

## Selection of a Traffic Control Strategy for Long-Range Travel Forecasting

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**Abstract.** This paper addresses the problem of determining the number and placement of signals on traffic networks for long-range urban travel forecasting. An algorithm for determining the signalization strategy was developed and given a large-scale test on the network for a metropolitan area of about 150,000 people. The algorithm attempts to mimic the actions of traffic engineers as they make adjustment to the traffic system over a long period of time. Tests indicate that the algorithm produces a network that closely approximates one that has been optimized for vehicle hours traveled, but one that still respects safety and fairness issues. The algorithm is highly computational, so limits needed to be arbitrarily placed on the precision of the traffic forecast, the precision of optimization steps, and on the number of intermediate forecast years.

### INTRODUCTION AND RESEARCH OBJECTIVES

There has been a growing recognition that travel forecasts should be properly sensitive to traffic flow and a longstanding realization that all alternative transportation plans should include, at the very least, all low-cost traffic engineering improvements, sometimes referred to as TSM (transportation system management) strategies. A large and important subset of TSM strategies concerns upgraded or optimized traffic control systems. A very difficult question arises when doing long-range transportation planning: What should be the design of the signal system when traffic patterns in the forecast year are estimated to be substantially different from today?

By even asking this question, it is assumed that the travel forecasting methodology can differentiate between forms of traffic control (signs and signals), understand the various ways in which signals can be operated, and calculate delay at traffic controls in a manner consistent with good traffic engineering principles. In addition, there is an expectation that travel demand is fully responsive to and reflective of the delays experienced by drivers on the network, at a minimum affecting both the distribution of trips across the network and route choice.

This question was and continues to be asked in the Cedar Rapids metropolitan area, where the Linn County Regional Planning Commission (LCRPC) is currently preparing the transportation plan for the metropolitan area through 2030. LCRPC already had a travel forecasting network containing explicit traffic controls for its base year (1, 2), but no formal mechanism beyond trial and error for determining the nature of traffic controls in future years. The network contains explicit representation of all signalized and stop-controlled intersections on the major street network.

The problem with long-term traffic control is similar in concept to what has been identified as the network design problem (NDP) from the transportation research literature (3, 4). The NDP attempts to find the best combination of links or link capacities to satisfy a given demand. Long-range planning in urban areas should also find the best network for the demands by specifically changing the nature of traffic control. Finding the exact combination of traffic controls and control strategies to optimize a network for a whole metropolitan area would be enormously difficult. Consequently, this paper explores an algorithm that mixes optimization techniques with elements of standard traffic engineering practice and travel forecasting theory to obtain a desirable network.

Several practical issues must be faced when building an algorithm to produce such a long-range design.

1. There is a strong relationship between the implementation of a traffic control change and the distribution of travel in response to such changes (e.g., drivers discouraged from making left turns onto busy streets off a two-way stop control would not be so discouraged if the control were changed to a signal or all-way stop).

2. The design for the forecast year is dependent upon the order in which traffic control changes are implemented in previous years.
3. The design should be reasonably consistent with good traffic engineering practice that not only tries to attain the best performance of the traffic system but maintains a locally acceptable level of safety and tries to achieve a reasonable degree of fairness toward all drivers.
4. A critical element in the design decision is determining which of the many unsignalized intersections in the metropolitan area should get signals. The most authoritative source of guidance on judging when to upgrade signed intersections to signals is the Manual on Uniform Traffic Control Devices (5).
5. It is reasonable to pursue lowest cost strategies first, e.g., get the best performance out of the existing signals before attempting to add signals.
6. In a growing city, signals that were warranted and installed at one time are almost never removed.
7. The algorithm must be computationally tractable.

There are a number of different measures of effectiveness that could be tested. In this research the algorithm attempts to achieve a low value for vehicle hours traveled (VHT), which would normally occur when delays at intersections are low. The next section describes an algorithm that creates an approximately optimal network for long-range travel forecasting and address the issues cited above.

