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# Assessing Longitudinal Arterial Performance and Traffic Signal Retiming Outcomes

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## ABSTRACT

Agencies often find it difficult to justify investments in active traffic management. Historically, it has been a challenge to obtain data that would help make the case for those investments. While new data sources have emerged recently, there remains very little documentation of the potential long term benefits from signal retiming using associated performance measures. This study presents a use case for an active traffic management strategy on a signalized corridor over a 5-year period, during which traffic volumes increased by approximately 36%, and offset optimization was performed every 2-3 years. Despite the considerable volume growth, the number of vehicles arriving on green increased by more than 41%, and the percentage of vehicles arriving on green increased by 10%, a gain of 6 percentage points. Furthermore, drivers experienced an average of 5% reduction in travel time and travel time reliability costs after each optimization. The re-timing resulted in a 5-year Net Present Value of approximately \$3.7 million, and Benefit-Cost Ratio of 52. Agencies can utilize these strategies to quantitatively assess how traffic performance and signal timing degrade over time, in a manner similar to physical infrastructure assets. The results highlight the benefits and associated business case of adopting a long-term active traffic management strategy, based on data-driven performance monitoring and decision making.

## INTRODUCTION

Every year, agencies spend approximately \$1 billion on traffic signal-related maintenance and upgrades. Approximately half of this goes to maintenance and repair of physical infrastructure, while only 20% is dedicated to retiming and optimization of progression (1). Many agencies are reluctant to dedicate a larger percentage of their budgets for routine retiming, due in part to considerable uncertainty about how traffic signal timing “ages” in response to changing volumes and travel patterns. As a result, agencies often retime corridors on fixed schedules or according to “rule-of-thumb” estimates, rather than considering data-driven performance measures (2).

Historically, studies examining longer-term microscopic trends in traffic performance have approached the topic from an external perspective, without active intervention on the system(s) in question. For instance, Day et al. compiled a statewide, multi-year ranking of signalized corridors using measures of travel time and travel time reliability (3). The extent to which specific timing plan modifications impacted these travel times was not extensively considered. Numerous other research programs have been established for the purpose of passively monitoring corridor travel time and travel time reliability (4, 5, 6). For those studies which do consider active signal timing intervention over a number of years, the primary focus has been on fully automated solutions, such as adaptive traffic control. For example, Stevanovic et al. conducted a 10-year evaluation of the SCATS system in Utah, using microsimulation, and found that data-driven timing strategies offered substantially improved performance to static timing plans (7).

One notable study which previously estimated large-scale, long-term performance measures for traffic signal systems was performed by the Bavarian Road Administration. This research used anonymized GPS data to calculate measures of vehicle delay near established traffic signals. While this study did consider changes in vehicle delay due to signal timing, signal controller event data was not incorporated in the evaluation process (8).

Based on current research, there exists a significant need for published data and results for specific signal timing improvements, assessed over a much longer period of time than traditional before/after analyses, which tend to focus on only a few weeks of data surrounding an

intervention. This study aims to partially fill a gap in the literature on long-term active traffic management, by examining a moderately-congested signalized corridor over a period of 5 years, and looking at how periodic retiming driven by high-resolution event data can mitigate degradation in travel times and signal timing performance. The results can help agencies to better understand signal timing in an asset management context, and provide evidence that active long-term monitoring and planning for the maintenance of non-hardware signal assets (such as signal timing plans) can generate significant returns.

## METHODOLOGY

### Five-Year Signal Timing Plan Maintenance and High Resolution Data Collection

State Road (SR) 37, shown in Figure 1, was selected for the longitudinal study, and is actively maintained by the Indiana Department of Transportation (INDOT). In 2012, a new signal was installed at the 135<sup>th</sup> Pl. intersection, which may account for some of the volume growth. Also during the study period, the interchange at SR37 and I-69 was expanded from having one lane to two lanes in each direction. This improvement eliminated occasional queuing near 126<sup>th</sup> St., which affected the southbound direction in the AM peak and the northbound direction during the PM peak. Construction was ongoing for most of 2013, and the additional lanes opened in November 2013. While this eliminated some peak period queue spillbacks affecting the south end of the corridor, the added ramp lanes may also have accelerated the growth in corridor traffic volumes over the final years of the analysis period.

The signals used in this analysis are all controlled with NEMA, TS/2 signal controllers, capable of logging high resolution signal controller data. The side streets and mainline left turn movements are controlled using stop bar detection, while the arterial through movements contain advance loop detectors only, set back approximately 400' from the intersection.

Three different offset optimizations were carried out during the analysis period: summer 2010, summer 2013, and summer 2015. Each optimization was performed using high resolution event data and an objective function designed to maximize total arrivals on green. This methodology will be described further in the next section.

For all three offset optimizations, data was gathered separately for weekday and Saturday time-of-day (TOD) plans. For the 2010 and 2013 offset optimizations, approximately three weeks of data before and after the optimization were gathered to generate the relevant performance measures. For the 2015 offset optimization, one week of data was collected before the optimization, and two weeks after the optimization. For the weekday and Saturday time periods, data was collected from 0600 to 1900. A total of five timing plans were considered on weekdays and four timing plans on Saturdays.

### Offset Optimization

Optimization of progression requires an understanding of vehicle arrival characteristics at each signalized approach. It is reasonable to expect that measuring these properties in the field will result in better outcomes than relying on theoretical relationships or idealized assumptions.

High resolution signal controller event data is used to develop a record of phase changes and vehicle detections (9, 10). Using this data, one can develop profiles of vehicle arrivals and relate them to the probability of green (11). These *flow profiles* can serve as a means to predict what will happen if the offsets are adjusted, by displacing the vehicle arrival and green time distributions accordingly (12). For example, an offset adjustment of +10 seconds corresponds to

