

INTEGRATING BUS SERVICE PLANNING WITH ANALYSIS, OPERATIONAL CONTROL, AND PERFORMANCE MONITORING

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ABSTRACT

High quality transit service requires two feedback loops. The first loop, which works in real time, is operational control – taking measures to restore service to schedule. The second loop, which works off-line over a longer time frame, is service planning – making a schedule that reflects realistic operating conditions, is achievable, and allows for and expects interventions for operational control.

At the heart of both quality loops is a performance monitoring system based on an on-board computer with location tracking capability. It communicates in real time its location and deviation from schedule; for service planning, it records its trajectory during the day and uploads it at night into a database used for service planning.

This paper shows how service planning can be integrated with operational control using simple illustrations based on the systems that are in place in Eindhoven, the Netherlands. The operational control systems used there are holding at timepoints, and conditional priority at signalized intersections. Late buses request, and are given, priority, while early buses experience normal intersection delay, thus restoring service to its schedule. The analysis and planning system used is TRITAPT (TRIP Time Analysis in Public Transport), a program developed at the Delft University of Technology.

First, we illustrate the impact of operational control (holding and conditional priority, both alone and in combination) in improving service quality. Their main benefit is to reduce schedule deviation. By virtually eliminating early trips, they greatly reduce waiting time for services for which arriving passengers follow a schedule.

Next, we show how analysis of data gathered daily using on-board computers can be used to create a better schedule. Statistical analyses of delays by segment and of schedule and headway deviations along the route are illustrated. Planning tools include generation of recommended scheduled route times based on experienced running times, and determination of timepoint times (“passing moments”) for stops all along the route.

Finally, we show how integrated planning and control leads to the best performance. Methods for determining a scheduled route time that accounts for the effect of control are described and illustrated. The strategy followed in Eindhoven of creating a schedule based on absolute priority at signalized intersections, but then using conditional priority to give the operation a stronger means of control, is illustrated. The result is an achievable schedule with high speed and small schedule deviation. However, the need for continuing monitoring and schedule improvement is also emphasized.

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INTELLIGENT TOOLS FOR QUALITY FEEDBACK LOOPS

Due to the high cost of manual data collection, transit route service has traditionally been planned and executed with relatively little attention given to monitoring performance. Not surprisingly, service often deviates from the plan – trips run early or late. As a result, passengers wait longer and sometimes miss their connections. Headways become irregular, making some trips overcrowded, causing waiting passengers to be skipped and slowing operations. Unreliability has often been cited as one of the major deterrent to building transit ridership.

Delivering high quality transit service requires tools for both real-time operational control and for improving the service plan based on analysis of historical performance data. The prerequisite to both sets of tools is a system of automated performance monitoring. These components form two feedback loops, as illustrated in Figure 1.

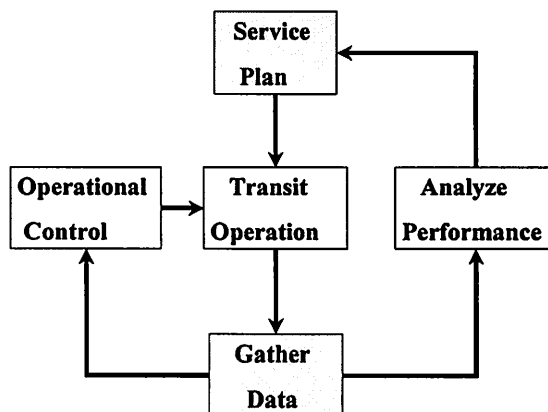


Figure 1 Service Quality Cycles

The first feedback loop is in real time, as information about schedule deviations, overloads, and incidents trigger control tactics meant to restore the service to the service plan. The second feedback loop involves statistical analysis of historical performance data to design a better service and control plan. This second feedback loop enables the

transit agency to assess the impact of changes to the schedule, the control plan, the traffic system, personnel management, or any other aspect of service delivery, and thus continually improve service quality.

While the concepts of performance monitoring, quality control, and a continuous improvement cycle are not new, tools for applying these concepts have been lacking in the transit industry. Advances in computing and communications technology have made possible the development of powerful tools for performance monitoring, operational control, and off-line performance analysis and service design. This paper focuses on three tools being used in the bus system of Eindhoven, a city of some 300,000 inhabitants in southeastern Netherlands. The tools are:

- *For gathering performance data:* on-board computers tracking vehicle location and schedule deviation, recording events, and communicating with traffic controllers.
- *For real-time operational control:* conditional priority at signalized intersections, meaning that late vehicles are given priority while early vehicles are not.
- *For analyzing performance data and improving service design:* a database and analysis tool called TRITAPT (TRIP Time Analysis in Public Transport) (1) that stores and analyzes performance data and designs improved schedule plans.

Attention is also given to the value of other existing and yet-to-be-developed tools in the two quality cycles for transit service delivery.

GATHERING PERFORMANCE DATA

The heart of the data gathering system is the on-board computers which serve as “event recorders” or “trip time analyzers.” The essential features of the system are:

1. Tracking location
2. Knowing the schedule the bus should be following
3. Automatic communication of essential information for real-time control
4. Storing and uploading of extensive event data for off-line analysis
5. Design and implementation to maximize acceptance by operators
6. Every vehicle is equipped

1. Tracking location. Many technologies, including global positioning, can be used to track vehicle location. In Eindhoven, VECOM™ loops, capable of two-way communication, are present at each signalized intersection as part of the priority system. The on-board computers receive a loop’s identification as they pass the loop, updating their location. Dead reckoning is used between loops. Location is also updated when the doors open, based on a route description with known bus stop locations.

2. Knowing the schedule. While transit systems normally keep a schedule constant for a period of several months, there are often temporary and minor changes due to construction, special events, and so forth. Therefore, the schedule is loaded automatically into the computers every day at pull-out. At the same time, the on-board computers’ clocks are all synchronized. Knowing the schedule and location enables the on-board computer to monitor schedule deviation. Between timepoints (every stop and signalized intersection is a timepoint), the schedule is interpolated.

3. *Communicating essential information in real time.* For major incidents (accidents, fires), the operator communicates by radio. The radio system can also provide for automatic communication if delay exceeds a certain threshold, or if a mechanical or security alarm is activated. The more common types of disturbances are handled by automatic, decentralized control. The on-board computer sends its identification and early/on-time/late status to the traffic controller via the VECOM loops at each signalized intersection, which then use the conditional priority strategy to minimize delay for buses that are late, while allowing early buses to experience normal intersection delay. The on-board computer also maintains a small display of schedule deviation visible to the operators, who, by changing driving behavior when ahead of or behind schedule, also exercise some real time control.

The Eindhoven system does not have traditional automatic vehicle location (AVL) in the sense that location information is not transmitted in real time to a central facility. This is because, except for major incidents that can be reported by radio, there is relatively little that supervisors at a central facility can contribute to reducing a schedule deviation.