**THE SIGNAL SYSTEM DESIGN ALGORITHM**

The signal system design algorithm is illustrated in Figure 1. Figure 1 contains two flow diagrams; the flow diagram labeled “Traffic Forecast” on the right occurs twice in the main flow diagram on the left. The traffic forecast is embedded into two loops, one that optimizes cycle lengths and a second one that selects unsignalized intersections for signalization.

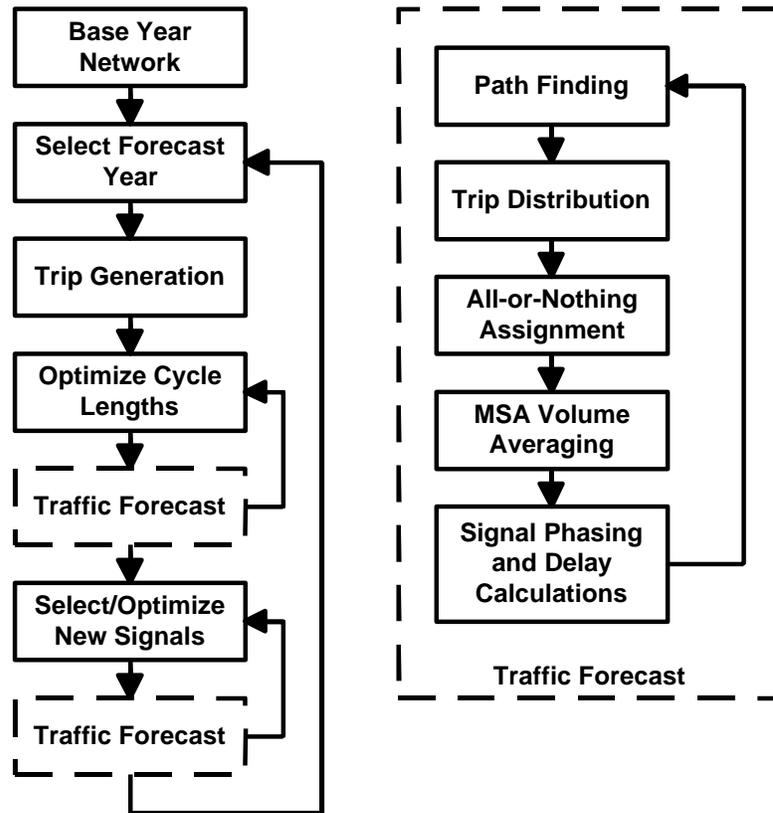


Figure 1. Overview of the Algorithm for Long-Term Signalization

### Traffic Forecast

The traffic forecast primarily consists of two of the steps from a traditional four-step model, trip distribution and traffic assignment. Of the remaining steps, trip generation is handled elsewhere and mode split was not considered. The method of successive averages (MSA) is used with feedback to trip distribution in order to find an elastic-demand traffic assignment (i.e., where trip distribution properly considers congestion on the network). MSA (6) has proven particularly useful in finding user-optimal equilibrium solutions when there are both elastic demands and explicit traffic controls in the network (7, 8, 9). Unless otherwise stated, traffic assignments employed 10 unweighted averages of 11 all-or-nothing assignments.

Trip distribution is performed with a gravity model for trip purposes representing approximately 95% of the urban area travel. Direct home-to-school trips, external-to-external trips, and some airport trips are either Fratar factored or “pre-modeled” and are, therefore, insensitive to network travel time and delay calculations.

