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Lessons Learned from Field Operational Test of Integrated Network Management in Amsterdam

S. P. Hoogendoorn, J. Van Kooten, and R. Adams

The Amsterdam Practical Trial (APT) is a multiyear program initiated by the Dutch Ministry of Transport and the Environment and is carried out in close cooperation by Rijkswaterstaat, the City of Amsterdam, the Province of North Holland, and the Amsterdam Metropolitan Region. The APT aims to integrate innovative roadside and in-car developments networkwide. After the proof of concept was finished in 2009, two parallel tracks started in the Amsterdam region: the roadside track (aiming at an innovative, automated working system with ramp metering and traffic lights) and the in-car track (aiming at individualized travel and traffic information in the car for commuter traffic and for large-event traffic). This paper aims specifically at the innovative APT roadside system. Development of this system began in 2012, with the system becoming operational in April 2014. After all technical and functional tests were completed, the system parameters were tuned and finalized the implementation phase. Starting April 14, 11 weeks were taken to collect the data for the ex post assessment. In doing so, the authors have used an alternating assessment design, implemented by switching the system on and off every week so that a fair comparison could be made. From the collected data, it could be concluded that while the system caused additional delays on the urban network and ramps, the throughput on the freeway arterial was improved. Detailed analysis of the data showed the system performed as expected and which improvements can be made to further increase its effectiveness. These optimizations are discussed, as are the expected effects of implementing them in the system. How they are operationalized in Phase 2 of this innovative project will also be discussed.

The Amsterdam Practical Trial (APT) aims at gaining practical experience with applying integrated network management in a large-scale regional (urban and freeway) network. Integrated network management aims to improve the effectiveness of traffic management measures by integrated and coordinated deployment. Next to being one of the first large-scale field pilots of integrated network management, the APT is also geared toward the integration of innovative roadside and in-car developments that will eventually become crucial in using new technology to advance traffic management to meet future demands (*1*). For that purpose, after the proof of concept was fin-

ished in 2009, two parallel tracks were started in the Amsterdam region: the roadside track (aiming at an innovative, automated working system with ramp metering and traffic lights) and the in-car track (aiming at individualized travel and traffic information in the car for commuter traffic and event traffic). For the successful realization of this ambition, cooperation is a key factor; public road authorities, private companies, and the scientific community have to work together with the right people to make this challenging concept work in daily, operational traffic in a large city such as Amsterdam.

The focus of this paper is on the roadside track, for which the results of the first phase of the pilot are now available, and on the next phases of the project, for which the integration of the two tracks becomes a key objective. In the first phase of the project, the emphasis for the roadside track was on the freeway arterial (the A10 West), on its on- and off-ramps (referred to by the urban arterials s101 to s107 they connect to), and on one connecting urban arterial (the s102). Figure 1 shows the arterials considered. The s102 is fully equipped with intersection controllers, and all on-ramps on the freeway arterial are equipped with ramp-metering installations. In the subsequent phases of the APT, other areas of the Amsterdam network will be considered, while other control measures—including in-car measures—will be integrated in the control approach at the level of sensing, state estimation and prediction, problem diagnosis, and control.

This paper describes the assessment and lessons learned from Phase 1 of the project. For the considered network in this phase, the main bottleneck is the Coen Tunnel just downstream of the s101 connection. This recurrent bottleneck causes severe delays in the afternoon peak hour daily. Detailed analysis of the traffic operations shows that after the onset of congestion, the capacity reduces by about 13%, negatively affecting throughput and further increasing delays [see Hoogendoorn et al. (*2*)]. The queue caused by the Coen Tunnel spills back to the s101, s102, and s104 connections, hampering not only traffic aiming to go through the Coen Tunnel but also vehicles using the off-ramps. Moreover, several smaller bottlenecks occur on the urban arterials; these are more difficult to pinpoint to an exact location. In general, these bottlenecks are characterized by queues at a controlled intersection that become too large, hampering other traffic flows.

To reduce these problems, the solution directions presented in Hoogendoorn et al. have been used as a basis for the integrated control approach developed during the first phase of the roadside track of the APT project (*2*). Without going into detail here, the approach uses the following principles for the algorithmic development:

• Prevent the capacity drop from occurring as long as possible. Since the free-flow capacity in the Coen Tunnel is 13% higher than

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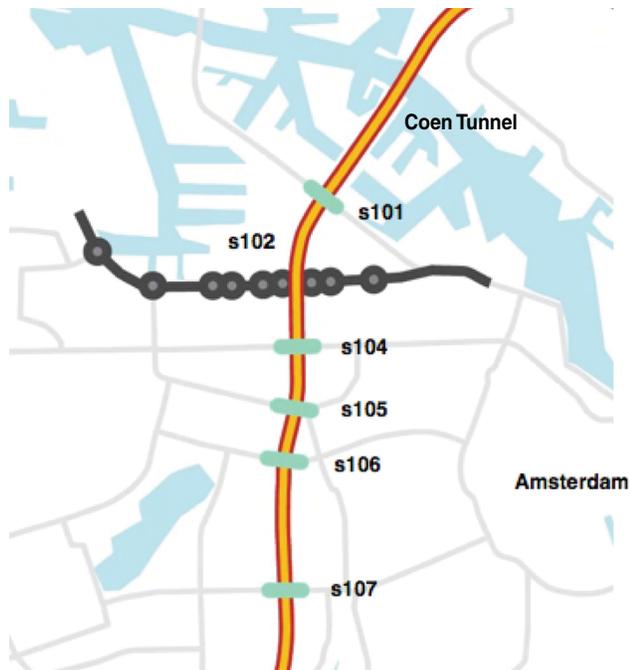
FIGURE 1   Overview of considered network for Phase 1, showing A10 West, connections, and s102 urban arterial.

the queue discharge rate after congestion has set in, preventing congestion will maximize the freeway throughput.