4. *Storing and uploading of extensive event data for off-line analysis.* The on-board computers record events such as passing detection loops, opening and closing doors, and crossing a speed threshold of 5 km/h. Each event record includes location and time stamps. Each evening, event records are uploaded by high-speed link to a central computer. From these event records, TRITAPT software reconstructs vehicle trajectories and identifies travel time components such as dwell time, time spent delayed in traffic, and so forth. The trajectory data is then added to a TRITAPT database for later analysis.

5. *Design to gain operator acceptance.* Acceptance of any automated data gathering or control system by operators is critical to its success. The system design includes key components that respond to operator concerns, and implementation was done slowly and carefully with ongoing communication with the operators and their union representatives. This aspect of implementation, which we call “process management”, can be as important as the technological innovations (2). On the technological side, the design includes a small screen visible to the operator that displays schedule deviation in steps of 10 s. This display allows them to confirm the system’s workings against their printed timetable and gives them a window into the “mind” of the system, making it less threatening. Another key component of process management is providing the operators with realistically achievable timetables, a subject we discuss later.

6. *Every vehicle equipped.* For real-time control, it is understood that every vehicle is equipped. However, for off-line analysis as well, the availability of data from every vehicle – rather than from a small subset of the fleet – means that a large sample size can be assembled in a matter of weeks. This allows rapid assessment of changes to the schedule or to control measures, and rapid response to systematic changes in traffic conditions. In addition, headway regularity, an important aspect of service quality on

high frequency routes, can only be evaluated if every vehicle is monitored.

OPERATIONAL CONTROL

For major incidents, special measures that involve supervision from the control center and temporarily abandoning the schedule may be needed. The Eindhoven system focuses on responding to common disturbances, for which operational control means taking measures to restore service to its schedule. It uses two methods of operational control. The first, available on all routes, is operator response, in which the operator adjusts his or her driving behavior by trying to speed up when late, and by slowing down or holding at a stop when ahead of schedule. The second, currently available on a few routes but with implementation underway for other routes, is conditional priority at signalized intersections.

Supporting Operator Response

The traditional method of operational control is to enlist the efforts of operators to stay on schedule. With strong supervision, operator response can be effective in slowing down vehicles that are ahead of schedule. The ability of an operator to catch up when late, however, is limited unless a lot of slack is built into the schedule, which is costly to the operating agency and frustrating to passengers.

To support operators, the monitoring system provides them with a real-time display of schedule deviation, making it easy for them to know which way to adjust their driving behavior. This system provides the operators with instant feedback. When they see the schedule deviation return toward zero as a result of their efforts, their intrinsic motivation to do a professional job is strengthened. However, if the timetable is not realistically achievable, they will become frustrated and lose motivation to stay on schedule. This emphasizes the need for the off-line service analysis and design component of the service improvement cycle.

Conditional Priority at Signalized Intersections

Advances in technology have made possible a powerful tool for operational control – conditional priority at signalized intersections. This strategy, which can be applied to any route with signalized intersections, means that the traffic control system grants priority to transit vehicles that are behind schedule, but not to vehicles that are early. Unlike operator response, which is effective only at holding late vehicles, conditional priority provides both a push and a pull to restore service to the schedule. Late vehicles get pushed ahead as they are ushered through intersections with little or no delay, while early vehicles tend to be held back via normal intersection delay.

Furth and Muller (3) describe the effects of conditional priority to both transit and automobile traffic based on an experiment in Eindhoven conducted in May 1998. They found that the central schedule deviation band (the band between the 15-percentile and the 85-percentile schedule deviation) at a stop two-thirds of the way along the route was [-1.0 to 2.2] minutes on a day with conditional priority, as compared with [-3.3 to 2.5] minutes on a day without conditional priority. (Negative deviations indicate that the bus

was early.)

Further analysis of the same experiment was done to illustrate how conditional priority tends to restore service to the schedule. In Figure 2, each line segment represents a single outbound vehicle trip during the 7-11 a.m. period, indicating its schedule deviation entering and leaving a major signalized intersection. On the day without priority, there is a general pattern of randomness, with a tendency for schedule deviation to worsen (greater spread). On the day with conditional priority, the restoring tendency is clear: late vehicles leave less late than when they entered, and early vehicles exit less early.

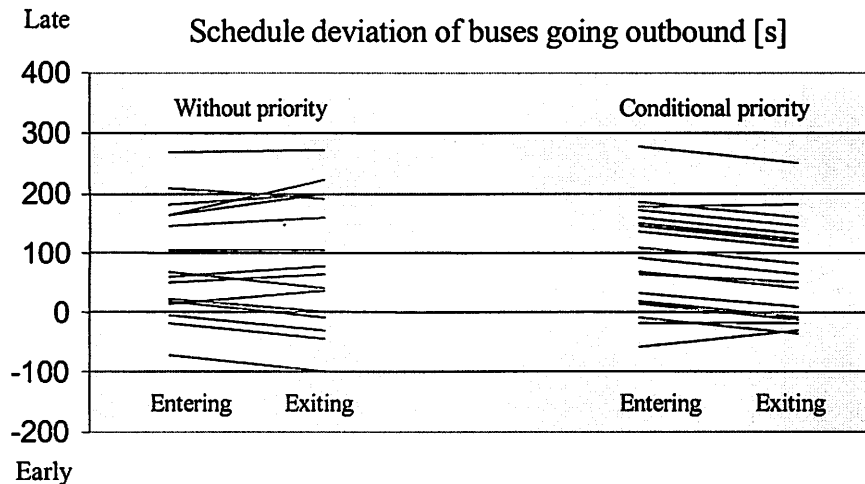


Figure 2: Restoring Effect of Conditional Priority at an Intersection on Line 1, Eindhoven

On average, the absolute value of schedule deviation decreased by 17 s on the day with conditional priority, versus an increase of 11 s on the day without conditional priority. The net restoration effect of conditional priority at a single intersection was therefore 28 s.

Effects of Operational Control

The ability of different forms of operational control to improve punctuality can be illustrated with a simple example analyzed by Monte Carlo simulation. In this example, a transit route consists of four segments, each with a average section running time of 10 minutes and a standard deviation of 2 minutes. Running times on the different segments are assumed independent. On-time dispatching at the start of the route is assumed. The schedule matches the mean running time.

Results are shown in Figures 3-6. In these figures, as well as in Figures 13-15, the diagram on the left highlights the central schedule deviation band, as defined earlier. The light dashed lines, shown for comparison, are the central deviation band for the base case (the uncontrolled situation, Figure 3). The diagram on the right shows in blue the cumulative distribution of departure times from the third timepoint. Again, the distribution for the base case is also shown (in black) for purposes of comparison.

Figure 3 shows the uncontrolled situation. The central schedule deviation band for departures at the third timepoint (the benchmark we will use for comparing different scenarios) is $[-3.5$ to $3.5]$ minutes. We have argued elsewhere (2) that, except on frequent services, passengers will have to arrive around the 2-percentile value of bus departure time to have an acceptably small chance of missing the bus. In this example, they would have to arrive at the stop around time 23 min, resulting in an average waiting time of 7 minutes (two standard deviations).