Intersection and link delays are calculated after the initial all-or-nothing assignment and again after each average of the MSA. Separate delay estimation procedures are implemented for each type of traffic control (signals, two-way stops, and all-way stops) and for uncontrolled street segments. These procedures closely follow those in the 1994 Highway Capacity Manual (10) and are described in detail elsewhere (7, 11, 12). It should be recognized that delay on any one approach of a traffic-controlled intersection is a complex function of all movements on all approaches of the intersection. Signal delay is calculated with operational analysis procedures of the HCM’s Chapter 9, including the calculation of the saturation flow rate for permitted left turns and uniform delay for permitted/protected phasing. Two-way and one-way stop delay is calculated from the procedure of the HCM’s Chapter 10. All-way stop delay is calculated from a pure M/G/1 (Poisson arrivals/general service times/one server) queuing model that has been calibrated to fit the regression equation for capacity found in the 1994 HCM (12). This M/G/1 queuing model performs iterations to find the service time at each approach in a similar manner to the procedure in the 1997 HCM, but the HCM’s delay formulas (both 1994 and 1997) are bypassed in favor of the M/G/1 delay formula. For all forms of traffic controls, acceleration delay as a function of cruising speed is added to the stopped delay provided by the HCM and lane utilization is allocated to balance volume-to-capacity ratios across each approach. Delay along uncontrolled segments and between intersections is calculated with the BPR travel-time/volume curve using parameters adopted from NCHRP Report #365 (13) and adjusted for the Cedar Rapids model application. For two-lane streets and highways, travel time calculations also incorporate opposite-direction traffic based on the HCM’s Chapter 8 guidance.

Signal phasing is selected and refined intersection-by-intersection at the same time that delay is calculated at each approach. At this point in the algorithm cycle length is held constant. Any of the following phasing plans for two opposing approaches may be selected (7) depending upon traffic conditions.

(LTR, LTR)  
 (L, L) then (LTR, LTR)  
 (LTR, ---) then (LTR, LTR)  
 (---, LTR) then (LTR, LTR)

Although this set of phasing plans is not comprehensive, it provides sufficient flexibility for determining average approach delay. The amount of green time allocated to each phase is determined by rule, according to good traffic engineering practice and with full recognition of assigned turning movements. Essentially, green time is allocated in proportion to the critical flow ratio for the phase. In order to improve the stability of the equilibrium solution, the critical flow ratio is constrained to be between 0.1 and 1.0 for the green time allocation, only. This method of allocating green time does not necessarily minimize delay for the intersection, but it tends to equalize levels of service across all lane groups and phases.

Arrival type, as defined in the HCM for measuring the quality of progression, is held constant throughout the algorithm. Arrival type is exogenously set in the base year network (usually at 3 or 4) and is always set

to 3 (random arrivals) for all new signals, as it is not possible to coordinate signals within the algorithm. The effect of holding arrival type constant is an overestimation of delay at some new signals.

### **Main Algorithm**

The signal system design algorithm starts with a base year network, containing all signalized and all stopped controlled intersections of arterials in the metropolitan area. The Cedar Rapids area network also contained a few street widenings and extensions that have already been programmed but not yet built.

It is believed that the chronological sequence of traffic control changes can affect the final outcome. As each new signal is added, it will cause a redistribution of traffic on the network, causing greater or lesser demand at nearby unsignalized intersections. Consequently, the algorithm considers the network in a series of forecast years. The network for each forecast year contains any signals that have been previously accumulated. For this case study four-year time intervals between forecast years were selected.

For each forecast year it was necessary to determine land use and travel generation patterns. Many metropolitan planning agencies (including Cedar Rapids) do not forecast land use for the short time intervals selected for this study, so some mathematical interpolation is needed. In the Cedar Rapids case complete land use and demand information was available only in 1994 and 2030. The demand information needing interpolation consisted of trip productions, trip attractions, and all directly inputted trip tables. Model parameters were held constant across all forecast years.

Before considering new signals, it is believed necessary to optimize the signals already present on the network. In traffic operations models, this optimization would consist of signal phasing, setting green times, finding offsets for optimal coordination, and setting cycle length. Finding optimal offsets was considered too ambitious given the amount of computation involved. Phasing and green times are already adequately set as part of the traffic forecast. Thus, the only variable needing optimization is cycle length. In order to avoid extremely long computation times, a decision was made to optimize all cycle lengths as a group. The objective was to select the percentage of base year cycle lengths that results in the lowest total network travel time (constrained for safety considerations, as discussed later). By optimizing on the percentage of base year cycle length it was possible to retain different cycle lengths for each of the several, independent signal coordination groups in Cedar Rapids.