• Do not unnecessarily hinder traffic flows in the network. This principle states that one should try to prevent spill back and blockades by keeping queues within acceptable bounds.

• Use spare capacity in the network optimally, given the prevailing traffic conditions. The allowed use of buffer space in the network (e.g., used to temporarily store traffic for ramp-metering purposes) depends on the network level of service; if traffic conditions deteriorate, more buffer space can be used.

• A bottleneck needs to be resolved at the level at which it manifests itself. A local problem should be dealt with locally, if possible, at least at first. When running out of space locally (e.g., the on-ramp is filled), space can be sought elsewhere in the network.

Although few practical approaches to the coordination of traffic management measures have been tested in the field, some of them have been found to be very successful. A good example is HERO, a heuristic approach for coordinated ramp metering (3). It is clear that the effectiveness of coordinated ramp metering depends on a number of factors: (a) the length of the on-ramps determining how long traffic entering the freeway can be metered and (b) the relationship between the traffic on the ramp and the bottleneck. In particular, ramps located at a substantial distance from the bottleneck with off-ramps in between may have only a limited share of vehicles that will actually pass the bottleneck.

For the Amsterdam situation, as for most regional networks around Dutch cities, the part of the ramp where traffic can be buffered is short; therefore, ramp metering can be effectively performed only for a relatively short period of time before the on-ramp queue spills onto the urban arterial, potentially causing spill back and gridlock. Deploying multiple ramp meters in a coordinated way could improve the situation but is still expected to provide too little buffer space for prolonged deployment. Moreover, for the A10 West freeway, where the active bottleneck during the afternoon peak is the Coen Tunnel—

except for the s101 and s102 on-ramps—the fraction of traffic on the ramps actually passing the tunnel is relatively small (in general smaller than 30% according to the dedicated data analysis using floating car data). As a result, metering traffic at these on-ramps to relieve the tunnel will most likely not be very effective.

Therefore, to increase the effectiveness of ramp metering by means of coordination, alternative buffering mechanisms are needed. That need is the reason that in the APT project, the focus has been on buffering traffic not only on the on-ramps but also on locations in the urban arterials that have a strong relationship with the active bottleneck and that do not disrupt other flows too greatly.

The rest of this paper is structured as follows. An explanation of the roadside system design is presented next [for details, see previous work by Hoogendoorn et al. (2, 4)] followed by a discussion of the steps taken in implementing the system. The overall outcomes of the assessment study are then discussed, and the following section goes into detail explaining the results. This detailed data analysis provides the basis for the so-called optimizations proposed next. The paper closes by stating the main conclusions and recommendations.

SYSTEM DESIGN AND FUNCTIONAL ARCHITECTURE

In this section, the functions for monitoring, problem diagnosis, and control that were identified when the overall control approach was designed are discussed. Since these functions have been elaborated in other papers in detail, only an overview of the system is presented here (2, 4). Figure 2 shows the functions in the modular functional architecture of the APT control approach. The figure shows two types of functions: monitoring and diagnostics functions (logical monitoring units) and control functions (logical control units). The hierarchical control design was chosen to reduce the controller complexity. The control task is split into local control, control of arterials, subnetwork control (in which a subnetwork is defined as one freeway arterial and its connecting urban arterial), and network control. For the latter three levels, so-called supervisors have been developed (as is explained in the following).

Logical Monitoring Units

The local monitoring units consist of all functions for state estimation and prediction, identification of bottleneck locations, calculation of remaining buffer space, and determination of the network level of service. They provide all necessary input for the logical control units.

The freeway state estimator uses loop detectors (placed at approximately every 500 m on the A10 West) to estimate the speed, flow, and density. On the basis of the freeway state estimates, the freeway bottleneck inspector determines the (predicted) location of a freeway bottleneck. This task is achieved by first determining hot zones (locations where the breakdown probabilities are high) with the use of historical data and combining this information with the prevailing speed estimates. Using this method allows the prediction of a breakdown 3 min ahead of its actual occurrence to be sufficiently reliable. When the (potential) bottleneck has been identified, the location of the bottleneck is returned to the logical control units. The parameter estimator estimates the critical density and the capacity at the bottleneck location(s). For that purpose, an adapted version of the Kalman filtering approach described in Hoogendoorn et al. has been used (4).