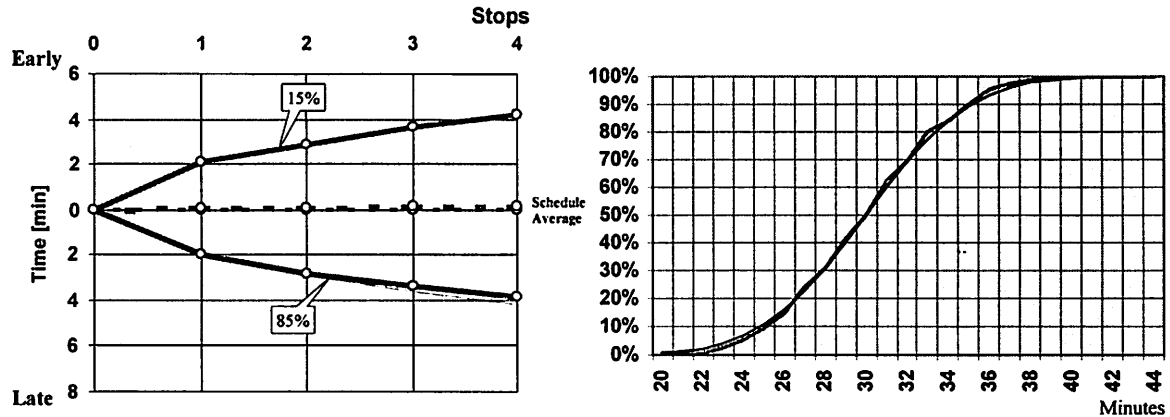


Figure 3: Schedule Deviation and Departure Time Distribution Without Operational Control

Figure 4 gives the same summary, assuming limited operational control by holding early vehicles at timepoints (segment boundaries). In our example, timepoints are separated by 10 min running time, making the departure profile in the left diagram sharply saw-toothed because early buses may be held at the timepoints for 2 minutes or more. In real applications in the Netherlands, every stop is a timepoint, and so the holding time at each timepoint is much smaller. The blue line connecting departure times at the timepoints more accurately portrays the departure time distribution for realistic application.

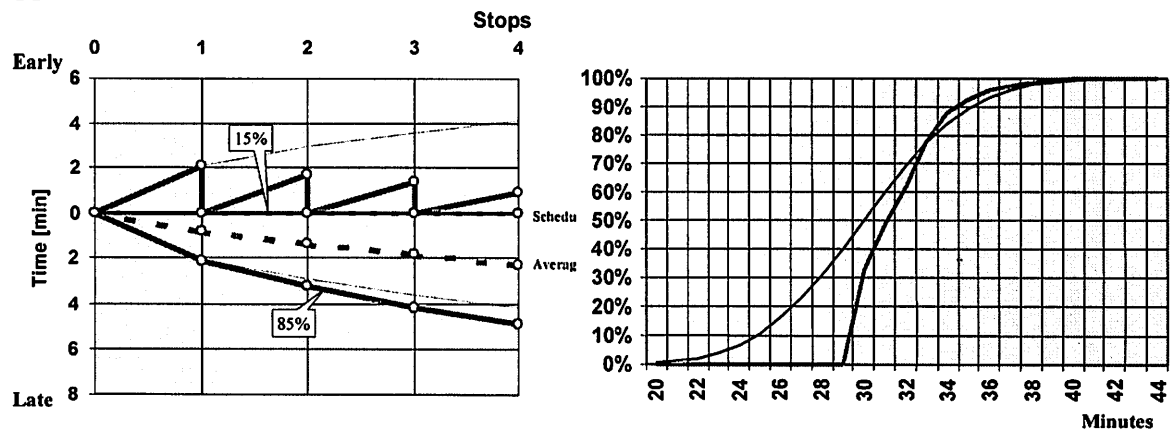


Figure 4: Schedule Deviation and Departure Time Distribution with Holding

Due to holding, the average schedule deviation at the third timepoint increases to 1.9 minutes, but the central schedule deviation band reduces in size to $[0.0$ to $4.1]$

minutes. A boarding passenger would not have to arrive before the scheduled departure time, and would have to wait, on average, only 1.9 minutes.

Figure 5 shows schedule deviations for a third case: conditional priority at intersections, which is assumed to be able to delay early vehicles and speed up late vehicles by up to 1 minute per segment. Schedule deviations become smaller still, with the central schedule deviation band reducing to $[-1.9, 1.9]$ minutes.

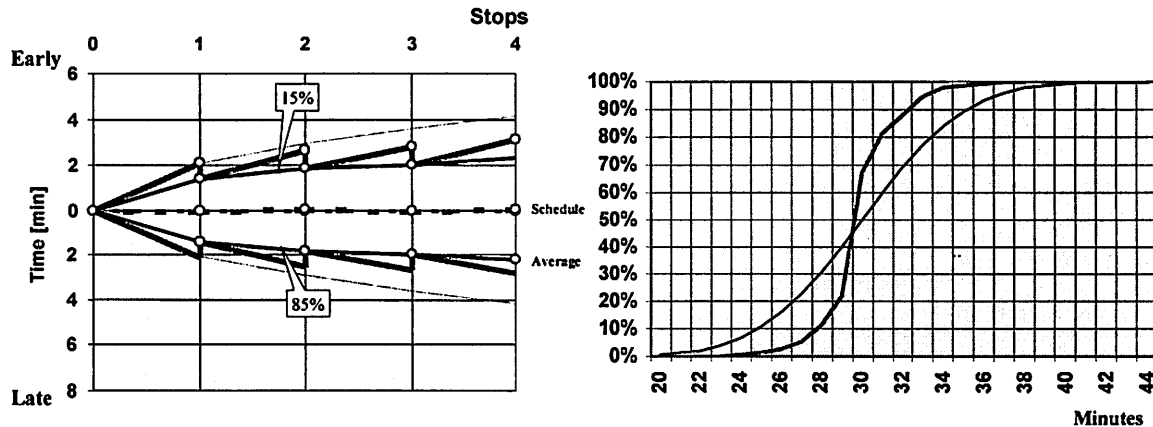


Figure 5: Schedule Deviation and Departure Time Distribution With Conditional Priority at Intersections

Finally, a fourth case, shown in Figure 6, shows schedule deviations with both conditional priority and, when necessary, holding. The mean schedule deviation is only 0.6 min, and the central schedule deviation band at the third timepoint shrinks to $[0.0, 2.0]$ minutes, only 28% as large as the uncontrolled band. It is noteworthy that, compared to the previous case, earliness is reduced by 1.9 minutes while lateness increases by only 0.1 minutes.