A Fibonacci search was employed to find the optimal percentage of base year cycle length. A Fibonacci search is an extremely efficient algorithm for finding the minimum of a function containing a single variable. The parameters of the search were selected such that the optimal value is constrained to between 80% and 140% with a precision of 1.09%. Each Fibonacci search required just 9 traffic forecasts.

Two separate criteria are used to upgrade signed intersections to signalized intersections. The first criterion is that the addition of a new signal should be performed only when there is a potential to reduce total network travel time. The second criterion is that intersections should be considered for upgrade in priority order as determined by the degree of violation of Signal Warrant #10 from the Manual on Uniform Traffic Control Devices (5). Warrant #10 allows signals to be installed if the peak hour delay at a signed approach is excessive. "The peak hour delay warrant is met when: the total delay experienced by the traffic on one minor approach (one direction only) controlled by a stop sign equals or exceeds four vehicle-hours for a one-lane approach and five vehicle hours for a two-lane approach" and certain minimum volume conditions are met. Of the eleven warrants, Warrant #10 is unambiguously closest to the design objectives.

Ideally, a search should be performed for the optimal combination of signal upgrades. However, such a search would be extremely time consuming and mathematically difficult. The set of decision variables are boolean (upgrade or not upgrade) for each unsignalized intersection, and it is unclear that a global minimum can ever be guaranteed. Therefore, the following steps in a heuristic search algorithm are proposed:

0. Set an initial warrant violation threshold (e.g., 2.0 times Warrant #10's numerical values).
1. Find all intersections beyond this threshold.
2. Install signals at these intersections.

3. Run a traffic forecast to determine if total network travel time has decreased. If yes, then proceed to step 4, otherwise stop.
4. Reduce the warrant violation threshold (e.g., from 2.0 times Warrant #10 to 1.8 times Warrant #10). If the violation threshold is 1.0 or greater then go to step 1, otherwise stop.

These steps in the algorithm would always produce an optimal solution if it can be assured that total network travel time is a convex function of multiplicative factors of Warrant #10. Unfortunately, this condition cannot be met all the time. However, by establishing enough threshold increments, it is possible to consider intersections in the order that conventional wisdom suggests would best improve the overall traffic situation. For this experiment, 10 different thresholds were considered at each time period. It should be noted that the worst violating intersections are upgraded to signals in the subsequent traffic forecast to determine the next worst intersections. Tests of this part of algorithm on the small Utown network were satisfactory.

As will be discussed later, computational considerations forced abandonment of step 3 when working with the Cedar Rapids network. That is, unsignalized intersections were allowed to be upgraded even if they would seem to cause an increase in total network travel time.

New signals are given an initial cycle length of 90 seconds. Left turn bays are built on all single-lane approaches that do not already have bays, provided there is sufficient room in the right-of-way. Arrival type is set to 3 (random arrivals).

Once all candidate unsignalized intersections have been assessed, the algorithm moves to the travel estimates for the next forecast year. The algorithm terminates when the analysis for the last forecast year has been completed.

### **Discussion of the Algorithm**

Both the search for an optimal cycle length and the search for an optimal combination of new signals at each iteration require that total travel time be a convex function of the respective decision variable. Computational problems (described later) prevented the rigorous testing for the existence of convexity in either case, but convexity appeared to be a reasonable assumption in the case of cycle length. It is difficult to determine ahead of time whether total travel time is a convex function of multiples of the MUTCD's Warrant #10 values. Since Warrant #10's purpose is to identify problem intersections, it should be a good, but not perfect, indicator of which intersections would most likely improve overall traffic when upgraded to signals.

The last traffic forecast, after all signals have been added, is the forecast for the alternative. In addition, the input network to the last traffic forecast contains all previously-defined signal system improvements.

The algorithm is quite different in structure and philosophy from a traffic operations program, such as TRANSYT-7F. A traffic operations program attempts to find the best cycle lengths, phasings and offsets for a signal system as it currently exists or would exist in the immediate future. A traffic operations program may perform a traffic assignment (such as SATURN and CONTRAM), but it does not attempt to deal with other aspects of travel demand. Because of the complexity of the optimization, traffic operations models work with only a limited subset of the whole metropolitan area network (and therefore cannot consider how signal system projects might impact the area beyond this subset).

