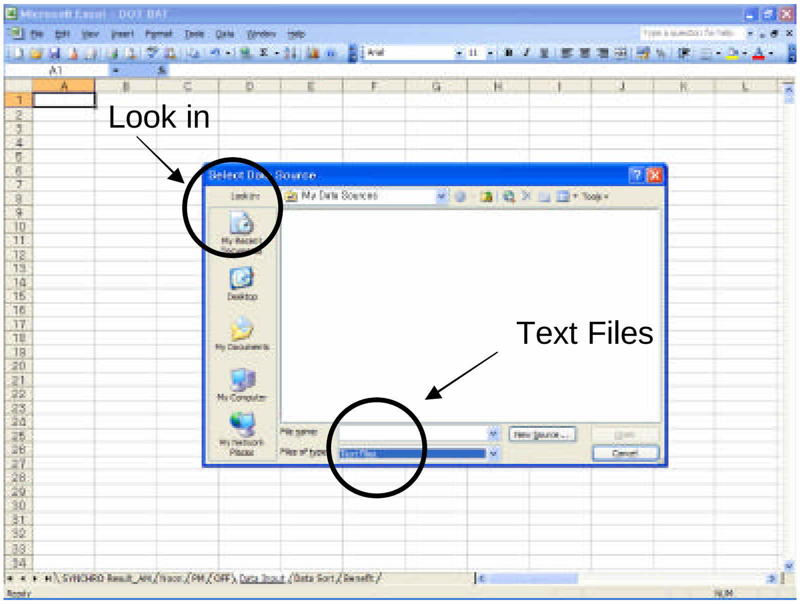


Figure B-2. Files of type box

4. In the **Look in** list, locate and double-click the created **SYNCHRO report file, ‘rt23amexnpv7SEP4’,** saved as text file.
5. In the **Text Import Wizard** window, click **Finish**.
6. In the **Import Data** dialog box, click cell A1, and then click **OK**. (Figure B-3)