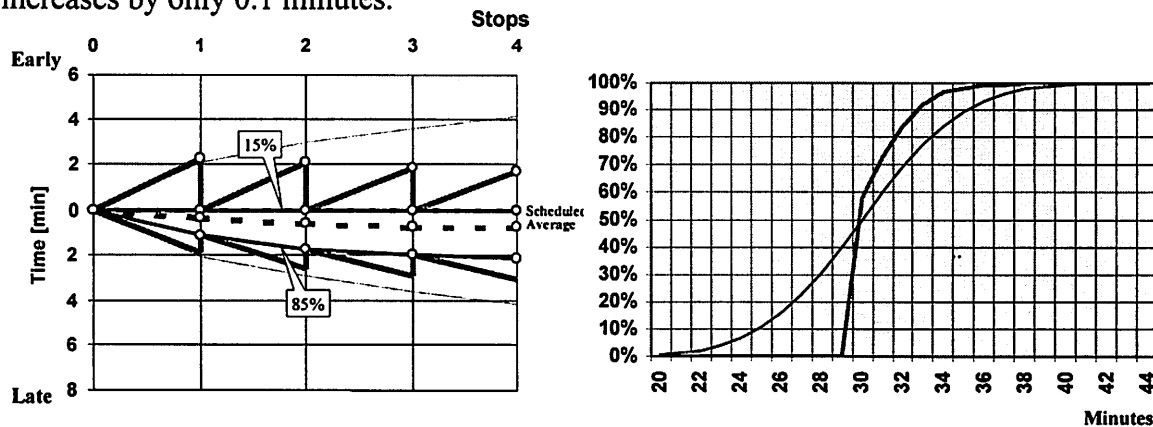


Figure 6: Schedule Deviation and Departure Time Distribution With Conditional Priority and Holding

ANALYZING PERFORMANCE DATA AND IMPROVING THE SERVICE PLAN

A review of the state of the practice in larger U.S. transit systems reveals how data-

poor most transit agencies are when it comes to updating route schedules and monitoring on-time performance (4). The majority relies on manually collected data with sample sizes that are far too small for any statistically significant results at the route level. Many of the agencies with AVL are unable to extract useful performance data for off-line analysis from their systems, a problem that has been noted elsewhere (5).

A few U.S. systems and several Canadian systems have automatic passenger counters, which, in addition to counting passengers, also serve essentially the same role as Eindhoven's on-board computers by recording trip events and reducing those records to vehicle trajectories and running time components. However, North American APC installations tend to involve equipping only a small fraction the fleet, rotating the equipped vehicles around the system to provide a data sample for all the trips in the daily schedule. The survey cited above found that most North American APC installations afford a sample of only 5 to 15 observations of each trip in the weekday schedule per year. The Eindhoven implementation, with on-board trip time analyzers on all the buses, illustrates the exciting possibilities for performance analysis and service design in a data-rich system.

Analysis of Performance Data

TRITAPT (1) (TRIp Time Analysis in Public Transport), a software package developed at the Delft University of Technology's Transportation and Traffic Engineering Section, processes data in two stages. In the first stage, event records are uploaded from the on-board computers each night at pull-in. Vehicle trajectories are reconstructed by matching event data to the schedule and route description, calibrating odometer data to known loop and stop locations. Event records are interpreted to allocate the time elapsed between one stop and the next into normal dwell time, control time (additional dwell time spent at a stop by a vehicle that is ahead of schedule), delay time (time spent stopped or at speeds of less than 5 km/h away from the bus stop), and in-motion time. The results are then stored in a database format with records for each stop-to-stop segment. The number and types of errors found in reducing the event data are also reported, which can indicate a need for hardware or software maintenance.

In the second stage, TRITAPT produces reports as requested through a menu driven interface. The reports can cover any user-specified set of dates and times. One available report, illustrated in Figure 7, shows a summary of delay time on each interstop segment along the route. The bars indicate mean delay, the arrows the maximum, and the asterisk the 85 percentile delay on each segment. With this report, segments with high or variable delay can be identified and targeted for remedial action; alternatively, this report can be used to assess the impact of a change in traffic control, operations, or any other action.

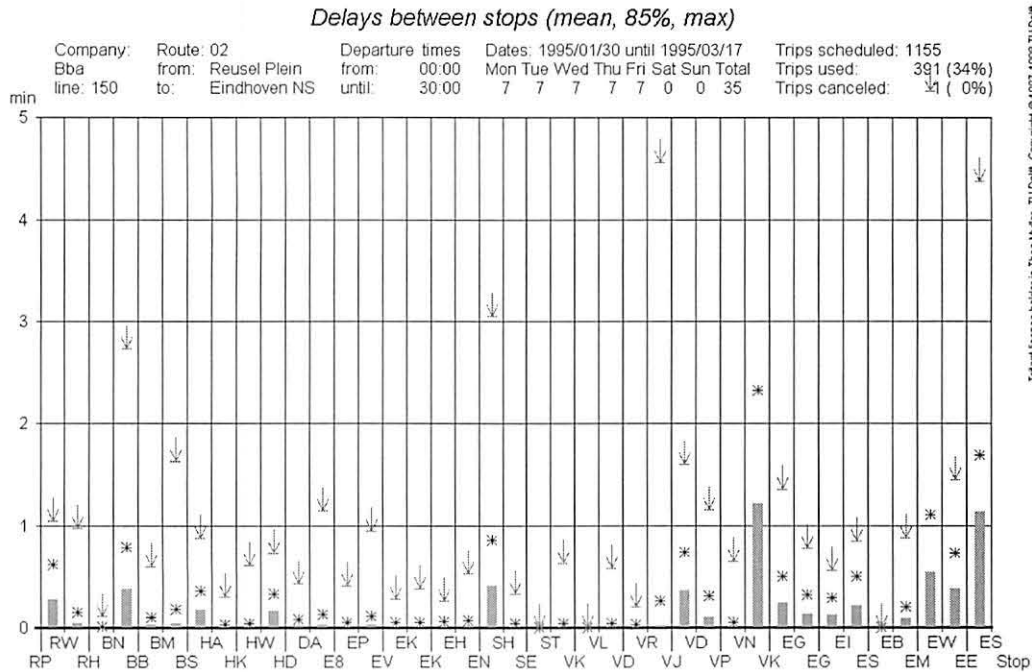


Figure 7: Delays Between Stops Report

Another useful report, illustrated in Figure 8, shows schedule deviations along the route. Each hairline represents a single trip; bold lines indicate the mean and the 15- and 85-percentile values.