Prior experience with the HCM methods in travel forecasting suggests that many two-way stop controlled approaches with high conflicting volumes need many more than 10 MSA averages to converge. This slow convergence stems from the low capacity of such approaches and the often large amount of traffic assigned in the initial all-or-nothing assignment. For example, if an approach with a calculated operational capacity of 100 vph is initially assigned 2000 vehicles, more than 20 MSA averages are required just to force the demand below capacity. Consequently, too few MSA averages (the normal practice at LCRPC) would tend to result in larger approach volumes at some intersections, which would tend to raise their priority in being upgraded to signals.

Since Warrant #10 explicitly deals with peak hour delay, it is especially attractive for this type of analysis. Other signal warrants could have been implemented, including those dealing with peak-hour or multihour volumes. The use of additional warrants would increase the number of new signals. Obviously, the algorithm does not consider the needs of progressive flow of traffic, the needs of pedestrians, crash experience and the system context when creating signals.

The algorithm was limited to upgrading signs to signals in an attempt to keep the computation time reasonable, remain consistent with the HCM, and to meet the immediate planning needs in Cedar Rapids. Other forms of network enhancements, such as upgrading signs other forms of traffic control and adding lanes to particularly congested locations, were deferred until the value of the current effect could be assessed.

### DESCRIPTION OF THE CEDAR RAPIDS NETWORK

Cedar Rapids is a Midwestern city of about 110,000 people (metropolitan area 150,000) with an employment base dominated by agribusiness, avionics and telecommunications. The metropolitan area is a significant employment and shopping destination for the surrounding area in spite of its relatively small urban area size, as urban areas larger in size are quite distant. Population density is lower than the national average.

Shown on this page (Figure 2) is the modeled street and highway network for the Cedar Rapids metropolitan area, which includes over 600 intersections modeled in accordance with Highway Capacity Manual procedures. About 230 of these intersections are signalized, and are shown as a box in Figure 2. About 80 intersections are all-way stops and the remaining intersections are some-way stops. Some-way and all-way stops are shown with a diamond shape. Shaded areas indicate the older, more densely developed areas where the algorithm is prohibited from adding turn lanes at intersections upgraded from signs to signals. The network is big for a city of this size. Overall the network contains almost 2600 nodes, 3800 links (one-way or two-way) including zonal access points, 482 zones, and 55 external stations.



Figure 2. Cedar Rapids Network Showing the Location of Signalized and Stop Controlled Intersections

There are several major differences in traffic modeling philosophy in the Cedar Rapids area from standard planning agency practice, the most important of which is the integration/iteration of the traditional traffic forecasting process with intersection traffic control analysis based on Highway Capacity Manual (HCM) methods.

Modeled traffic estimates are shown to deviate from traffic counts in Cedar Rapids substantially less than the model applications developed by other metropolitan planning agencies (1). At locations where traffic counts exceed 15,000 per day, the average 11% difference between modeled and counted volumes is not significantly different from the expected traffic count error reported by the U.S. DOT (14), and the differences between modeled and field-measured travel times is also within sampling error for over 2/3rds of the field observations.

The modeled street network includes all expressways and arterial streets, some collector streets and some commercial driveways and frontage roads where necessary to properly depict access. Intersection turn penalties are used methodically, including acceleration/deceleration for left and right turns, delay for turns on sections of major arterial streets with coordinated signals (to cancel calculated progression benefits meant for through vehicles), and major railroad crossings

Full-week and weekday trip generation by hour of day is based on vehicle-trip studies for housing and commercial developments that have been conducted and documented both locally and throughout the country. Census and national household survey data are used only to provide initial estimates of the spread of trips by hour of day, which is then adjusted to reflect hour-of-day patterns in local traffic counts (weekday pattern for arterial streets) and permanent traffic counters established statewide (freeway and weekend travel patterns).