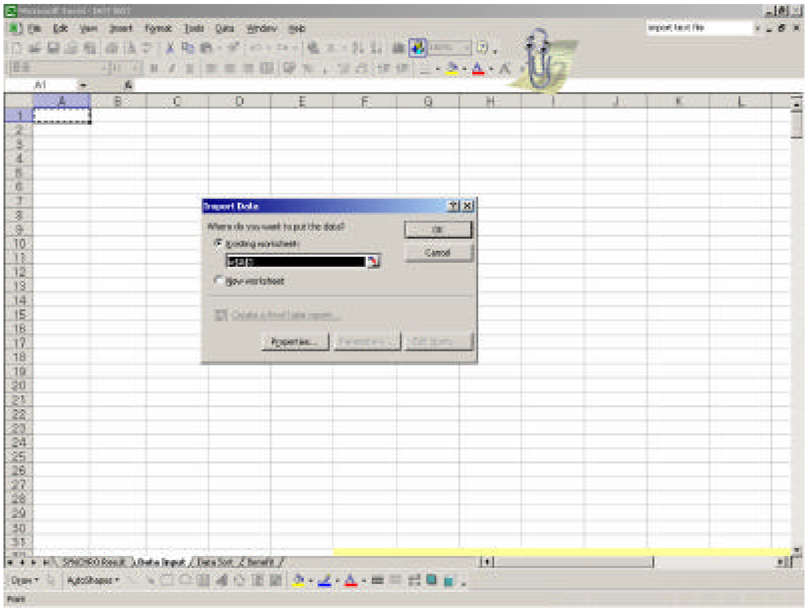


Figure B-3. Import Data Dialog Box

7. Completed **Data Input** sheet will be shown in Figure B-4.

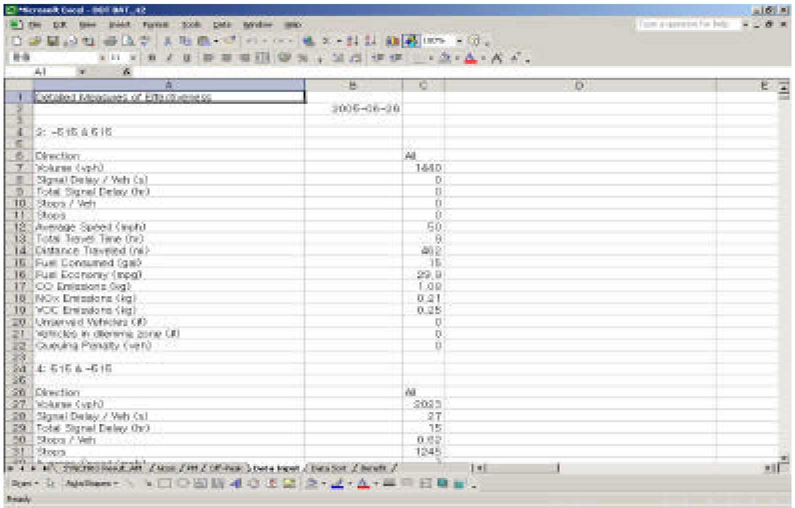


Figure B-4: Completed Data Input Sheet

Step 2. Sort SYNCHRO Results

1. Select **Data Sort** sheet.
2. On the Tools Menu, point to **Macro**, and then click **Macros**.
3. In the **Macro name** box, click '**Sort_Route_23**' (Figure B-5) to sort Input Data for Route 23 (**Sort_Route_42** for Route 42/322)

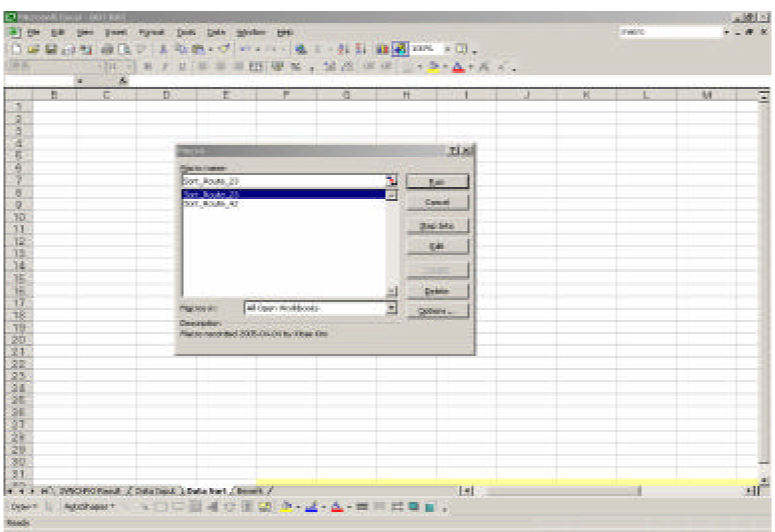
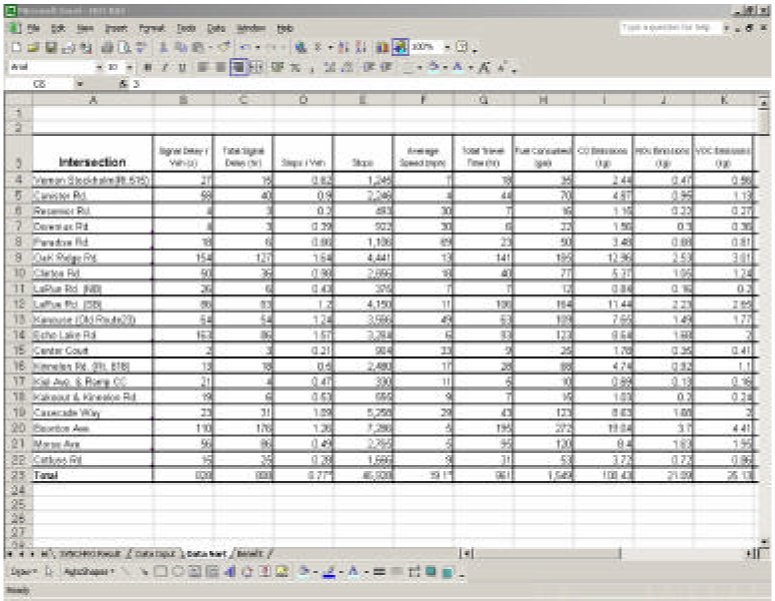