The queue estimator estimates and predicts the queues at the off-ramps, on-ramps, and intersections using a variety of estimation and prediction techniques (ensemble filtering). The approach selects the
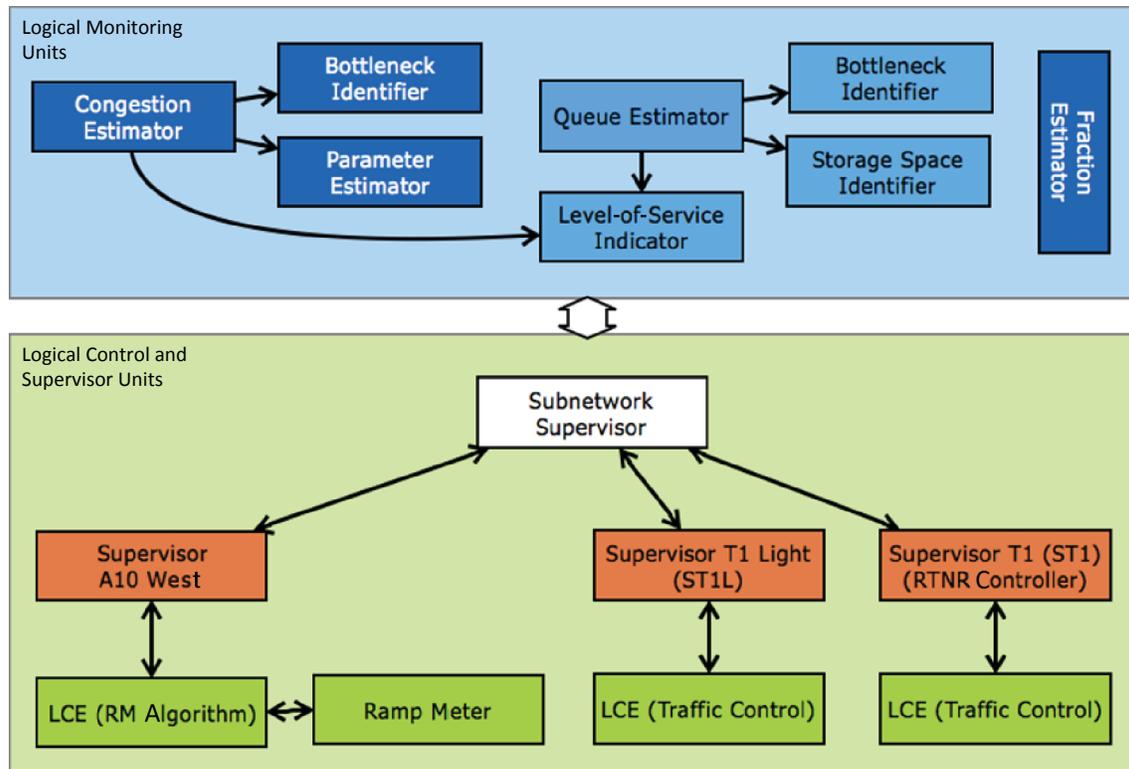
FIGURE 2 Functional architecture of APT control approach, indicator of logical monitoring units and logical control units [LCE = logical control unit (translated from Dutch); RM = ramp metering; RTNR = real-time network regulator; ST1L = urban arterial supervisor (translated from Dutch abbreviation)].

best queue estimation for a particular situation and provides the estimation to the bottleneck inspector and the buffer capacity indicator. On the basis of the queue estimates, the urban bottleneck inspector determines if there is a bottleneck at any location on the urban arterial. As explained in Hoogendoorn et al., an urban bottleneck is defined by either a queue causing spill-back problems or an (severely) oversaturated direction of an intersection controller (2). The queue estimates are also used to determine the remaining buffer capacity. For that purpose, the buffer capacity indicator compares the current queue lengths with the allowed buffers and returns the difference. The buffers describe the locations and lengths of the queues that are allowed given the prevailing network level of service, and they were determined in close collaboration with the Amsterdam municipality.

Finally, the network service level indicator determines the average level of service in the controlled regional network. It does so by looking at the total number of vehicles in the network and their spatial distribution according to the concept of generalized network fundamental diagrams presented in Knoop and Hoogendoorn (5).

Logical Control Units and Supervisors

The logical control units (ramp meters and intersection controllers) are controllers that can function autonomously but can also be overruled by their governing supervisors. For instance, when the density downstream of a ramp surpasses some trigger value, the ramp meter will immediately start metering locally to prevent congestion from occurring. At the same time, it will send a message to the freeway arterial supervisor (discussed later) that it has started metering and that it may need assistance in performing this task from upstream

ramp meters and from upstream intersection controllers. However, the ramp meter can also be addressed directly by this supervisor, for example, when a bottleneck is detected at some downstream location such as the Coen Tunnel.

The subnetwork supervisor plays a central role in the coordination scheme; it determines the relevant buffer configuration, which describes how much traffic may be stored, for example, at the legs of a controlled intersection. This determination is dependent on the level of service and the traffic situation at hand.

The urban arterial supervisor is responsible for coordinating the intersection controllers on the s102. It received the prevailing buffer configurations for the relevant buffers on the s102 from the subnetwork supervisor, as well as the location of the bottleneck on the urban arterial if present. Using this information, the urban arterial supervisor will equally distribute the queues over the available buffer spaces to prevent spill back of waiting queues from buffers in the urban arterial. How this distribution is achieved will be explained in the rest of the paper.

The connection supervisor realizes the coordination between a ramp-metering installation and its upstream located intersections. Every on-ramp has a feeding urban arterial, for which a set of buffers is defined that can be used to buffer as well. The subnetwork supervisor determines to what extent the urban buffers can be used, given the current situation at the freeway and urban network. The connection supervisor, in turn, instructs the involved intersection controllers to reduce their outflow toward the ramp.