Socioeconomic data utilized include 17 employment categories based on SIC code, area type and household data (persons, workers, vehicles and four categories of school enrollment per dwelling unit). A logarithmic regression equation was developed for trips generated from housing with the dual objective of replicating the relative differences between households found in a subset of the NPTS survey data and coming as close as possible to the vehicle trips per housing unit estimates for the metropolitan area from field studies. Linear regression equations are used for trip generation from employment categories. Ten trip purposes are used, including four different home-to-school purposes based on grade level. Non-home based travel is broken into two categories to separate out trips to/from the workplace at the end of a "trip chain" from home to work, due to the differences in hour-of-day and directional patterns. Truck travel is also estimated based on TMIP-sponsored research (15).

## **RESULTS OF IMPLEMENTING THE SIGNAL SYSTEM DESIGN ALGORITHM IN CEDAR RAPIDS**

### **Specifics of the Traffic Model for Cedar Rapids**

Unorthodox model coding is sometimes used to bypass limitations in the selection of signal phasings in the forecasting software, in order to model "split" phasing (opposing approaches on different signal phasing) and protected-only left turn phasing.

Coded saturation flows are based on standard HCM adjustment factors except for adjustments for left and right turns made from lanes shared with through movements, which are iteratively computed within the traffic forecasting model. On arterial streets, coded speeds and delays at intersections are the most important determinant of travel time. Therefore, the BPR curve parameters were adjusted on a trial-and-error basis in concert with other changes with the primary focus on better replication of the general freeway/arterial volume split.

### **Primary Run**

Figures 3 and 4 summarize the results of the algorithm. Figure 3 shows the cumulative number of new signals added to the network. Only a few signals were added in each forecast year until 2006 when 9

signals were added. The number of signals accelerated greatly in 2026 and 2030, when 29 and 36 signals were added, respectively. By 2030 a total of 121 new signals were added.

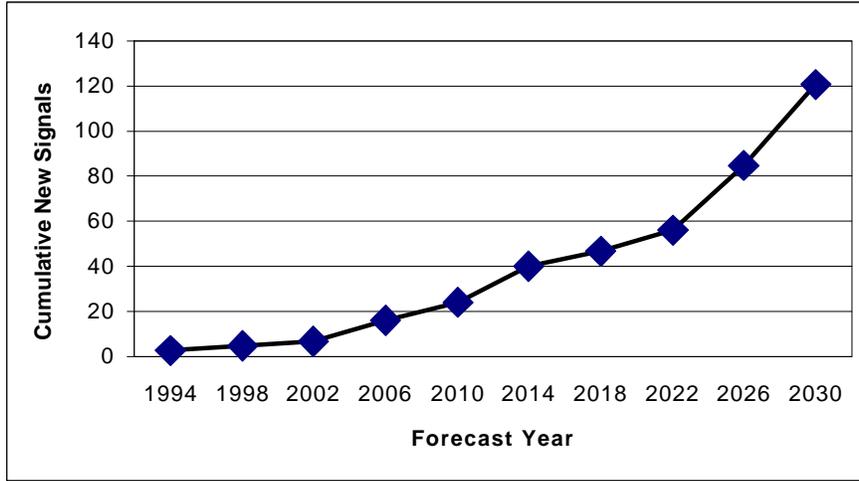


Figure 3. Cumulative New Signals by Year

Figure 4 shows the growth in VHT over the whole simulation. VHT bends upward only slightly, indicating the mitigating effect of the new signals. From 1994 to 2030 VHT increased by 182% from 10245 to 28994. The effect of delay is also mitigated by rerouting and redistributing traffic on the network. Cycle length (constrained to fall no lower than 80% of existing values) remained between 80% and 88% of existing in all of the forecast years. By 2030 the cycle length stabilized at about 85% of existing.

Of the 19 traffic forecasts made for the year 2030, the very last (accounting for all intersections warranting signals) had the lowest value of VHT. In the eight earlier forecast years, the last traffic forecast had either the minimum VHT for that year or very close to the minimum (within 0.2%).