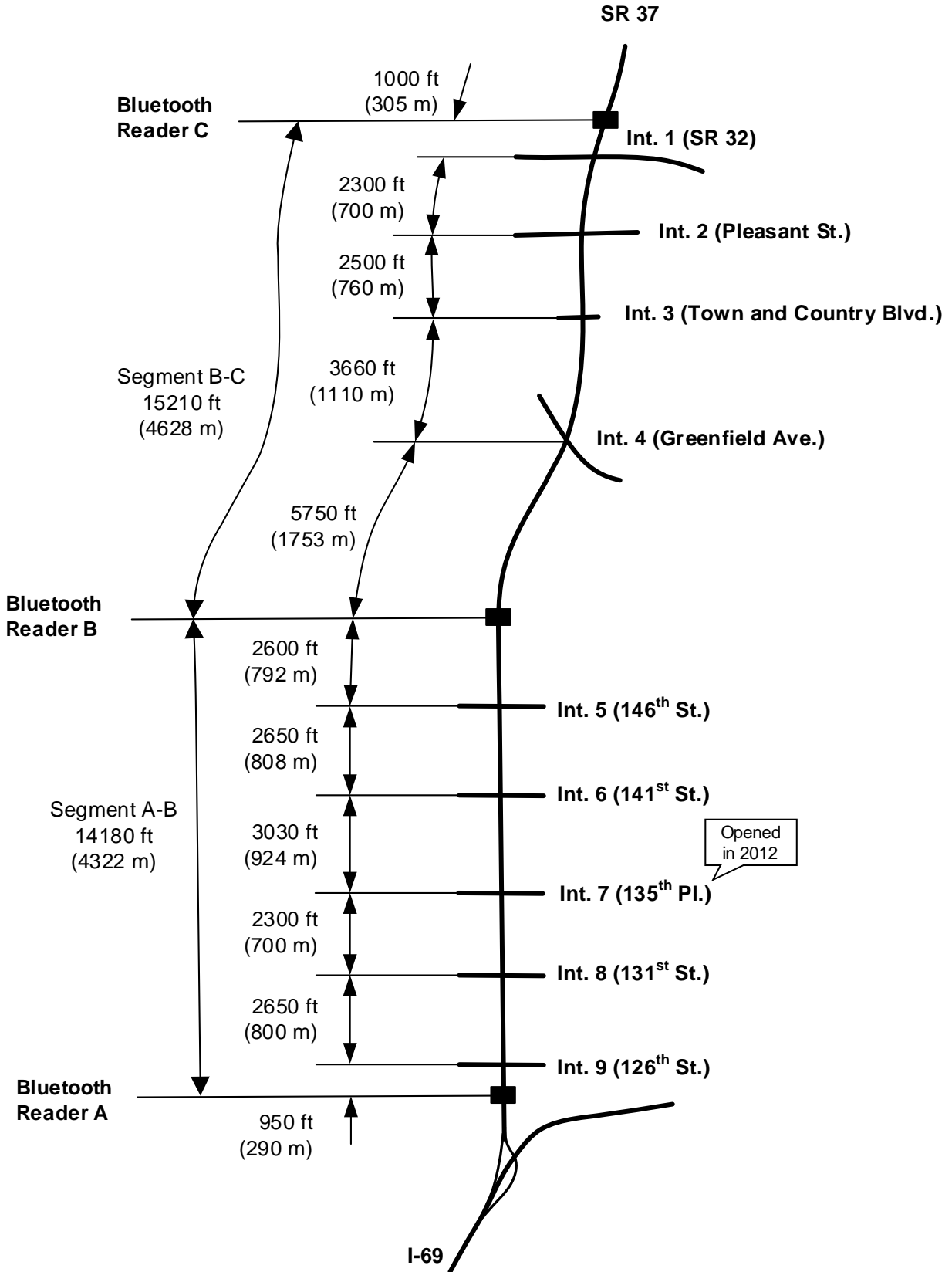


Figure 1 SR37 corridor overview and Bluetooth antenna positioning

a displacement of the local green times by +10 seconds, and of the downstream arrival profiles by +10 seconds as well. By relating the shift in predicted green times to the vehicle arrival profiles calculated from the signal controller event data, offsets along the corridor can be systematically optimized.

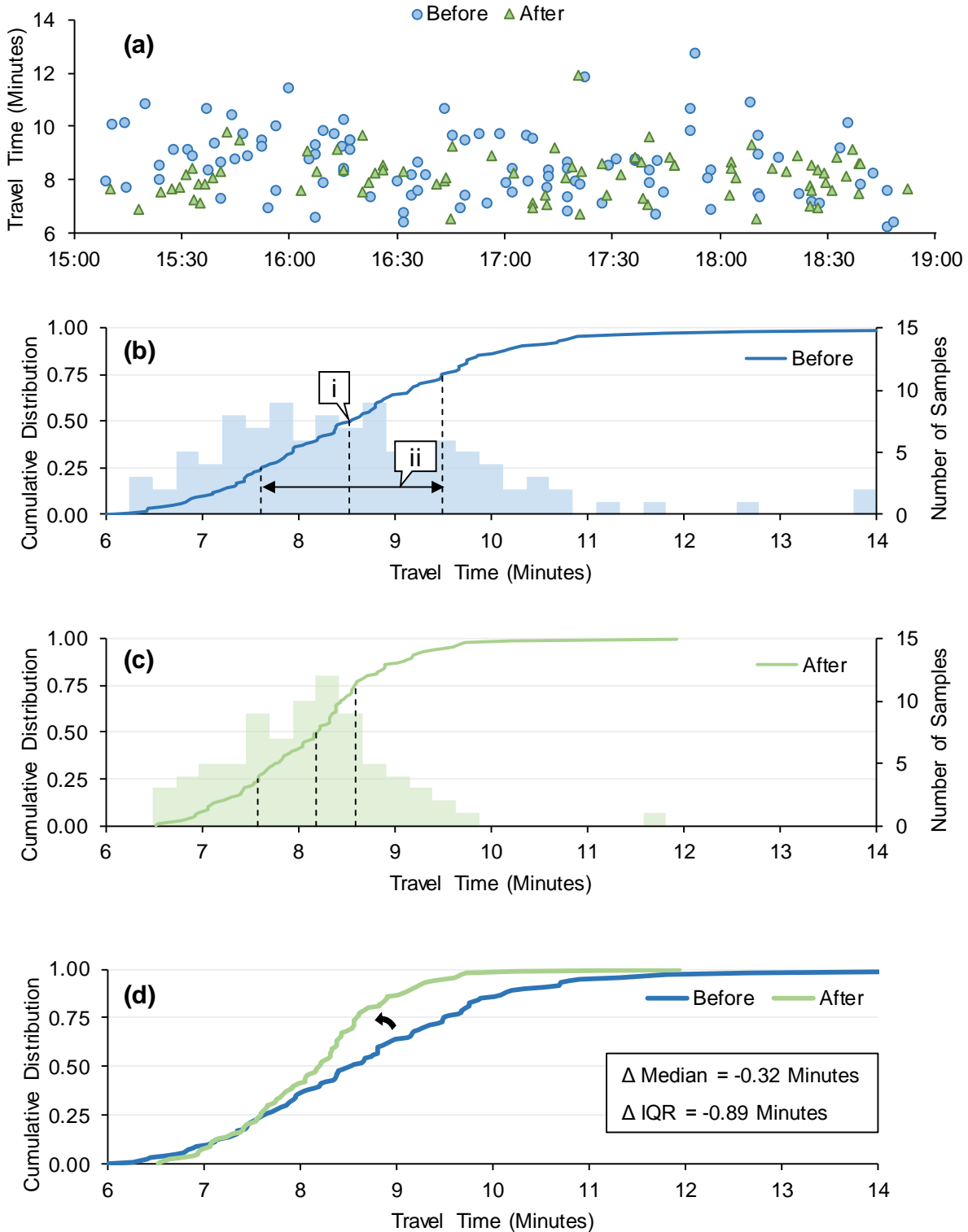
Numerous objective functions have been considered for optimally setting offsets—common strategies include minimizing total user delay (13, 14), or maximizing vehicle arrivals on green. A method for the latter on arterials with high resolution data (15) was initially demonstrated on SR 37 (16), but has also been used at other locations (17).