The freeway arterial supervisor (referred to as Supervisor A10 West in the figure) coordinates the ramp-metering installations along the freeway arterial. For that purpose, a dedicated coordinated ramp-metering scheme has been developed (4). The objective of the scheme

is to prevent traffic breakdown at the dominant (i.e., most downstream) bottleneck as long as possible or resolve the congestion at this dominant bottleneck if it has already occurred.

Feedback Coordination Mechanisms Using Master–Slave Approach

In this section, a brief presentation is given of the controller approach aimed at increasing the effectiveness of ramp metering by deploying the intersection controllers on the urban arterial. Similar to the HERO algorithm, the approach presented here is based on the master–slave concept. The general idea is as follows: first, a master controller is determined (3). This master can be a ramp meter or a metered connection (where the ramp metering is supported by the connecting intersection controllers or where intersection controllers mimic ramp-meter functionality) controlling the inflow to prevent or remove congestion (and thus the capacity drop) on the freeway. Figure 3 illustrates the concept for a freeway bottleneck. A master can also be an intersection controller at the end of an off-ramp that aims to prevent the off-ramp queue from spilling back to the off-ramp and subsequently to the freeway or an intersection controller on an urban arterial that prevents a bottleneck (e.g., spill back of queues). Although the APT system was designed to also deal with these bottleneck types, the situation did not occur in the considered network during the trial period, and the focus has thus been on freeway bottlenecks (2).

In many cases, directness and effectiveness as key criteria will be used for choosing the master; for ramp-metering control, this in most cases means that the master is the first on-ramp upstream of the active bottleneck. For other situations, generally it is the intersection controller at which a problem manifests itself.

The slaves can be the ramp meters on the upstream locations of the master (HERO), but they can also be the intersection controllers on the urban arterials. Focusing on the latter, a simple feedback mechanism has been designed allowing these intersection controllers to support the master in achieving its control task as effectively as possible. In doing so, the aim is to use the available buffer space at the intersection controllers evenly, given the buffer space use of the ramp meter. For a detailed description of the proposed algorithms and a thorough analysis of their functioning, see Hoogendoorn et al. (4).

FROM DESIGN TO IMPLEMENTATION

The overall design, monitoring, and control functions having been described, the implementation process and its constituent steps will now be briefly described. After all components of the functional architecture had been prototyped, detailed functional specifications were written. These formed the basis for implementation in the production software that connects to the actual hardware in the field.

To test the production software, an exact mock-up of the system was made in a Vissim simulation environment. In doing so, the technical tests of the production software could be performed in this virtual environment before tests were done in the field. This approach revealed many technical implementation issues and, hence, was found to be very valuable. The simulation environment was used only for the technical tests and to show whether the logic of the controller design functions. It was not used for tuning or for model assessment purposes because of the limited validity of the model predictions and because many of the phenomena that one aims to control (such as the capacity drop) were not well represented by the model.

The implementation in the actual system was found to be relatively straightforward after the tests in the simulation environment. Once it was completed, a stepwise approach was taken in testing and tuning all system components in the field. First, all monitoring functions were tested, after which the control functions were tested one by one—starting with the simple local functions—building up to the coordination functions (freeway supervisor and the urban arterial supervisor).

Schematization of the control concept in which the master (the ramp meter closest to the bottleneck) is supported by two slaves: the upstream on-ramp and the intersection controller on the urban arterial of which part of the traffic feeds into the on-ramp.

The feedback control law that is used for coordination ensures that the relative use of the slave buffers (on-ramp and buffers at the controlled intersection) is equal to the relative use of the on-ramp of the master.

For details on the feedback controller algorithm and the analysis of its functioning, see Hoogendoorn et al. (4).

FIGURE 3   Illustration of control approach for freeway bottleneck controlled with on-ramp and supported by slave ramp meter and slave intersection controller.

During the implementation process, the importance of having a properly functioning installed (hardware) base became very apparent. This for instance means that all ramp meters and intersection controllers need to function properly, technically and functionally. It also implies that the functional management of all relevant traffic management systems has to be adequately taken care of. Furthermore, the monitoring systems need to be able to determine the available space and the scarcity thereof. This requirement means, for instance, that one needs to be able to determine queue lengths at the controlled intersections, which has implications for the detector configuration (e.g., single loops near the stop line generally are not enough). Finally, communication between intersection controllers, ramp meters, and the control center needs to function properly. These lessons may seem trivial, but getting the installed base up to the required level was found to be more involved than expected. The result was that the APT system became fully operational only 1 day before the start of the trial period, leaving only one afternoon for tuning the system parameters. This time was found to be too short to optimize the system performance, as will be seen in the following.

EX POST ASSESSMENT APPROACH AND OVERALL RESULTS

The pilot began on April 14, 2014, and ended 11 weeks later on June 27, 2014. During this period, the system was active every even-numbered week and inactive every odd-numbered week. When the system was inactive, the normal traffic management system was operational (i.e., ramp meters with local metering functionality and a fixed-time coordinated network controller on the s102).

In this section, the overall results of the impact assessment study will be discussed [for details, see Beenker et al. (6)]. In doing so, the distinction between an urban network, the ramps, and the freeway network will be pointed out. To emphasize again, although the developed approach is generic with respect to the different kinds of bottle-

necks that can occur, for the Phase 1 field test, the key objective was to delay freeway congestion and reduce the recurrent congestion effects caused by the s101 and the Coen Tunnel.