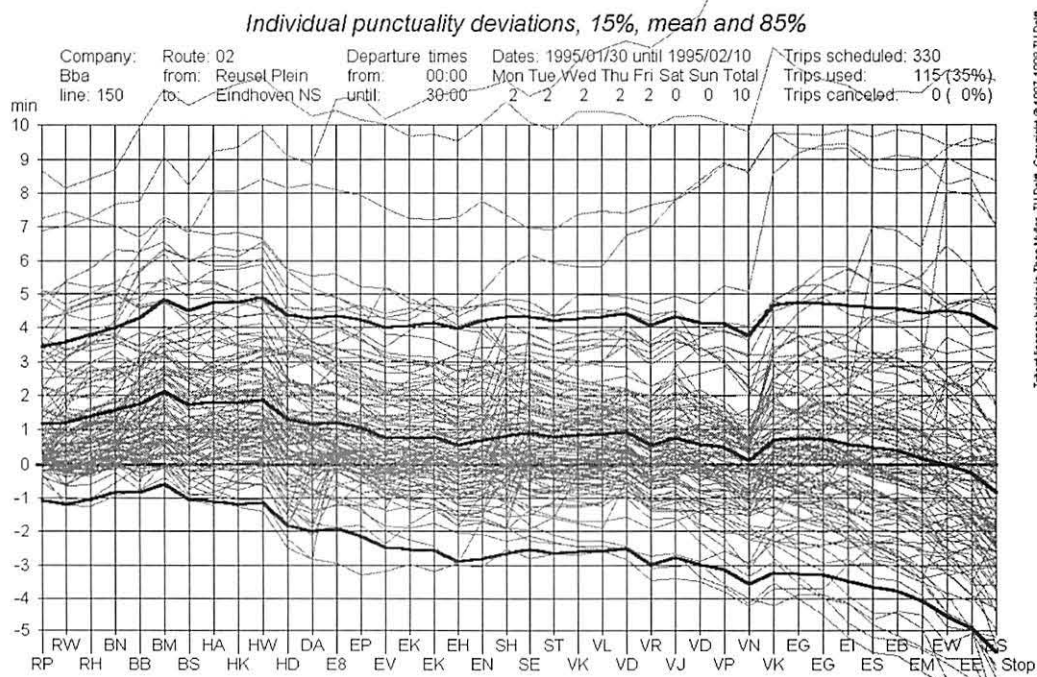


Figure 8: Schedule Deviation Report

Schedule adherence is affected by many factors – planning (which supplies the

timetable), the operating personnel, supervision, operational control, traffic volumes, and the traffic control system. A change in any one of these factors can affect schedule adherence. In a well-integrated system, the timetable and supervision and control tactics should be tuned to the actual level of demand and traffic congestion, resulting in a narrow schedule deviation band. On routes for which passengers follow a timetable, deviations earlier than -1 minute should be rare. Another report (not shown), suitable to high frequency routes, similarly displays headway deviations.

A trajectory report, shown in Figure 9, summarizes a day's performance for a line / direction by plotting a time-space diagram for each trip as well as for the schedule. With this tool, an analyst can easily see schedule deviations, headway variations, and correlations between trips operated by the same operator (each operator's trips appear in a distinct color). This report will highlight, for example, the impact of a missed trip or an intervention on subsequent trips, making it a useful tool for planning control strategies.

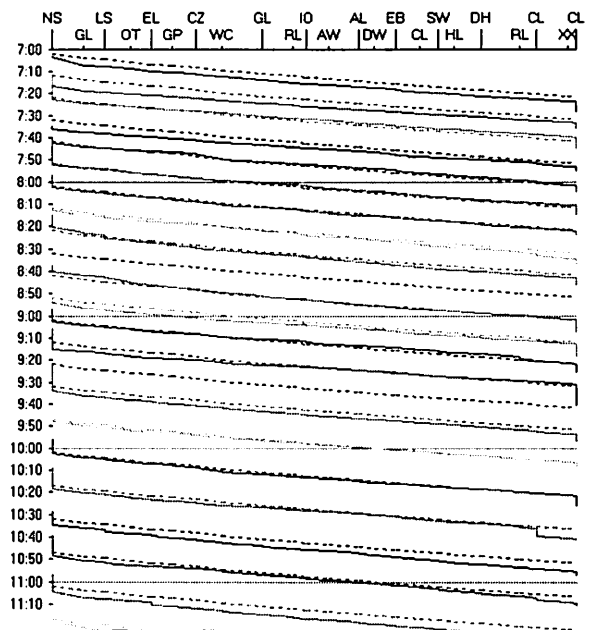


Figure 9: Actual (solid lines) and scheduled (dotted lines) bus trip trajectories

As an aid to the management of the (private) bus company Hermes operating in Eindhoven and to officials of the city government which subsidizes the operation, performance reports are automatically prepared every day for access by authorized users via the internet. An example report summarizing performance on a particular day is found in Figure 10.

This report indicates by color (varying by shades from green to red) the fraction of bus arrivals that were in the range 30 s early to 90 s late at each stop, the mean and standard deviation of schedule deviation at each stop, and the mean operating speed on each route segment. Each day, management and local government officials can review this and similar reports to assess quality of service offered on any previous day.

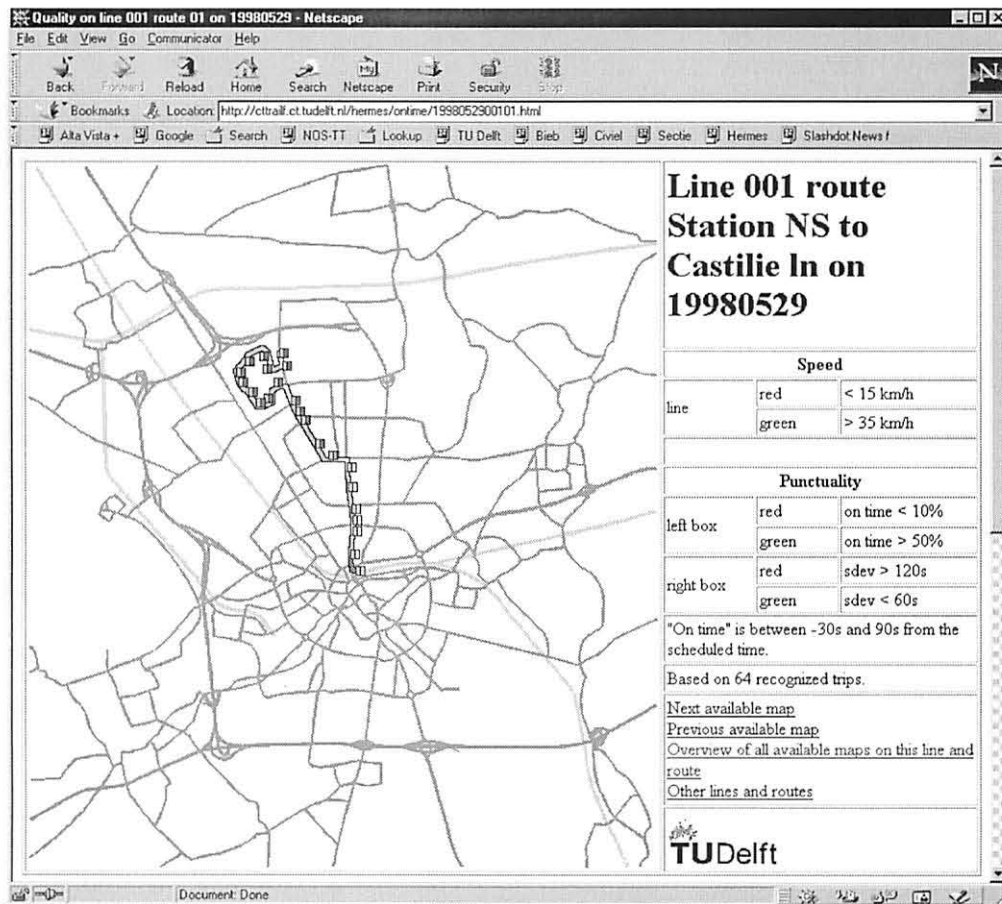


Figure 10: Internet presentation of transit quality on Line 1, Eindhoven

Service Design Tools

TRITAPT also features several reports that help the planner select the proper scheduled running time. The main purpose for distinguishing control time from normal dwell time is to enable one to determine net trip time (i.e., excluding control time) as a guide to establishing a new scheduled running time.