### **Travel Time Measurement**

Bluetooth Media Access Control (MAC) address matching was utilized to estimate travel times before and after each optimization (18). This methodology is significantly more robust than traditional pilot car studies, and the number of observed travel times over the analysis period represented approximately 5% of the total traffic volume. Outlier travel times, defined as 1.5 times above or below the interquartile range (IQR, the difference between the 25<sup>th</sup> and 75<sup>th</sup> percentiles for the observed data), were removed to eliminate errors from incorrect matching, and to account for intermediate detours/stops made by drivers, which could bias the results.

Figure 1 shows the location of Bluetooth data collection devices along the SR37 corridor. Three locations were used for the devices – Bluetooth Readers A and C established cordon points at the southern and northern ends of the corridor, respectively, while Bluetooth Reader B served as a dividing point, from which sub-corridor travel times could be computed. This was beneficial for the step of computing total user benefits from retiming; because relatively few drivers traverse the entire SR37 corridor, a more accurate estimation of corridor-level benefits was determined by summing the benefits on sub-corridor segments A-B and B-C.

The collection of such detailed travel time data, compared to historical means, has given agencies the ability to generate more comprehensive travel time performance measures (19, 20). One increasingly-common measure is that of a travel time distribution function (21). Figure 2 shows how individually measured travel times are converted into cumulative distribution functions (CDFs) for the purposes of assessing changes before and after an intervention (in this case, a signal offset optimization). Part *a* shows the individual observed travel times, herein measured using the Bluetooth devices. In this example, the travel times are measured from device A to device C for Saturdays in 2013, from 1500-1900. Part *b* shows a histogram of the travel times before the offset optimization. Travel times vary from 5 minutes to 15 minutes, with



**Figure 2 Comparison of travel times using cumulative distribution functions (CDFs) before/after offset optimization**

(a) Observed travel times (2013 NB segment A-C, 1500 – 1900)

(b) Histogram and CDF of “before” travel times

(c) Histogram and CDF of “after” travel times

(d) Combined travel time CDFs, with summary statistics

the majority in the 7- to 9- minute range. These travel times can be turned into a CDF to better characterize the overall distribution. Here, the median (50<sup>th</sup> percentile) travel time is approximately 8.5 minutes, as denoted by callout *i*. Callout *ii* shows the IQR, the distance between the 25<sup>th</sup> and 75<sup>th</sup> percentiles, which is approximately 2 minutes.

Likewise, part *c* of Figure 2 shows a histogram and corresponding CDF for the travel times after offset optimization. Here, the median travel time is slightly more than 8 minutes, and nearly all observed travel times are 9.5 minutes or less.

Part *d* shows an overlay of travel time CDFs before and after offset optimization. Note the leftward shift in the CDF after optimization. The median travel time decreases by 0.32 minutes (approximately 19 seconds), while the travel time IQR decreases by 0.89 minutes (approximately 53 seconds). Also note how the post-optimization CDF appears to rotate counterclockwise, relative to the pre-optimization CDF. Correspondingly, a greater improvement in travel times for the upper end of the post-optimization distribution is seen than for the lower end, and generally results in a steeper slope for the post-optimization CDF. This steeper slope indicates an improvement in travel time *reliability*. That is, drivers, on average, are experiencing more consistent travel times after optimization, irrespective of any improvements made in the average travel times.

### Outcome Assessment

To assess the impact of optimization, we consider performance measures based on high resolution data and travel time data. Signal-based performance measures include changes in total arrivals on green (AOG) and percent arrivals on green (POG). These quantify the number or proportion of vehicles successfully progressed through the signalized approaches, as determined by comparing the detected arrival time with the concurrent status of green. The calculation of this performance measure has been documented previously (22).

The median travel times, along with the IQR for each CDF, were assessed to determine potential gains and losses in the system with each optimization. In estimating user travel time benefits that result from the post-optimization scenarios, we incorporate both the monetary value of travel time savings and the value of improvements in reliability. The measure for travel time reliability was chosen to be the standard deviation of travel time through the corridor, in line with previously established methodology (23), (24). The travel time benefits for passenger and commercial vehicles are computed as:

$$Benefit_i = TTSV_i + TTRV_i \quad (1)$$

Where

$Benefit_i$  = total travel time benefits for vehicle type  $i$  (\$)

$TTSV_i$  = travel time savings value for vehicle type  $i$  (\$)

$TTRV_i$  = travel time reliability value for vehicle type  $i$  (\$)

And

$$TTSV_i = \Delta TT * Vol * P_i * Occ_i * TTV_i * 1 \text{ hr} / 60 \text{ min} \quad (2)$$

$$TTRV_i = \Delta SD * Vol * P_i * Occ_i * SDV_i * 1 \text{ hr} / 60 \text{ min} \quad (3)$$

Here,



$\Delta TT$  = The change in mean travel time along the corridor, as measured using the Bluetooth data (min)

$\Delta SD$  = The change in the standard deviation of travel time along the corridor (min)

$Vol$  = The traffic volume through the corridor during the analysis period, measured using count detectors on the intersection approaches (vehicles)

$P_i$  = The percentage of the traffic stream that vehicle type  $i$  comprises

$Occ_i$  = The average vehicle occupancy of vehicle type  $i$  (persons)

$TTV_i$  = The time value of money for an individual in vehicle type  $i$  (\$/person-hr)

$SDV_i$  = The monetary value of a unit change in travel time standard deviation for an individual in vehicle type  $i$  (\$/person-hr)

In this analysis, two vehicle types were considered: passenger cars and commercial trucks. The value of travel time was drawn from the 2011 version of the Urban Mobility Report (25), and updated to 2015 values using the Consumer Price Index (CPI). For additional details on the theory behind specific travel time and travel time reliability calculations, refer to Li et al. (17).