Effects on A10 Freeway

Figure 4 shows the evolution of delays on the freeway per minute (the collective delays over the entire peak are found by looking at the total area under the graphs) for the APT active and APT inactive situations. The figure convincingly shows the effect of coordination on the freeway flow conditions: the collective delays on the freeway are reduced by an average of 190.3 vehicle hours per peak period [see Beenker et al. (6), p. 50].

Looking deeper into the causes for the improvements on the freeway operations, one can conclude that the coordination scheme at the core of the developed method resulted in delaying the onset of congestion by 21 min compared with the situation in which the system was inactive. This number was established by looking at the breakdown instants of (on average) 16:27 and 16:06 when the system was active and inactive, respectively.

Effects on Urban Network

The system has had a negative effect on the total delays on the urban network and the on-ramps. The total delays increased by 203.8 vehicle hours; 77.5 of the 203.8 vehicle hours were experienced on the on-ramps (6). This finding implies that the overall effect of the system was not positive, but neutral. However, as will be seen in the rest of the paper, the detailed analysis of the data collected during the system's operation shows, first, what the key reasons are for the effect not being as expected. As will be seen, improved tuning and configuration of the system's components are very likely to yield large improvements, reducing the effect on the urban network while maintaining the positive effect on the freeway network.
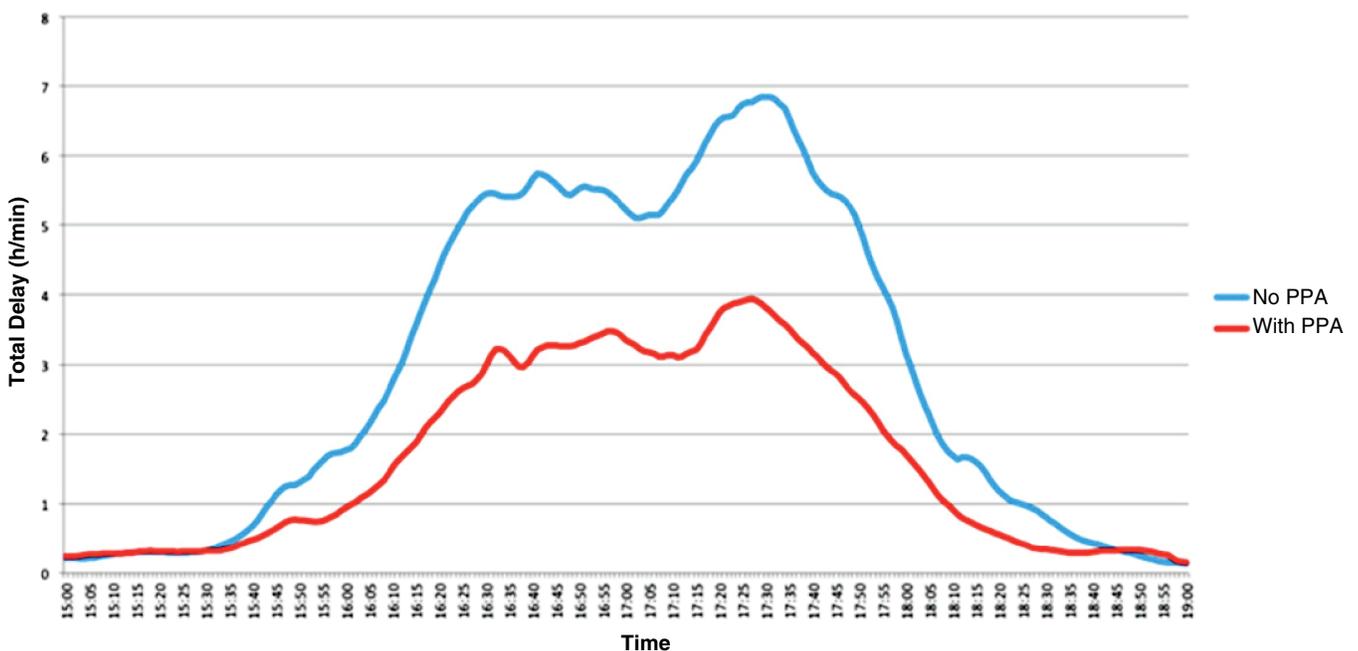
FIGURE 4   Average evolution of collective delays on A10 freeway [PPA = Praktijkkproef Amsterdam (Practical Pilot Amsterdam)].

DETAILED ANALYSIS AND IMPLICATIONS

A detailed analysis of the available data provides additional insight into the overall results presented in the previous section. In this section a discussion will be presented of some of the key findings, which deal with the choice of buffers, moment of activation and its effect, target value of the master ramp meter, and queue protection (or flushing) scheme that was used.

Choice of Buffers

To assess the effectiveness of the buffers, a simple approach is proposed that directly uses the data collected, making as few assumptions as possible. More specifically, the approach uses the following as input:

• Collective (extra) delays per buffer (ramps and intersections) compared with the situation when the system was inactive,
• Fraction of traffic in a buffer that passes the bottleneck (in this case, based on GPS data collected from navigation devices), and
• Collective delay improvement on the freeway.