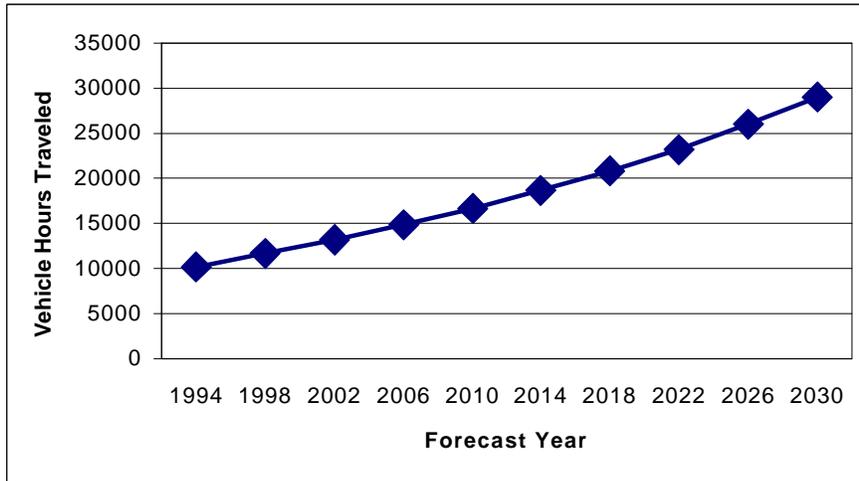


Figure 4. Forecasted Vehicle Hours Traveled by Year

An inspection of the 2030 network failed to identify any obvious geographical pattern in the location of the new signals. While the placement of new signals can be expected to follow forecasted patterns of urban growth, much would depend on how close many of the currently unsignalized intersections are to meeting signal warrants from existing levels of urban development.

## DISCUSSION

*Computation Time.* As implemented for the Cedar Rapids area network, there were between 9 and 19 traffic forecasts in each of 10 forecast years. Each traffic forecast required 11 complete passes through trip distribution and traffic assignment to complete the 10 MSA averages. On a 500 mHz Pentium III computer, the algorithm takes approximately 33 hours to finish.

*Resolution of the Traffic Simulation.* Test runs completed during the process of developing the algorithm revealed that the optimization steps only worked when the traffic forecast could discern very small changes in the network. One limiting factor is the quality of convergence of the equilibrium assignment. Because only 10 MSA averages were completed for each traffic forecast on the Cedar Rapids network, considerable convergence error still existed. This convergence error was problematical when adding just one or two signals to the network, as the resulting volume changes can be smaller than the convergence error of the assignment. Another limiting factor might be Braess's Paradox, which is a well-known and unavoidable property of user-optimal equilibrium traffic assignment. When Braess's Paradox occurs, a local improvement to the network causes an increase in total network travel time. Lastly, there can be multiple equilibrium solutions to any network that contains a large number of traffic controls (17). The possibility of multiple solutions also interferes with finding optimal solutions, a problem that cannot be fixed by simply increasing the number of MSA averages. Consequently and as noted before, it was necessary to bypass the formal optimization of new signals.

Table 1 is the result of the 2006 forecast year, which indicates that five of the six traffic forecasts involved the addition of only 1 new signal. It is seen that on balance there was a considerable reduction in total network travel time (almost 70 vehicle hours for the 8 signals), but the travel time reduction for any given signal seems to have a large random component. Similar results were seen in the other forecast years.

Table 1. Vehicle Hours Traveled after Implementing Signal Meeting a Threshold Multiple of Warrant #10 – PM Peak Hour from the 2006 Forecast Year

Multiple of Warrant #10 (Before New Signals)	Number of New Signals	Vehicle Hours Traveled
1.8	1	16684
1.6	1	16685
1.4	3	16656
1.2	1	16578
1.025	1	16611
1	1	16622
		16614

*Safety Considerations.* The analysis shows that for most of the forecast years vehicle delays can be minimized by implementing shorter signal cycle lengths than are currently utilized in the Cedar Rapids metropolitan area. However, it is recognized within the engineering community that safety concerns often warrant the operation of traffic control in a manner that does not minimize these delays (16). First, the selection of the control device is often made on safety considerations alone and not capacity or delay, and planners cannot be expected to predict which intersections will in the future meet specified accident warrants for signalization or all-way stops (5).