## ASSESSMENT OF SIGNAL TIMING OVER FIVE YEARS

### Signal Performance Measures

Figure 3 through Figure 6 demonstrate the impacts and benefits of active maintenance of the signal timing plans over the 5-year period. Numerous improvements were seen in all categories of performance measures, especially in 2010, as one might expect due to the absence of a prior data-driven retiming strategy.

At the same time, it is also important to note that changes in travel time as a result of offset optimizations were not universally positive. Figure 3 illustrates these differences. Part *a*, *c*, and *e* show improvements in travel time and travel time reliability for both the northbound and southbound directions, for the 1500-1900 TOD plan on Saturdays in 2013. Similarly, parts *b*, *d*, and *f* show that for northbound traffic, travel time and travel time reliability improved post-optimization, for the 1200-1500 TOD plan on Saturdays in 2015. However, southbound travel times here actually worsened, with a 0.26-minute increase in median travel time, and a 1.87-minute increase in travel time IQR. This tradeoff reflects the fact that during offset optimization (and signal timing in general), one is often forced to make a choice between two conflicting demands. Often progression improvements for one direction at an intersection can only be made at the expense of the opposing direction. In such cases, the benefit of the decision must be considered in terms of the total system impact, such as by calculating the cumulative user benefit. Although an individual route might experience some degradation, the overall system benefit may still be positive.

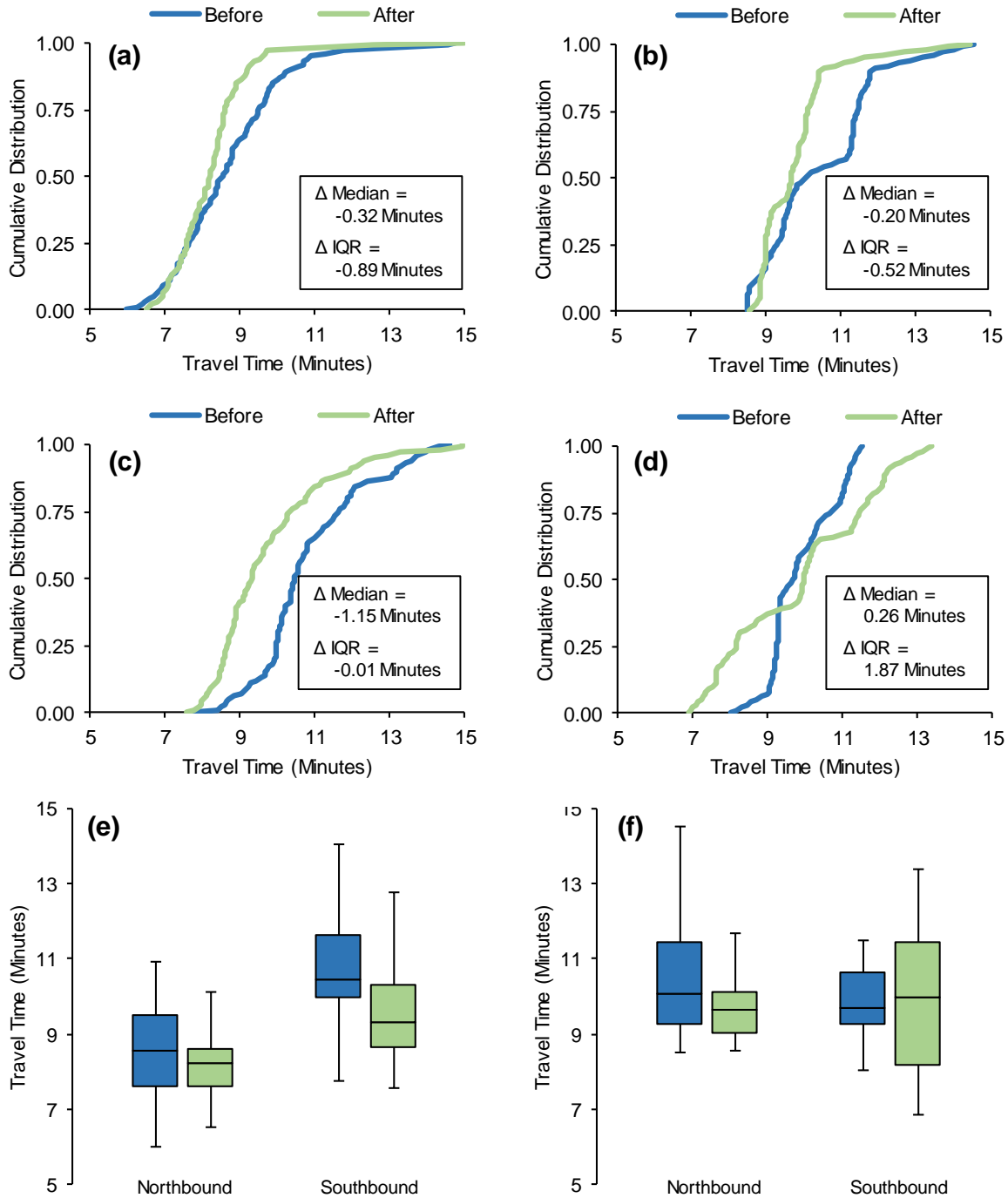
Figure 4 shows the change in AOG and POG for each direction on SR37, as a result of the offset optimizations in 2010, 2013, and 2015. In parts *a* and *b*, AOG is broken out by direction, while AOR is shown for northbound and southbound combined. This provides excellent context for the need to consider long-term active traffic management strategies. During each optimization period, AOG and POG usually increased. One exception is a decrease in AOG in 2015, which coincides with a decrease in volume within the before and after periods. There

are also some interesting dynamics between years as well. For example, AOG and POG appear to have increased between 2010 and 2013, which may be a function of arterial traffic volumes growing at a faster pace than side street volumes during that time period. However, AOG and POG decreased between 2013 and 2015.