The approach works as follows: Based on the collective (extra) delay in a particular buffer j, the average queue length is determined. The underlying principle is simple: 1 vehicle hour of collective delay means that one vehicle has been in a queue for 1 h. In other words, the average number of vehicles (during 1 h) in the queue is equal to the average collective delay in the buffer. These numbers are indicated in Column C of Figure 5. The number of vehicles that are queued effectively depends on the fraction of these vehicles destined for the bottleneck under control; see Column B. A linear relationship is assumed, meaning that the number of effectively queued vehicles is equal to the fraction times the average number of vehicles in the queue. The resulting numbers per buffer are shown in Column D. For instance, of the 17.2 vehicles in the queue in Buffer 60 on the s106 arterial, 56.6% will travel to the bottleneck, implying that 9.7 vehicles are effectively queued. Accordingly, one can conclude that of the (average) total number of vehicles queued in the buffers (203.8 vehicles), about half of these vehicles are effectively queued (105.2 vehicles).

On the basis of this analysis, one can conclude that by effectively queuing 105.2 vehicles—or stated differently, by causing 105.2 vehicle hours of "just delays" (i.e., delaying vehicles moving to the bottleneck)—190.3 vehicle hours of total delays on the

(A)		(B)	(C)	(D)	(E)
Buffer ID		Fraction	Avg. (Extra) Veh. in Queue		In Config.?
			Actual	*Effective*	
s101	14	100.0%	10.3	10.3	1
s102	11	100.0%	8.7	8.7	1
s102	16	100.0%	1.7	1.7	1
s102	31	92.8%	20.9	19.4	1
s101	24	90.4%	12.7	11.5	1
s101	27	85.5%	2.1	1.8	1
s101	25	84.3%	3.5	3.0	1
s101	28	78.3%	5.6	4.4	1
s104	40	63.9%	9.3	5.9	1
s107	70	62.7%	9.4	5.9	1
s106	*60*	*56.6%*	*17.2*	*9.7*	1
s102	4	51.8%	0.0	0.0	0
s102	8	45.8%	3.6	1.6	0
s102	6	43.4%	5.1	2.2	0
s102	10	39.8%	13.1	5.2	0
s105	50	39.8%	10.4	4.1	0
s104	44	30.1%	0.7	0.2	0
s105	58	30.1%	0.0	0.0	0
s102	18	27.7%	0.1	0.0	0
s104	41	25.3%	0.4	0.1	0
s104	43	22.9%	5.2	1.2	0
s102	3	22.3%	0.0	0.0	0
s105	54	20.5%	0.4	0.1	0
s106	61	18.1%	8.9	1.6	0
s102	17	15.7%	0.1	0.0	0
s105	55	15.7%	1.3	0.2	0
s106	65	15.7%	14.5	2.3	0
s105	56	13.3%	0.0	0.0	0
s105	57	12.0%	13.9	1.7	0
s102	19	9.6%	21.3	2.1	0
s107	71	9.0%	0.9	0.1	0
s102	9	8.4%	2.5	0.2	0
Total (reference):			203.8	105.2	
Total (new config):			101.4	0.0	

FIGURE 5   Calculation of effectively queued vehicles and estimation of effect of changing buffer configuration, based on collective delays computed per buffer in Beenker et al. (6). Buffers are shown in picture (only buffers directed toward A10 are considered and only in northbound direction) [veh. = vehicle; config. = configuration; VRI = intersection controller (translated from Dutch); TDI = ramp-metering installation (translated from Dutch)].

freeway are saved. An approximate 1:2 ratio is the result, implying delaying just one vehicle for 1 min on the urban network or ramps yields a reduction of 2 vehicle minutes of collective delays on the freeway. A direct consequence of this simple analysis is also that buffers with a fraction less than 50% are not likely to be effective under the current functioning of the system.

System Activation

The bottleneck identifier was developed to identify or rather predict the moment congestion would occur at the bottleneck location. Hoogendoorn et al. described the functioning of this component, in particular focusing on the method that was geared toward providing a 3- to 5-min-ahead prediction of traffic breakdown (2). Looking at the assessment data, one can see that while the APT system was activated by the bottleneck identifier at 15:21 (on average), a breakdown in the situation at which the APT system was not active occurred at about 16:06. It is probable, therefore, that the system started coordinating (34 min) too soon. As a result, unnecessary delays on the urban network and the ramps of about 157 vehicle hours in total were caused. Furthermore, premature activation causes the buffer space to be depleted sooner and, hence, has an effect on the time congestion can be delayed by metering as well since a fair share of the buffer space has already been used before ramp metering becomes useful.

Metering Target Values

The ALINEA-inspired feedback control scheme that has been used to determine the metering rate aims to control the traffic density downstream of the on-ramp toward a certain target value. The target value generally chosen is equal to the critical density value, that is, the density observed when the system is functioning at capacity. Since this value is not known beforehand, and since it is likely to be dynamic (i.e., it depends on the traffic composition, weather, ambient conditions, etc.), the parameter estimator (see Figure 2) estimates the critical density with the approach proposed in Knoop and Hoogendoorn (5). In the test phase, however, it was observed that estimates were too volatile, and the decision was made to fix the critical density at 84 vehicles/km.

To analyze the functioning of the ALINEA-inspired ramp-metering strategy compared with the normal metering strategy—the so-called RWS-C algorithm—the flow patterns observed downstream of the ramp were considered. The table below shows an overview of this analysis. For the sake of interpretation, the queue discharge rate once congestion has set in at the bottleneck was also determined.