Figure B-5. Macro Selection

4. Click **Run**. By running macro, the sorted results will be shown in **Data Sort** sheet (Figure B-6)



Intersection	Signal Delay / Veh (s)	Total Signal Delay (hr)	Stops / Veh	Stops	Average Speed (mph)	Total Travel Time (hr)	Fuel Consumed (gal)	CO Emissions (kg)	NOx Emissions (kg)	VOC Emissions (kg)
Vernon Stockholm(Rt.515)	27	16	0.82	1,246	7	18	35	2.44	0.47	0.56
Canistear Rd.	58	40	0.9	2,246	4	44	70	4.87	0.95	1.13
Reservoir Rd.	4	3	0.2	483	30	7	16	1.16	0.22	0.27
Ceremax Rd	4	3	0.29	922	30	6	22	1.58	0.3	0.36
Paradise Rd	18	6	0.88	1,106	65	23	50	3.48	0.68	0.81
Oak Ridge Rd.	154	127	1.64	4,441	13	141	195	12.96	2.53	3.01
Clinton Rd	90	36	0.98	2,666	18	40	77	5.37	1.05	1.24
LaRue Rd. (NB)	26	6	0.43	376	7	7	12	0.84	0.16	0.2
LaRue Rd. (SB)	86	83	1.2	4,150	11	106	164	11.44	2.23	2.65
Kanouse (Old Route23)	54	54	1.24	3,566	49	63	109	7.65	1.49	1.77
Echo Lake Rd	163	86	1.57	3,284	6	93	123	8.64	1.68	2
Center Court	2	3	0.21	984	33	9	25	1.78	0.35	0.41
Kinnelon Rd. (Rt. 618)	13	18	0.6	2,480	17	28	68	4.74	0.92	1.1
Kiel Ave. & Ramp CC	21	4	0.47	330	11	6	10	0.69	0.13	0.16
Kakeout & Kinnelon Rd	19	6	0.63	666	9	7	16	1.03	0.2	0.24
Cascade Way	23	31	1.09	5,258	29	43	123	8.63	1.68	2
Boonton Ave	110	176	1.36	7,298	5	195	272	19.04	3.7	4.41
Morse Ave	96	86	0.49	2,255	5	95	120	8.4	1.63	1.95
Cathyon Rd	15	39	0.28	1,666	9	31	53	3.72	0.72	0.86
Total	[illegible]	[illegible]	0.77	46,208	19.17	961	1,549	108.43	21.09	26.13

Figure B-6. Completed Data Sort Sheet

5. On the **Tools** Menu, point to **Macro** again, and then click **Macros**
6. In the **Macro name** box (Figure B-7), click one of the following macros to transfer **signal delay**, **fuel consumption**, and **vehicle emission** results to **SYNCHRO Results sheet** (e.g., for existing AM peak period, click 'Existing_AM'). There are 8 Macros designed for different time periods:

- Existing_AM
- Existing_Noon
- Existing_PM
- Existing_Off-Peak
- Optimized_AM
- Optimized_Noon
- Optimized_PM
- Optimized_Off-Peak

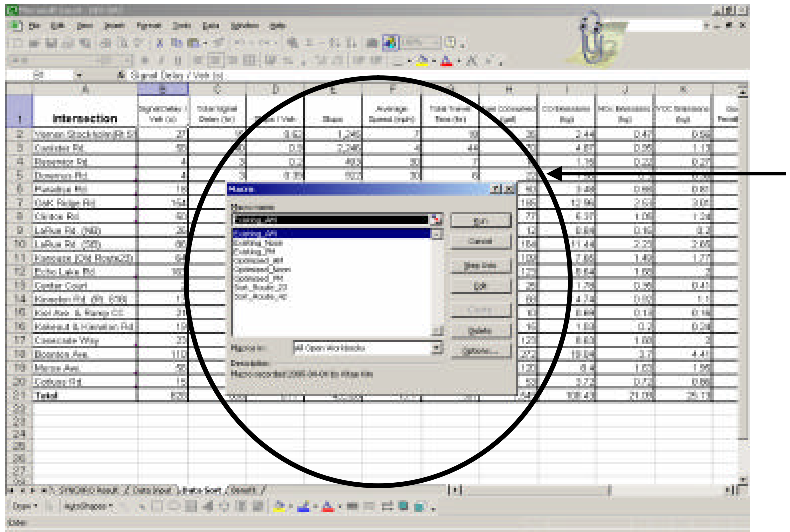


Figure B-7. Macro Selection

Step 3.