In part *a*, it can be seen that total arrivals for Saturdays, by intersection, increased from approximately 20,000 in 2010 to 25,000 in 2015, a change of 25%. Likewise, part *b* shows that total arrivals per weekday, by intersection, increased from approximately 25,000 in 2010 to 29,000 in 2015, a change of 16%. Despite the significant increase in traffic volumes, the growth in AOG actually outpaced the growth in total arrivals, increasing by 46% between 2010 and 2015 for Saturdays, and by 28% between 2010 and 2015 for weekdays. This is due in large part to the ongoing and repeated optimization of progression along the corridor.

In part *c* and *d* of Figure 4, POG is the sum of the northbound and southbound percent arrivals. For example, for Saturdays in 2015, post-optimization, northbound AOG comprised approximately 31% of all arrivals, while southbound AOG comprised approximately 39% of all arrivals. Callout *i* shows that total POG for this scenario was the sum of these two percentages, or 70%. The figures here demonstrate moderate growth in POG between 2010 and 2015. For Saturdays, POG increased from 59% to 69%, a 10% increase (17% improvement over the initial value of POG). Likewise, weekday POG increased from 60% to 65%, a 5% increase (8% improvement). For part *c*, on average, Saturday offset optimizations resulted in 4% higher POG (8% improvement) and in part *d*, on average, weekday offset improvements resulted in an increase of 1% (2% improvement).

With offset optimization and mainline signal timing improvements, one must also be cognizant of the needs of side street traffic and potentially worsening driver delay. Improvements can always be made to progression on the mainline by simply increasing green time, but this strategy increases delay for drivers on the minor approaches. Figure 5 demonstrates for both Saturdays (part *a*) and weekdays (part *b*), despite the growth in arterial AOG and POG, the total green time given to the northbound and southbound mainline movements was not significantly increased. The green time totals exclude the 135<sup>th</sup> St. intersection, which was not present when the 2010 offset optimizations were performed, to avoid distorting the comparison.



**Figure 3 Comparison of offset optimization outcomes. (a)/(c)/(e) demonstrate northbound and southbound travel time improvements, while (b)/(d)/(f) show northbound improvements at the expense of southbound vehicles**

**(a) Northbound before/after travel time CDFs, 2013, TOD plan 1500-1900**

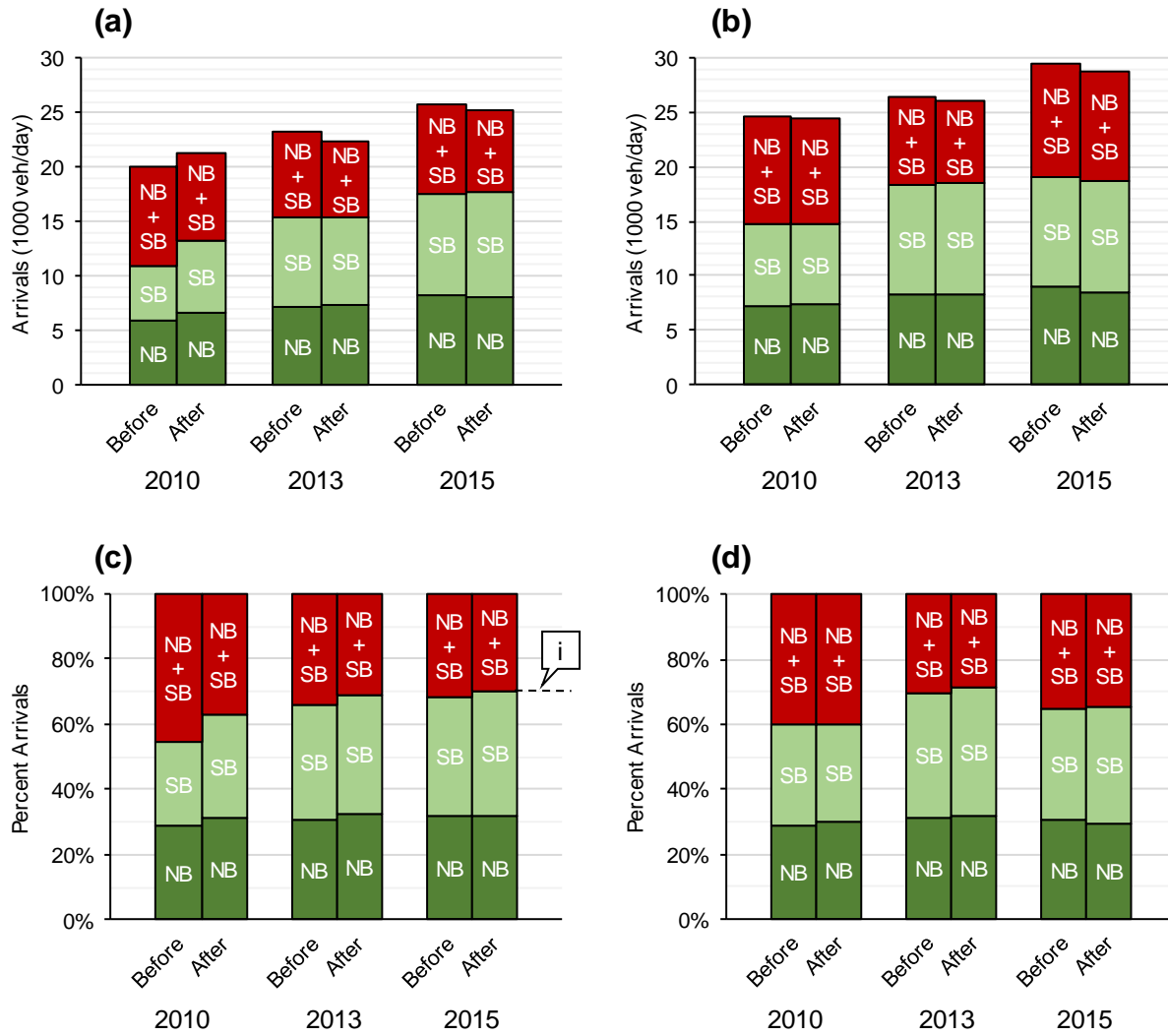
**(b) Northbound before/after travel time CDFs, 2015, TOD plan 1200-1500**