Indicator	Value	Improvement (%)
Queue discharge rate	5,580	
Mean volume during metering (PPA inactive)	6,300	12.9
Mean volume during metering (PPA active)	6,060	8.6

The table shows that with the APT ramp-metering strategy, it is possible to maintain flow rates that are about 9% higher than the queue discharge rate. The original strategy, however, is able to maintain a considerably higher flow rate, which is about 13% higher than the queue discharge rate. This finding means that for each hour of metering, the APT strategy will cause an additional 240 vehicle hours of delay on the urban network and on-ramps, compared with the original strategy. However, the APT strategy was able to prevent

breakdown longer (about 21 min) than the original strategy, possibly because the RWS-C controller did not meter sufficiently and, thus, did not always prevent congestion from occurring.

Buffer Protection Strategy

The APT system includes a queue protection approach (or, rather, buffer protection approach) that ensures that when buffers become too full, queues are essentially flushed, meaning that the metering rate is set at its maximum value and that the intersection controllers give maximum green to the directions in which traffic was buffered. Analysis of the data shows that the result is an immediate breakdown on the freeway. The severity of the resulting bottleneck was found to be somewhat higher than when the system was inactive, implying that a more advanced buffer protection system may yield reduced freeway delays.

In the following section, how the results discussed here will be used to improve the APT system further will be shown. To the extent to which that is possible, a prediction of the expected effect of these modifications will be provided. Moreover, a discussion will be provided on which new functionalities will be added in Phase 2 of the roadside track of the APT project, which in the end will see further integration with the in-car track.

OPTIMIZATION, IMPACT PROJECTION, AND EXPERIMENTAL SETUP FOR PHASE 2

The preceding section discussed in detail the analysis of the APT system's functioning. Based on that analysis, optimization directions for the next phase of the project can be provided. These directions will be discussed briefly in this section. Furthermore, the other improvements that will be part of Phase 2 of the APT project will be presented.

Optimizing Buffer Configuration

The approach discussed previously can be used to provide an estimate of the effect of changing the buffer configuration on the collective delays on the freeway and the urban network and ramps. For any buffer configuration, the total delays on the urban arterial and ramps and the number of effective vehicles queued can be determined. Assuming that the benefits on the freeway scale linearly with this number, the resulting benefits on the freeway can be approximated. As an example, Column E in Figure 5 indicates a buffer configuration that results if only buffers with a fraction larger than 55% are included. Using this configuration, one can see that the estimated number of vehicles queued is only 101.4; the number of effectively queued vehicles is still relatively large (82.2). This observation, in turn, means that a limited reduction in system effectiveness is expected; a rough estimate would lead to a reduction of

$$(\text{delay impact})_{new} = \frac{(\text{effective queue})_{new}}{(\text{effective queue})_{old}} \cdot (\text{delay impact})_{old}$$

$$= \frac{82.2}{105.2} \cdot 190.4 = 148.3$$

against a collective delay on the urban network and ramps of 101.4 vehicle hours.

Ensuring Timely Activation of APT System and Bottleneck-Type Specific Control

The functioning of the bottleneck inspector that determines when the APT system is activated has been discussed, and it was concluded that the bottleneck inspector activated the system 34 min too soon, on average. Detailed analysis of the data shows that this result can be attributed to a large extent to the ill predictability of the occurrence of congestion at the considered bottleneck location. The result was the decision to not use predictions for the occurrence of on-ramp bottlenecks but instead react in a very timely way to its occurrence with the use of a feedback mechanism. Looking carefully at the data gathered during Phase 1, one can expect that the delay on the urban arterial and the on-ramps can be reduced by approximately 33% and that the effective metering duration can be increased since the buffers will be more or less empty when ramp metering is really needed; however, this effect has not been quantified.

This modification is not the only one made to the bottleneck inspector; next to on-ramp bottlenecks, the functionality is generalized to identify different types of bottlenecks or congestion (weaving-area bottlenecks, wide moving jams, infrastructure bottlenecks such as tunnels, spillback from the urban network onto the freeway, etc.). The ability to identify different types of bottlenecks will allow one to adapt the control strategy accordingly. In some cases, the implication is that one will actually refrain from applying control if it is known beforehand that the control will not be effective in solving the problem. For instance, when a queue caused by a severe incident downstream spills back into the controlled freeway, little can be done to improve the situation on the freeway. Buffering traffic on the urban network will probably have only negative effects in this case. Another example is so-called wide moving jams; the bottleneck inspector will identify this type of congestion and will predict its path, as well as the control task that needs to be executed to resolve the wide moving jam (i.e., how many vehicles are "too many" in the jam). A Specialist/COSCAL-inspired algorithm will be used to remove the wide moving jam, if possible [see Hegyi and Hoogendoorn (7)]. However, if there is not sufficient buffer space on the ramps and the urban network to resolve the wide moving jam, it makes no sense to attempt to remove it.

Setting Target Values for Ramp Metering with Improved Parameter Estimation

The way the incorrect setting of the target value of the ALINEA-inspired ramp-metering strategy yields ramp metering that was too strict was discussed previously. Although this could have been resolved by taking a longer tuning period, for Phase 2 the choice was made to improve the Kalman filtering approach used in the parameter estimator [see Hoogendoorn et al. (4)]. The modified algorithm shows improvements in the critical density and capacity estimates. In general, a higher value of the critical density is found, which would in turn lead to a less strict metering strategy. More specifically, where in the trials a critical density of 84 vehicles per kilometer was used (three-lane road), the improved parameter estimator results in a value of 90 vehicles per kilometer.