Repeat Steps 1 and 2 until all time periods (AM, Noon, PM, and Off-Peak) of existing and optimized signal timing conditions are evaluated. Go to Step 4.

Step 4. Input Parameters

1. Select **SYNCHRO Results** sheet

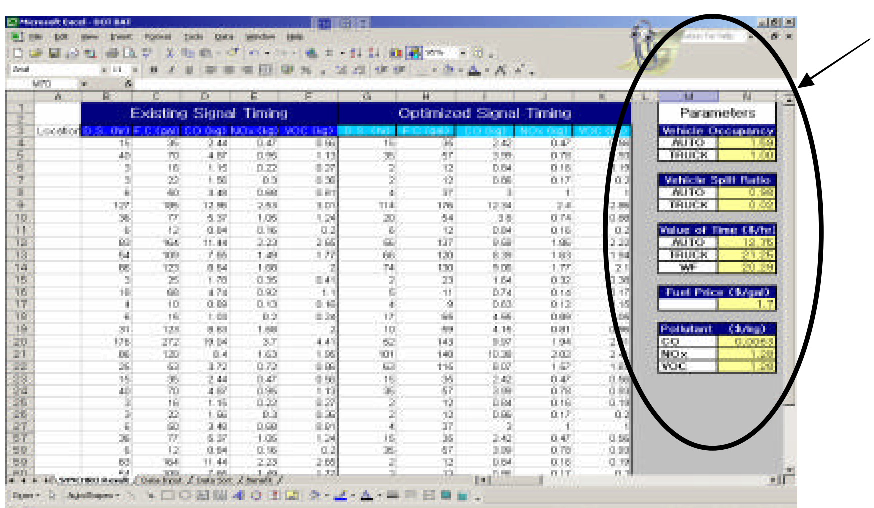


Figure B-8. Completed SYNCHRO Results

2. On the **SYNCHRO Results** sheet, Input the value of following model parameters (Figure B-8)
    - vehicle occupancy
    - vehicle split ratio
    - value of time
    - fuel price
    - pollutant unit price

Step 4. Calculate Benefit

1. Click **Benefit sheet**, all evaluated time period (AM, Noon, PM, and Off-Peak), daily, and yearly benefits will be shown. (Figure B-9)

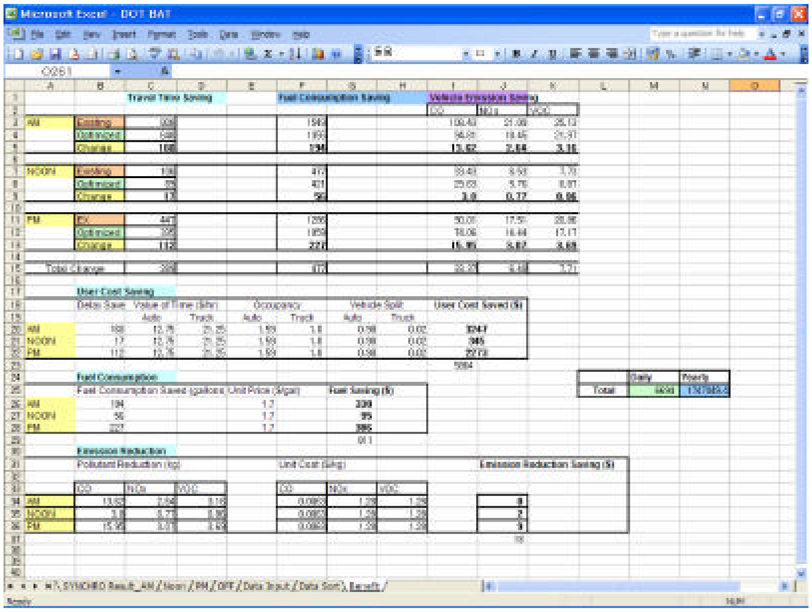


Figure B-9. Completed Benefit Sheet