**(c) Southbound before/after travel time CDFs, 2013, TOD plan 1500-1900**

**(d) Southbound before/after travel time CDFs, 2015, TOD plan 1200-1500**

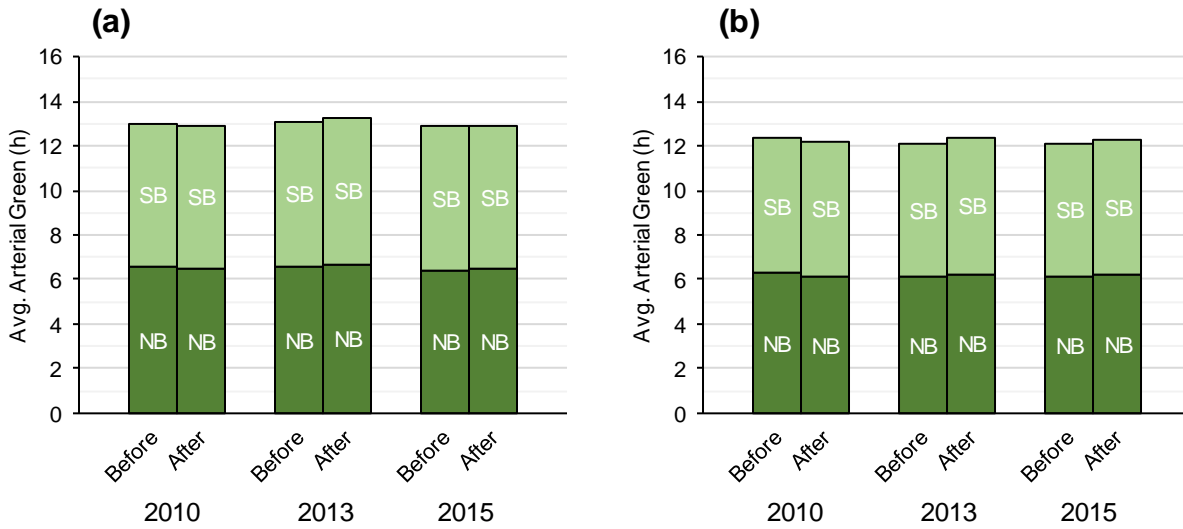
**(e) Northbound and southbound before/after travel time box-whisker plots, 2013, TOD plan 1500-1900**

**(f) Northbound and southbound before/after travel time box-whisker plots, 2015, TOD plan 1200-1500**



**Figure 4 Comparison of arrivals on green (AOG) and percent arrivals on green (POG) for weekdays and Saturdays from 0600-1900, before/after offset optimization**

- (a) Average AOG and combined northbound/southbound arrivals on red (AOR), per intersection, Saturdays**
- (b) Average AOG and combined northbound/southbound arrivals on red (AOR), per intersection, weekdays**
- (c) Average POG and combined northbound/southbound percent arrivals on red (POR), per intersection, Saturdays**
- (d) Average POG and combined northbound/southbound percent arrivals on red (POR), per intersection, weekdays**



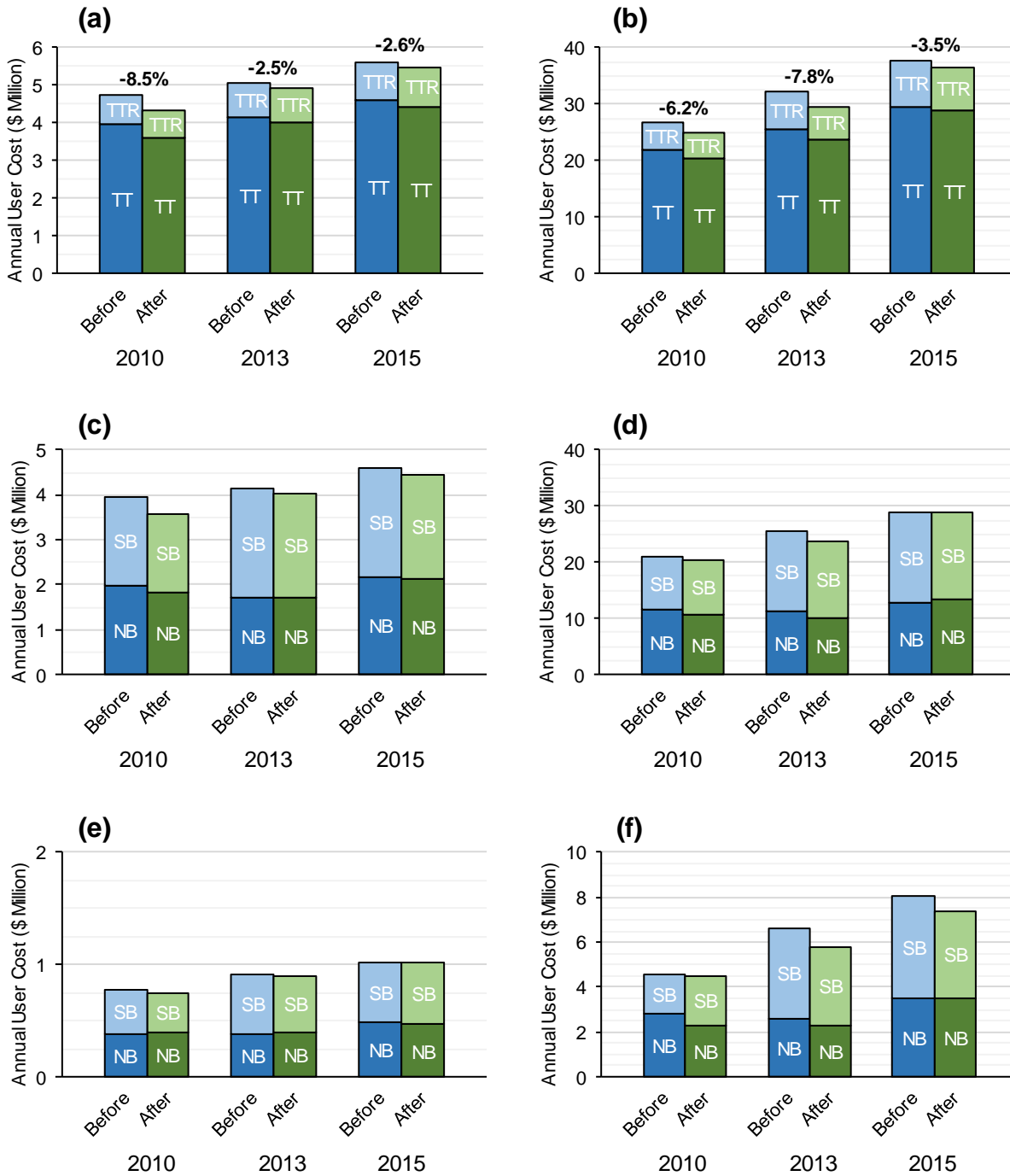
**Figure 5 Comparison of arterial green time, excluding 135th St., for weekdays and Saturdays from 0600-1900, before/after offset optimization**