TRITAPT provides a statistical summary of net trip times for selected percentile values for each trip in the daily schedule (Figure 11).

In this report, the lighter lines indicate the 50-, 80-, and 90-percentile net trip times for each scheduled trip. The heavy line and dots represent suggested scheduled trip times based on the criteria that trip times should be in whole minutes, should lie above the 80-percentile and (preferably) below the 90-percentile net trip time, making them realistically achievable for operators. They should be constant among neighboring trips when possible. For example, in the figure shown one might recommend a running time of 43 for the period 14:00-16:00.

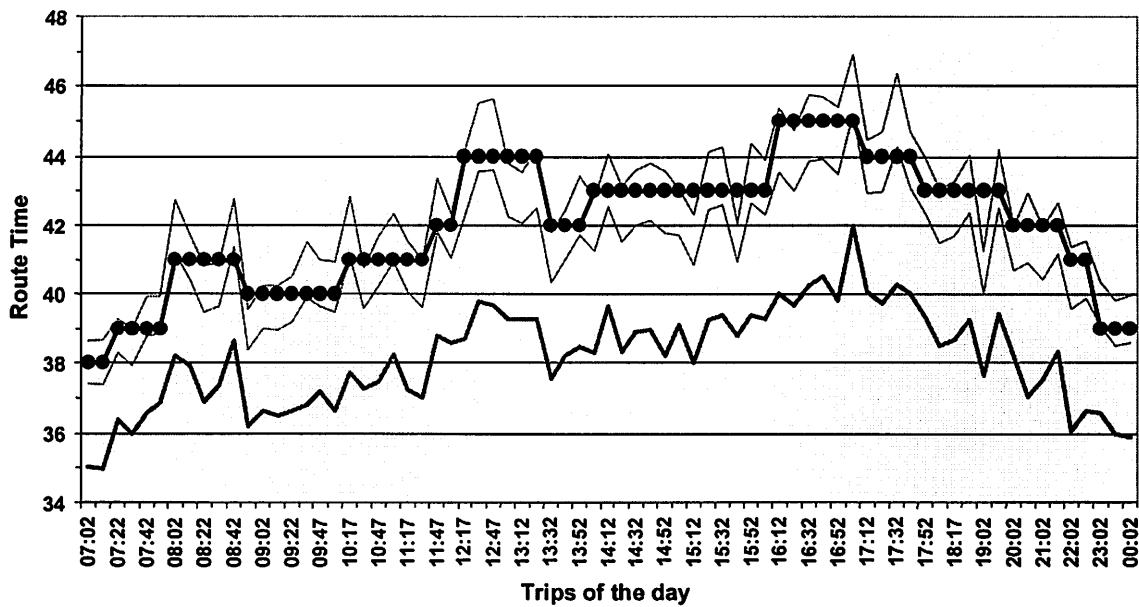


Figure 11: The 50-, 80-, and 90-percentile net trip times and suggested scheduled trip times

Another service design tool is a report, illustrated in Figure 12, suggesting running times by segment, based on historical net running time data and the desired percentile value for running time. This report follows the “passing moment” logic of schedule design described in the following section. The results are also available in a table.

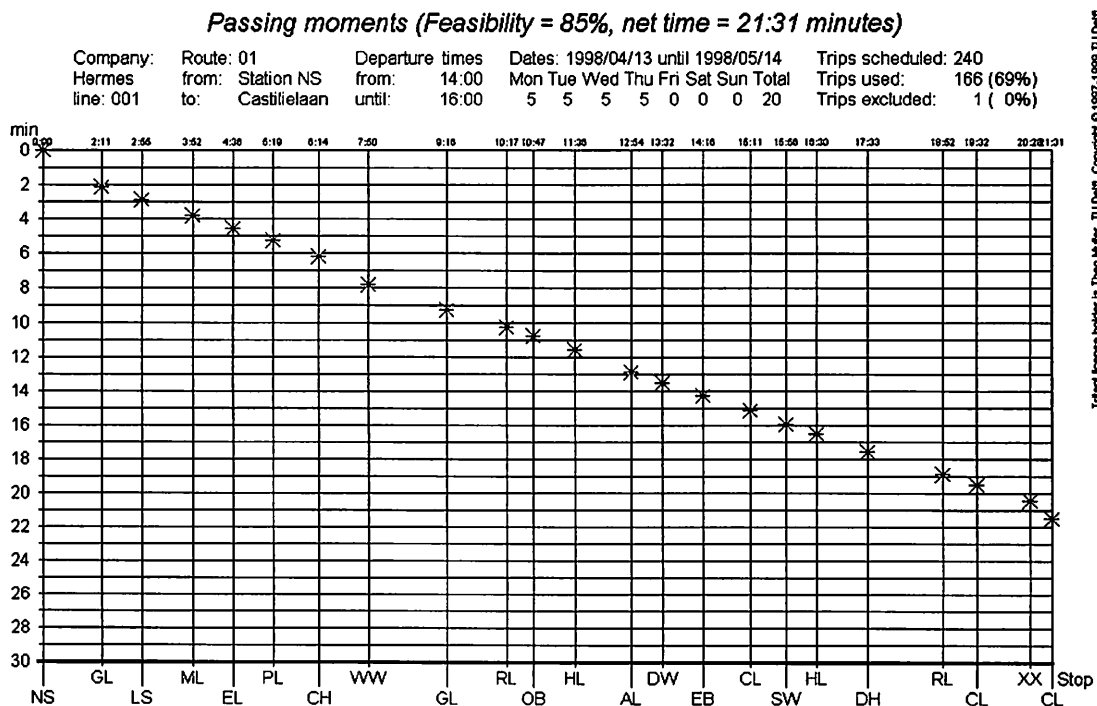


Figure 12: Passing Moments

INTEGRATING SCHEDULE DESIGN WITH OPERATIONAL CONTROL AND PERFORMANCE ANALYSIS

Operational control is usually introduced with the goal of keeping the service on schedule. However, the issue can be turned around to ask, what is the proper schedule when a system of operational control, especially conditional priority at signalized intersections, is in place? This is the last piece of the service quality feedback loop: modifying the service design based on performance. When a system of operational control is anticipated, a new paradigm for determining scheduled running time is in order.

The ideal scheduled running time is one that balances several objectives. For the passengers, good service quality is achieved with a high speed (low scheduled running time) and high punctuality. Early departures are especially to be avoided. The objectives of speed and punctuality are clearly in conflict, as punctuality normally suffers as the schedule becomes tighter. (This highlights the value of giving transit priority at signalized intersections, since it improves both speed and punctuality.) For the transit agency, minimizing operating cost means minimizing the sum of scheduled running time and necessary layover, which is largely a function of the variation in running time. These two quantities can be combined in an objective of minimizing a suitable percentile, say the 97-percentile value, of running time, which would reflect a constraint that no more than 3 percent of the trips should begin late because of delays propagated from the prior trip. The operators are interested in a scheduled running time that can be achieved most of the time so that they can enjoy their scheduled layover and avoid the stress of running late. Operators' satisfaction is critical to operational control because of the influence they have on punctuality at dispatch points, timepoints, and en route.