Looking at the results shown before, it is reasonable to expect that a flow rate that is 11.6% higher than the queue discharge rate can be sustained (3% on top of the current flow rate of 8.6% over the queue discharge rate). The resulting value is lower than the flow rate achieved by the RWS-C algorithm (12.9% increase over the queue discharge rate). However, since under the RWS-C metering strategy breakdown still occurred, a more conservative value was chosen. Under this assumption, one can calculate that an additional 42% of delays on the on-ramps and the urban arterials will be saved.

Additional Improvements and Innovations in Phase 2

Most of the optimizations discussed so far deal with improving the APT system given the lessons learned in Phase 1. Next to these improvements, novel concepts will be introduced that further increase the general applicability of the system, as well as make it robust to future changes in the way traffic management is accomplished (e.g., higher penetration of in-car technology). First, a further generalization of the functionality of the controller components to deal with different types of bottlenecks will be made, as was already briefly explained.

Second, steps will be taken in the use of floating car data (from the in-car track of the trial) to first optimize monitoring components. By means of advanced data fusion, one will be able to (a) see which improvements in information quality can be achieved (e.g., how much better are the queue estimates when floating car data are used), (b) investigate whether fewer inductive loops can be used, and (c) see how new types of information can be used in improving the control approach (e.g., use real-time information about the routes travelers take to dynamically determine fractions of traffic going from the buffer to the bottleneck under control and decide dynamically whether this buffer would be effective). Finally, an examination will be made of new control paradigms that could be coined as anticipatory traffic control, where traffic management measures are deployed in such a way that they anticipate the effects information services road users have on board will have on route choice and route demand. These latter innovations are intended to prepare for the next phase of (network) traffic management, in which more and more of the monitoring and control functionality will be dealt with by using in-car technology and by other stakeholders.

CONCLUSIONS AND RECOMMENDATIONS

This paper has discussed the main assessment result of the coordinated and integrated traffic management approach developed in the Amsterdam Practical Trial (APT) project. It has been shown that although the assessment results are neutral on the level of the overall throughput of the regional network, it may be concluded that the general principles on which the approach was built hold; network conditions can be improved by means of coordinated deployment of traffic management and control measures.

Here, it has been shown how detailed data analysis reveals clear improvement directions and how an estimate of the effects of implementing these directions can be provided. These improvement directions form the basis for the changes to the system that will be tested in Phase 2 of the project, next to other generalizations to the system.

These generalizations are important to further enhance the application range of the concept. Striving for a nationwide or even international deployment requires that the concept be able to adequately tackle different types of freeway and urban bottlenecks. In Phase 2, important steps in this direction will be made, as has been illustrated in this paper. In addition, many monitoring and control components

have been developed that can be readily deployed in the APT or in other traffic management systems. Examples are the queue estimator, freeway state estimator, urban arterial controller, and (improved) parameter estimator. The use of these components can strongly improve the functioning of currently deployed isolated or coordinated traffic management systems. In illustration, the parameter estimator can determine the actual critical density and capacity, the use of which in the current local ramp-metering systems can greatly improve its performance.

Next to the lessons that have been learned from the field trial and next to the development of the components that can be used in other systems as well, an important result of Phase 1 of the project is that experience has been gained in the process of organizing such a complex project. The importance of close collaboration between public partners, private partners, and academia has already been mentioned, but it has also been learned that an overly rigid approach to developing such complex software in a very dynamic context can be counterproductive. As a result, Phase 2 deploys more agile software development paradigms that are already resulting in a much timelier product development.

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REFERENCES

1. Hoogendoorn, S. P., M. Westerman, and S. Hoogendoorn-Lanser. Future Scenarios for Traffic Information and Management. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2256,* Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 79–86.
2. Hoogendoorn, S. P., R. L. Landman, J. Van Kooten, and M. Schreuder. Integrated Network Management Amsterdam: Control Approach and Test Results. In *Proceedings of IEEE Conference on Intelligent Transportation Systems,* ITSC, 2013, pp. 474–479.
3. Papamichail, I., and M. Papageorgiou. Traffic-Responsive Linked Ramp-Metering Control. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 9, No. 1, 2008, pp. 111–121.
4. Hoogendoorn, S. P., R. L. Landman, J. Van Kooten, M. Schreuder, and R. Adams. Design and Implementation of an Integrated Network Management Methodology in a Regional Network. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2489,* Transportation Research Board, Washington, D.C., 2015, pp. 20–28.
5. Knoop, V. L., and S. P. Hoogendoorn. Empirics of a Generalized Macroscopic Fundamental Diagram for Urban Freeways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2391,* Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 133–141.
6. Beenker, N., I. Schelling, M. Schoemakers, B. van Engelenburg, H. J. Kwakernaat, and M. Schreurder. *Evaluatie Praktijkproef Amsterdam Wegkant* (in Dutch). Presented at *Nationaal verkeerskundecongres*, Zwolle, Netherlands, 2015.
7. Hegyi, A., and S. P. Hoogendoorn. Dynamic Speed Limit Control to Resolve Shock Waves on Freeways—Field Test Results of the SPECIALIST Algorithm. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 13, No. 1, 2010, pp. 519–524.