**(a) Average northbound/southbound arterial green time, per intersection, Saturdays**

**(b) Average northbound/southbound arterial green time, per intersection, weekdays**

### Travel Time and Travel Time Reliability Impacts

Figure 6 shows the change in annualized user travel time and travel time reliability costs with each offset optimization. In parts *a* and *b*, it can be seen that the year-over-year growth in travel time costs largely mirrors the growth in traffic volumes along the corridor. For part *a*, Saturday travel time and reliability costs increased by approximately 22% between 2010 and 2015. For part *b*, weekday travel time and reliability costs increased by approximately 38% between 2010 and 2015.



**Figure 6 Annual travel time (TT) and travel time reliability (TTR) costs for weekdays and Saturdays, from 0600-1900, before/after offset optimization**

- (a) Combined annual northbound/southbound TT and TTR costs, Saturdays
- (b) Combined annual northbound/southbound TT and TTR costs, weekdays
- (c) Annual northbound/southbound TT costs, Saturdays
- (d) Annual northbound/southbound TT costs, weekdays
- (e) Annual northbound/southbound TTR costs, Saturdays
- (f) Annual northbound/southbound TTR costs, weekdays

Despite the increase in traffic volumes and the travel time and reliability costs, a substantial user benefit was borne out by all three offset optimizations. For example, in 2010, the optimization resulted in an 8.5% decrease in total user cost for Saturdays, while 2015 optimization realized a 2.6% decrease in user cost. On average, total user costs decreased by 4.5% each time an offset optimization was performed, compared to annualized pre-optimization user costs. Weekday improvements were similarly substantial. On average, total user costs decreased by 6% each time an offset optimization was performed.

It can also be seen that specific time periods saw variable magnitudes of improvement in travel time and travel time reliability. Parts *c* and *d* of Figure 6 demonstrate the changes in annualized travel time costs only, for Saturdays and weekdays, respectively. In parts *e* and *f*, changes in annualized travel time reliability costs for Saturdays and weekdays, respectively, are shown. Generally, it appears that for Saturdays, most of the user benefit was derived from improvements in average travel times (part *c*); there is little to no change in travel time reliability costs before and after offset optimization (part *e*). In contrast, for weekday time periods, in addition to benefits due to travel time improvements (part *d*), significant user benefit was realized due to travel time reliability improvements (part *f*). For example, in 2013, annualized travel time reliability costs fell from \$6.7 million to \$5.9 million, a decrease of 14%.

Table 1 and Table 2 show the total user benefits due to offset optimization for all TOD plans and directions, for Saturday and weekday time periods, respectively. In total, offset optimizations during this 5-year time period resulted in a cumulative user benefit of approximately \$3.6 million. The costs are also shown in per-vehicle terms, which are computed by dividing the change in user costs for each year by the volume per direction within that year. The magnitude of the changes is decreasing by year, which can be explained partly by the increasing traffic volume, as well as the decreasing extent of the signal timing changes. That is, in 2010, the first year that the optimization technique was used, there were substantial changes, but in subsequent years the changes were less drastic.

**Table 1 Annual TT and TTR user benefits (\$US) from offset optimization, Saturdays from 0600-1900**

NORTHBOUND							
TOD Plan	2010		2013		2015		
	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	
0600 - 0900	8,416	-10,128	1,953	-795	-3,354	6,363	
0900 - 1200	21,313	-20,321	-2,412	8,465	-20,726	11,069	
1200 - 1500	31,971	3,265	-1,463	-30,081	53,974	-6,352	
1500 - 1900	76,531	8,411	2,229	8,679	24,048	11,198	
TT/TTR Benefit	138,231	-18,773	307	-13,732	53,942	22,278	
TT +TTR Benefit	119,458		-13,425		76,220		
TT/TTR Benefit per Vehicle	6.64	-0.90	0.02	-0.72	2.40	0.99	
TT +TTR Benefit per Vehicle		5.74		-0.70		3.39	
SOUTHBOUND							
TOD Plan	2010		2013		2015		
	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	
0600 - 0900	25,621	12,431	12,051	-22,299	1,675	6,543	
0900 - 1200	71,886	2,098	15,529	15,681	74,745	38,667	
1200 - 1500	68,733	19,810	46,034	43,562	4,001	-48,375	
1500 - 1900	69,283	15,218	33,770	-4,941	9,010	-17,837	
TT/TTR Benefit	235,524	49,557	107,385	32,003	89,432	-21,002	
TT +TTR Benefit	285,081		139,388		68,430		
TT/TTR Benefit per Vehicle	12.41	2.61	4.70	1.40	3.71	-0.87	
TT +TTR Benefit per Vehicle		15.02		6.10		2.84	

**Table 2 Annual TT and TTR user benefits (\$US) from offset optimization, weekdays from 0600-1900**

NORTHBOUND							
TOD Plan	2010		2013		2015		
	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	
0600 - 0900	142,577	5,618	143,214	40,521	-102,789	30,824	
0900 - 1100	144,873	79,592	33,514	47,637	-89,166	10,003	
1100 - 1300	221,600	79,306	-39,587	-93,912	-196,196	21,843	
1300 - 1500	160,105	61,867	136,255	104,544	-213,871	-5,855	
1500 - 1900	314,852	272,327	688,192	178,591	-197,887	-67,667	
TT/TTR Benefit	984,006	498,710	961,588	277,381	-799,909	-10,853	
TT +TTR Benefit	1,482,716		1,238,969		-810,762		
TT/TTR Benefit per Vehicle	43.53	22.06	43.91	12.67	-33.02	-0.45	
TT +TTR Benefit per Vehicle		65.59		56.57		-33.46	