Second, once signalization is selected, the selection of phasing and cycle lengths will also include safety as well as congestion concerns. For example, the selection and minimum timings for protected left turn phases, yellow and all-red interval timings, and many "split phasing" schemes are done primarily for safety rather than capacity. Safety can also affect traffic progression on arterial streets. For example, minimum side-street green times for pedestrian crossings, even if rarely used, must be planned for within a signal coordination scheme. The comparisons of system performance between current and delay-minimizing signal cycle lengths can therefore be considered part of the cost of a good traffic safety program.

## ALTERNATIVE RUNS

Several alternative runs were performed to better understand the properties of the signal system design algorithm.

*Single Time Period.* To test the hypothesis that the time sequence of intersection upgrades matters, a run of a single forecast year of 2030 was completed without any analysis of intervening years. In this case, there were only 96 signals added and the final VHT was 29447, somewhat higher than at the end of the primary run. It appears that a single year forecast fails to account for a substantial amount of traffic rerouting that would lead to additional signals. This run also gives a feeling for the overall improvement in VHT that can be attributed to signal upgrades alone. The VHT with optimized cycle length but no upgrades was 32551. Therefore, approximately 3000 vehicle hours of time savings can be attributed to the 96 new signals.

*Run with All-or-Nothing Assignment.* The algorithm was run with all-or-nothing assignment to help determine whether convergence error, Braess's Paradox or multiple equilibrium solutions were interfering with finding a minimum VHT in accordance with Warrant #10. All-or-nothing assignment would produce unrealistic results but would be free of all these effects. When the algorithm was run with all-or-nothing assignment there were 31 new signals required in the base year (1994), and a nearly linear increase in signals in years thereafter. A total of just 92 signals were accumulated by 2030, possibly because there were fewer used paths between origins and destinations and therefore fewer heavily congested signed approaches. Inspection of VHT at each threshold of each forecast year indicated that half of the forecast years possessed good convexity. In the remaining years the first encountered local minimum was at or near the global minimum for that year.

*Run with More MSA Iterations.* A single run was made with 50 MSA averages to determine whether improved precision in the assignment step could facilitate finding an optimum solution within each forecast year. This run required slightly over 100 hours of computation, and this many averages is deemed impractical for real planning purposes. It was found that the improved precision had little effect on the determination of cycle length, which had been calculated reasonably well with only 10 MSA averages. The increased precision seemed to eliminate much of the convergence error, but did not appreciably improve the convexity of VHT with respect to multiples of Warrant #10. This run created only 86 signalized intersections, possibly because it tended to better reallocate traffic away from congested stop-controlled approaches to adjacent signalized intersections.

## CONCLUSIONS

The new emphasis on traffic controls in travel forecasting networks creates a substantial burden to determine the nature of traffic control systems in future years. The burden can be lessened by allowing a computer program to mimic the historical development of the traffic controls over a long period of time.

The time sequence of conversions of stop-controlled intersections to signals is important. Several intermediate forecast years should be evaluated and upgrades should occur in priority order during any forecast year. However, multiple forecast years adds greatly to the amount of computation.

A completely optimized network could not be obtained because of convergence error remaining after 10 MSA averages in the traffic forecast and the fact that MUTCD's Warrant #10 is an imperfect indicator of potential reductions in VHT. More MSA iterations were judged impractical because of the network size and the large number of times that a traffic forecast needs to be made. Instead, a network exhibiting a low VHT was obtained by fully implementing MUTCD's Warrant #10. It may be possible to find a better criterion for minimization than multiples of Warrant #10, although the safety implications of deviating from the MUTCD should be carefully considered.

The algorithm for selecting new signals is promising. Although similar in intent to the network design problem, it differs computationally. The algorithm produces realistic and practical results that do not depend on the abstract concept of link "capacity". Instead the algorithm deals with those specific elements of the traffic system that can be directly manipulated by a traffic engineer. With more computational

power or a lot more patience, additional aspects of traffic system design could be implemented, including arrival types for signal coordination, ramp meters, new turning lanes, roundabouts and other minor geometric changes.

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