A starting position for establishing scheduled running times is to use mean values. They are simple to understand and construct, since the sum of the mean running times on all the segments of a route equals the mean running time of the route. However, unless a route has little running time variation or is very short, scheduling for mean running time on a route without operational control will lead to large negative schedule deviations (early departures), as illustrated in Figure 3. If there is no control, using shorter run times (and a longer layover) is preferable, so that even if the schedule deviation band is just as large, most of the deviations will be positive (late) rather than negative (early).

Where holding at timepoints is practiced, it should be recognized that holding will increase the mean running time. One way of recognizing the effect of holding, which we call the adjusted timepoint method, is to include the expected holding time in the scheduled running time. Scheduled time of a segment is then mean uncontrolled running time plus the expected holding time at the timepoint at the start of the segment. Assuming an on-time dispatch, a normal distribution of running time, and a strategy of holding trips until the mean uncontrolled running time has elapsed, it can be shown that the average holding time for a segment is 0.40 standard deviations of running time.

An improved paradigm for establishing running times when operational control is active is to base them on net completion time for a chosen feasibility condition. For any timepoint, net completion time is the time needed to reach the end of the route, excluding holding time. If the selected feasibility condition is 85 percent, the scheduled time from a timepoint to the end of the route will be set equal to the 85-percentile net running time from that timepoint to the end of the route. Thus, timepoint times, called passing moments because vehicles are not allowed to pass until this moment, are determined by

working backwards from the end of the route. The 85-percentile completion time for the whole route serves as the scheduled trip time. The difference between the passing moments at adjacent timepoints is the scheduled segment running time. The passing moment system is described in more detail in (2).

Like the adjusted timepoint method, the passing moment method anticipates the use of operational control. However, its advantage is that, unlike the adjusted timepoint-method, it does not lead to an increase in scheduled trip time as the number of timepoints grows. Regardless of the number of timepoints, the route time is unchanged. Another advantage is the flexibility it affords by allowing the planner to choose the feasibility parameter. Compared to a schedule based simply on mean net running times, a schedule based on passing moments will have a few extra minutes of route time (assuming the feasibility condition exceeds 50 percent; a passing moment schedule with a 50 percent feasibility condition will essentially duplicate a schedule based on mean running time). However, unlike an adjusted timepoint schedule, those extra minutes will not be evenly distributed over the route. Instead, they will be distributed more heavily to segments near the end of the route. This makes it less likely that vehicles will be held at timepoints near the start of the route, where the completion time is more uncertain. The result is that vehicles are more likely to run late than early over most of the route, but late vehicles get time to catch up toward the end of the route.

A strong advantage of the passing moment method is that it fosters acceptance by operators. They are more willing to be held at a timepoint if they know that, once released, they still have an 85 percent chance (or whatever value is selected as the feasibility condition) of completing the trip on time.

Figures 3-6 showed the effect of operational control on schedule adherence for a given schedule, one that simply used mean running times. However, as this section has emphasized, using mean running times is not usually an optimal schedule, and schedules should be modified to anticipate the effects of operational control. Figure 13 shows, for the same example route as was used in Figures 3-6, the schedule and expected performance based on the adjusted timepoint method with holding.

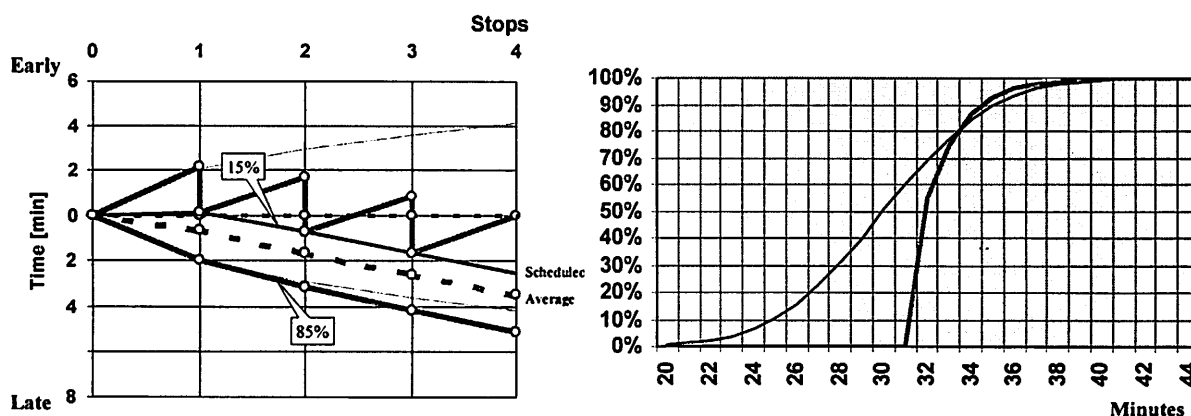


Figure 13: Schedule Deviation and Departure Time Distribution
With Adjusted Timepoint Scheduling and Holding

It should be noted that in the left diagram of this figure and in those that follow, the deviations on the vertical axis are with respect to mean uncontrolled running times. Deviations from the revised schedule can be read by simply comparing the deviations

with the schedule. While the scheduled departure time at the third timepoint in Figure 13 has become 1.8 minutes later than the original schedule, the 85-percentile schedule deviation is only 0.2 min later than the 85-percentile schedule deviation that occurred with the original schedule and holding at timepoints (Figure 4). At the same time, the width of the central schedule deviation band has decreased from 4.1 to 2.5 minutes, a significant improvement in reliability.

Figure 14 shows, for the same example route, the schedule and expected schedule deviations resulting from using the passing moment scheduling method with a feasibility condition of 85 percent.

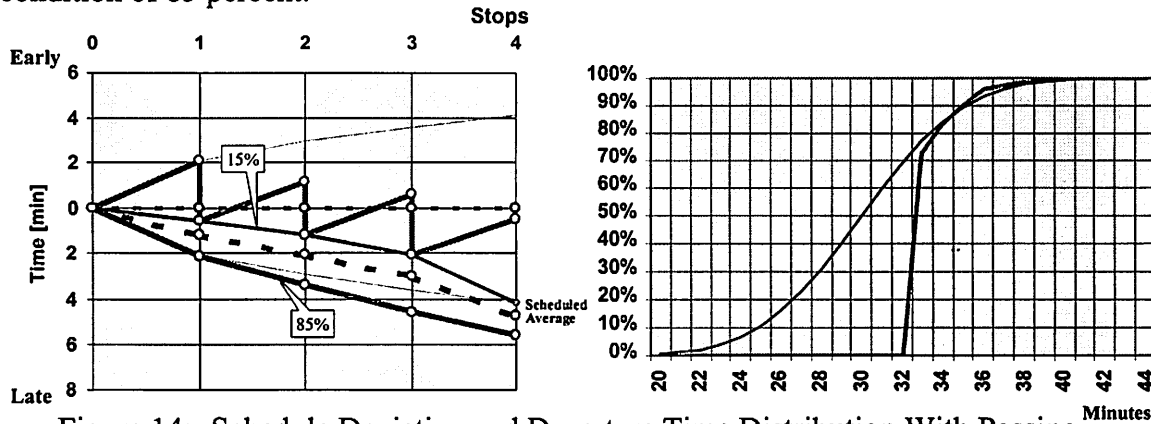


Figure 14: Schedule Deviation and Departure Time Distribution With Passing Moment Scheduling and Holding

The outcome is similar to the adjusted timepoint method. Compared to the original schedule with holding, the scheduled route time increases, the central schedule deviation band is tighter, and the 85-percentile departure time from the third timepoint is barely changed. For this example, the 85 percent feasibility condition results in a slightly more generous schedule than the adjusted timepoint method; an 80 percent feasibility condition would have yielded a tighter schedule that required no more time than the adjusted timepoint method.