SOUTHBOUND							
TOD Plan	2010		2013		2015		
	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	Travel Time Benefit	Travel Time Reliability Benefit	
0600 - 0900	63,853	-11,174	139,008	86,141	522,782	640,498	
0900 - 1100	-127,391	-96,595	64,897	46,056	30,402	-73,496	
1100 - 1300	-85,704	26,693	-84,460	-16,493	-175,879	-118,710	
1300 - 1500	-76,748	-69,276	-253,692	42,813	111,149	74,051	
1500 - 1900	-245,040	-327,425	818,647	430,469	148,735	171,536	
TT/TTR Benefit	-471,029	-477,777	684,400	588,986	637,189	693,879	
TT +TTR Benefit	-948,806		1,273,386		1,331,068		
TT/TTR Benefit per Vehicle	-23.31	-23.64	26.96	23.20	23.52	25.61	
TT +TTR Benefit per Vehicle		-46.95		50.16		49.13	

### Return on Investment

One of the most significant uncertainties that agencies are concerned with when undertaking any long-term infrastructure management program is the return on investment. As previous research has shown, the benefits of signal timing typically far outweigh the costs (26, 27).

For this study, a 5-year benefit-cost ratio (BCR) and net present value (NPV) analysis of the signal timing interventions was undertaken (28). For the sake of preserving the clarity of the message, the assumptions of this analysis were kept basic: user benefits and agency costs were assumed to be fixed (deterministic), and only those benefits from travel time and travel time reliability were considered, as summarized in Table 1 and Table 2. a list of the agency costs that were considered is provided in Table 3. The controller cost was provided by INDOT, while the cost associated with programming/retiming for hi-res data controllers assumed a labor rate of \$50/hr. The annual signal O&M costs are based on a review of current literature (29, 27, 26).

The formulas for BCR and NPV are as follows:

$$BCR = \frac{PWB}{PWC} \quad (4)$$

$$NPV = PWB - PWC \quad (5)$$

where  $PWB$  is the present worth of benefits and  $PWC$  is the present worth of costs. For a single benefit or cost incurred at some time in the future,

$$PW = \frac{X}{(1+i)^n} \quad (6)$$



where  $X$  is the realized benefit or cost,  $i$  is the discount rate (selected here as 6.3% (30)), and  $n$  is the number of years from present at which the benefit or cost is realized. Similarly, for a recurring benefit or cost (such as signal O&M),

$$PW = X * \left( \frac{1-(1+i)^{-n}}{i} \right) \quad (7)$$

where  $X$  is the recurring amount of the benefit or cost. From the assumed values for benefits and costs, the 5-year BCR was estimated to be 52.5, and the 5-year NPV was estimated to be \$3.69 million. Although these figures are subject to some fluctuation due to uncertainty in the estimated costs and benefits, it is evident that repeated retiming of this corridor over the 5-year period resulted in a significant return on investment for the agency.

**Table 3 Assumed signal maintenance costs for economic analysis**

Cost Item	Amount	Frequency
Hi-Res Signal Controller	\$2,000 per intersection	One-time expense
Modem/Ethernet Radio Cost	\$1,000 per intersection	One-time expense
Initial Controller & Modem Setup	\$1,000 (all intersections)	One-time expense
Retiming	\$2,000 (all intersections)	2010, 2013, 2015
Other signal O&M	\$1,000 per intersection	Annually

## CONCLUSIONS & FUTURE RESEARCH

The results of this study demonstrate that for corridors with moderate traffic growth, without intervention, timing plans and travel times show marked deterioration over a period of just a few years. This presents a challenge to many public agencies, who continue to retime traffic signals on an imprecise schedule, or rely on limited feedback, such as public complaint calls. As a cost-effective alternative, this paper demonstrates that high resolution signal controller data, periodic travel time assessment with re-identification technologies, and associated performance measures can be used to actively monitor long-term degradation of traffic conditions, and make better informed decisions about when to undertake retiming. Outcome assessment by travel time measurement allows a positive impact to be independently confirmed.

Generally, it was found that by adopting active traffic management strategies supported with high resolution event data, agencies can derive substantial user benefit by periodically revisiting and retiming corridors, at least biennially, and perhaps annually. A summary of routine optimization and specific impact is shown below:

- 3 different offset optimizations were carried out on a moderately-congested signalized corridor over a 5-year period.
- Total intersection arrivals increased approximately 36% between 2010 and 2015 (or 6% annually). During this time, an additional intersection and several new lanes were constructed on the south end of the study corridor.
- AOG along the corridor outpaced the growth in overall volumes increasing by 41%.

- POG increased by 12.1% (8 percentage points) over the 5-year period for weekdays, by approximately 8.8% (5 percentage points) for weekends.
- Average travel times along the corridor closely matched the growth rate of total traffic volumes, although for all three offset optimizations, net user travel time and travel time reliability costs decreased by approximately 5%. The 5-year BCR and NPV from re-timing amounted to approximately 71.9 and \$3.7 million, respectively.

Future research in this area should consider time periods other than summer to capture alternative travel patterns (such as school-related traffic). Alternatively, this same dataset and long-term assessment of signal timing could be used to evaluate the impacts of the roadway widening project at the southern end of the corridor. Similar to improvements from signal timing, the benefits of a capital improvement project are rarely measured *post hoc*.

Agencies could also conduct additional longitudinal studies using consistent performance measures for the purpose of establishing thresholds for retiming. This research establishes the premise that agencies can realize sustained benefits with active management of signal timing, but decisions about when to perform such timing could be enhanced further by using a consistent performance threshold to gauge corridor-level performance degradation.

This research demonstrates that without active management, signal timing and traffic performance can degrade considerably, similar to physical infrastructure assets. It also shows that by using performance measures to actively manage a corridor, agencies can have measureable impact. The after action outcome assessment is particularly important to demonstrate to decision makers the impact their investments have. Embracing performance-based management and outcome assessment is consistent with MAP-21 principles. Agencies that incorporate these methods into their management practices would be better positioned for long term system investments, by being able not only to cite one-time benefits from a before/after perspective, but to additionally quantify the benefits of continuing efforts.

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