If conditional priority is available with the ability to “push ahead” late vehicles by 1 minute per segment, and holding is used to delay early vehicles, expected schedule deviations become very small for a schedule based on passing moments. The central bandwidth will be less than 1 minute for a timetable based on 85 percent uncontrolled completion times. However, this schedule, while providing excellent punctuality, is unbalanced with respect to passengers’ other service quality objective, high speed. The timetable should be tighter to take advantage of the ability of conditional priority to push ahead late vehicles.

But how much tighter should the scheduled running time be? It still makes sense to base schedules on 80- or 85-percentile completion times, but they should be completion times that account for the effect of priority. However, the effect of priority on the running time distribution is difficult to predict, because it depends on the traffic control system, the traffic level, and parameters used in the priority system. In Eindhoven, parameters that are under the control of the transit system are thresholds that define when a bus is considered “late” and therefore will be granted priority. Should the threshold be 10 s? or 60 s? or, perhaps, -10 s?

The uncertainty of the effects of operational control underscores the importance of a

feedback system for schedule planning. One can implement a control strategy such as conditional priority under any schedule. But it then becomes vital to gather and analyze data to determine what the effective speed was, how great were the schedule deviations, how often was priority requested, and so forth. In response to these results, the schedule should be modified so that the schedule and the control system work together optimally.

A possible starting point for creating a new schedule when conditional priority is available is to use 85-percentile completion times assuming absolute priority. Such a schedule and the expected schedule deviations for our example is shown in Figure 15. Our results, while based on simplistic assumptions about the effects of absolute priority (e.g., we assumed a one minute reduction of the mean running time of each section, and no change in the running time variability), illustrate a step toward an integrated operations planning / operations control system. We do not claim this to be the optimal schedule; continual feedback and recalibration is still necessary. Nevertheless, the results are impressive.

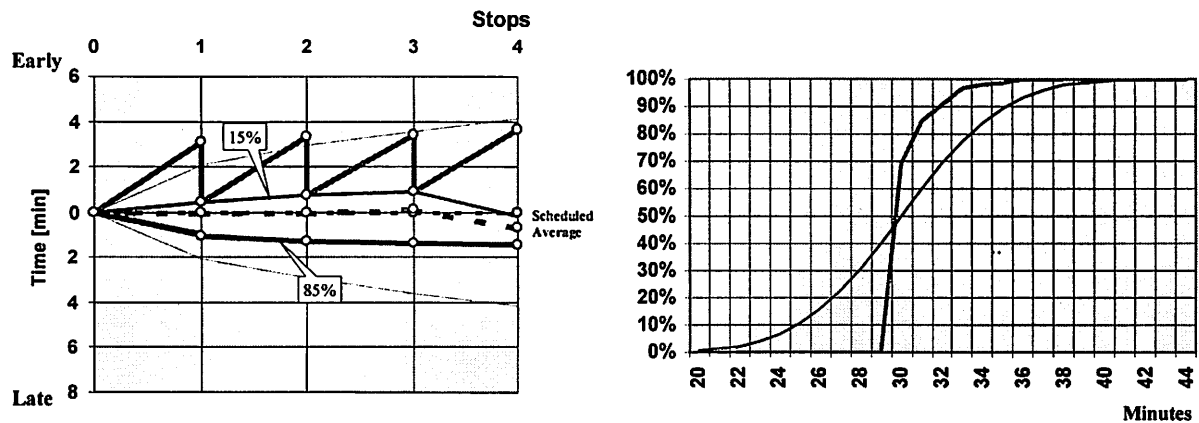


Figure 15: Schedule Deviation and Departure Time Distribution With Integrated Scheduling and Control

The blue line, connecting the passing moments, is both the schedule and the 15-percentile time. Because the passing moments are earlier than any previous schedule shown, fewer vehicles will be held. Many vehicles (roughly 60%) will arrive late at timepoints and will therefore get priority at intersections. As a result, the average route time in this case is about equal to the original mean running time, but the central deviation band at the third timepoint is 2.5 minutes, a 70% reduction compared to the original, uncontrolled situation (Figure 3). The cumulative distribution of departure time at the third timepoint (the blue line in the figure on the right) shows that no trips depart early, about 80% depart by time 30 minutes (one minute late, according to the passing moment schedule), and that those that are later are much closer to the schedule than in the original situation.

When priority at signalized intersections was installed along Eindhoven's Line 1, the system was first allowed to run under the existing schedule for several months with absolute priority. Vehicles were often ahead of schedule, and operators were often forced to hold at stops. Data gathered during this time gave planners an idea of what the distribution of completion time could be if buses were always granted priority. That

distribution was then used to generate a new schedule using 85-percentile completion times. That new schedule was further adjusted several times based on analyses performed using TRITAPT until the result was a schedule with a narrow schedule deviation band with few deviations earlier than 1 minute. Schedules continue to be reviewed and updated periodically based on historical performance data.

CONCLUSIONS AND NEEDS FOR FURTHER DEVELOPMENT

Intelligent tools for monitoring transit performance, operational control, and data analysis, if integrated well with service design, can provide the two kinds of feedback loops necessary to have a high quality operation: a real time loop that seeks to keep the service in accordance with its design, and a planning loop that seeks to improve the service design in response to historical performance. This paper describes the tools that have been used to great advantage in Eindhoven.

Several challenges still remain as we move toward a system of integrating planning with operational control. One is the need for complex but realistic simulation models that will better predict the impacts of operational control on performance. Such a tool could reduce the amount of experimentation done in the field, helping transit agencies more quickly arrive at an optimal schedule, and helping them make decisions about investing in technology with more confidence. Another is a clearer method for balancing the varied objectives of passengers, operators, and the transit agency in determining scheduled running times. A third area is the design of control parameters. With conditional priority it is possible to set a different lateness threshold at every signalized intersection. At intersections that are near saturation, it may be preferred to have a more relaxed lateness threshold so as not to interfere as often with the traffic control cycle. It might also be possible to request different levels of priority, depending on how late a vehicle is. For example, the transit vehicles could request absolute preemption when they are more than 90 s late, and request less extreme priority measures such as green extension when they are between 0 and 90 s late. Both simulation tools and normal experimentation with feedback will be needed to design a timetable and control system that together achieve the best possible service.

ACKNOWLEDGEMENTS

This research is part of the Seamless Multimodal Mobility Research Program of the TRAIL Research School sponsored by the Delft University of Technology.

ENDNOTES

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