1 INTRODUCTION
The steadily increasing numbers and lengths of traffic jams on freeways are a source of inconveniences for road users and for the transportation system, as is reflected by increasing total travel times, economic losses, environmental pollution, and reduced traffic safety. Part of the problem is believed to be caused by an underutilization of the existing infrastructure. In other words, better utilization of the network capacity can be a solution to manage congestion better, next to increasing the capacity by expansion of infrastructure and reducing traffic demand by pricing. As a control measure, ramp metering has proven to be an efficient way to improve this problem [1]. Meanwhile, contemporary Dynamic Traffic Management (DTM) tends to focus on the integrated and coordinated deployment of measures. Hence, an integrated control strategy on a network-wide level is needed.

The ring-road A10 around the city of Amsterdam is one of the busiest urban freeways in the Netherlands. Several on-ramps have been equipped with ramp metering controllers since 1989 [2]. In the near future, the remaining on-ramps along the A10 will also be equipped with ramp metering controllers. In order to further exploit the effect of local control, a coordinated ramp metering control algorithm, the HERO/RWS algorithm (HERO refers to HEuristic Ramp metering coOrdination; RWS is the commissioning organization), has been developed for the current Dutch ramp metering systems and it will be applied on the Amsterdam A10 freeway network in the near future. The aim of this algorithm is to postpone congestion on freeways by effectively using ramp storage space from upstream on-ramps. The control scheme is simple and real-time operable. VISSIM-based microscopic simulation results show that the HERO/RWS coordinated control outperforms non-coordinated control. This control algorithm turns out to provide less congestion, higher mean speeds and lower travel time spent on the freeway.

2 STATE-OF-THE-ART
Ramp metering is implemented via installation of traffic lights at freeway on-ramps that control the amount of traffic flow allowed onto the freeway, as shown in Figure 1. The traffic lights are operated in dependence of the currently prevailing traffic conditions on both the freeway and the ramps. The corresponding traffic-responsive control logic is the connecting element between the measured traffic conditions and the traffic light settings. The research on freeway ramp metering control has a long history [1]. In the study described in this paper, simulations have been performed using VISSIM (a microscopic traffic/transportation simulation tool) to investigate the algorithm.

The next section will provide a brief state-of-the-art on ramp metering and its coordination. Then, the details of the HERO/RWS algorithm are described, followed by a brief description of the methodology and the case study on the A10-West network to assess the HERO/RWS algorithm. Then, VISSIM-based simulation results and discussions are presented. The conclusions and further research in this field are given in the last section.
2.1 Local Ramp Metering Control

The aim of local ramp metering control is to reduce the inflow from the on-ramp to the freeway to postpone congestion on the freeway since this will lead to a drop of capacity (free flow capacity is higher than the queue discharge rate). Apart from shorter travel times on the freeway, secondary blocking of upstream off-ramps is prevented. For local ramp metering control (that is, agent-based ramp metering control), the most popular strategies are the Demand Capacity (DC) strategy, ALINEA and their variations.

The DC strategy \[5\] is (according to engineering terminology) a feed-forward control: the metering rate is calculated using a pre-specified capacity value and the incoming freeway flow, see eq. (1).

\[
r(k) = \begin{cases} 
q_{\text{cap}} - q_{\text{in}}(k-1), & \text{if } o_{\text{in}}(k-1) \leq o_{\text{cr}} \\
r_{\text{min}}, & \text{else} 
\end{cases} 
\]

where \(k=1,2,\ldots\) is the discrete time index; \(r(k)\) is the ramp flow (in veh/h) to be applied during the new period \(k\); \(q_{\text{in}}(k-1)\) is the measured upstream freeway flow (in veh/h) over all lanes during the previous time period; \(o_{\text{in}}(k-1)\) is the measured upstream freeway occupancy (in %) (averaged over all lanes) during the previous time period; \(q_{\text{cap}}\) is the downstream freeway (pre-specified) capacity; \(r_{\text{min}}\) is the minimum admissible ramp flow; \(o_{\text{cr}}\) is the critical occupancy. Such a pre-fixed capacity value may lead to further efficiency degradation due to the fact that in reality the capacity is stochastic. When the capacity in reality is lower than the assumed value, the congestion will start before the ramp metering is activated, while the ramp metering is activated too early when the real capacity is higher than the assumed value.

ALINEA control \[6\] is a feedback strategy in which the inflow is determined as proportional to the difference between the ideal occupancy and the observed occupancy (2).

\[
r(k) = r(k-1) + K_{\text{R}}[\hat{o} - o_{\text{out}}(k-1)] 
\]

where \(K_{\text{R}} \geq 0\) is a regulator parameter and \(\hat{o}\) is a targeted set (desired) value for the downstream occupancy. Typically, but not necessarily, \(\hat{o} = o_{\text{cr}}\) may be selected, in which case the downstream freeway flow comes close to \(q_{\text{cap}}\). The same value of \(K_{\text{R}}\) has been used in all known simulation or field applications of ALINEA without any need for fine-tuning. If occupancy \(o\) is measured in the range \([0,100]\)% then \(K_{\text{R}} \approx 70\text{ veh/h}/%\) is recommended.

In the Netherlands, the RWS strategy is used in field applications \[2\]. This strategy is a variation of the DC strategy. The control mechanism of each RWS control agent is based on real-time traffic information, namely the measured speed and flow values around the on-ramp instead of occupancy rate. These traffic data are measured by double inductive loops located at upstream/downstream of on-ramps. Control activation and deactivation are based on speed and flow thresholds (e.g. 70/80 km/h, 1650/1500 veh/h/lane). When the speed on the freeway upstream or downstream of the on-ramp drops, the metering will reduce the inflow from the on-ramp to a minimum. When the queue on the on-ramp becomes too large, the access from the on-ramp is set to a maximum.

At the time of writing, there are 35 locations in the Netherlands using the RWS ramp metering control \[7\]. Stanescu \[8\] has shown that the capacity value \(q_{\text{cap}}\) based on current conditions would improve the impact of the RWS algorithm and obtained positive results. The local control does not address the problem of optimal coordinated utilization of the overall infrastructure, nor does it guarantee an even distribution of queues over the ramps. Furthermore, due to the limited storage space of a single on-ramp, the on-ramp queue easily spills back to the nearest urban intersection, affecting urban traffic. Hence, a coordination strategy is needed.

2.2 Coordinated Ramp Metering Control

Reducing the inflow of the on-ramp leads to queuing on the on-ramp. This may lead to spill back on the urban network. When the queue on the on-ramp exceeds a specific length, the cycle time of the ramp metering controller is reduced, thus increasing the inflow onto the freeway, which is likely to cause congestion on the freeway. An alternative would be to reduce the flow on the freeway by activating an upstream controller, the so-called coordinated ramp metering control. This will spread the extra waiting time over multiple on-ramps, thus causing equity in the network.

Several coordinated ramp metering strategies have been proposed, but field installations are limited (mainly in the USA, some in Australia \[1\]). These strategies may be subdivided into optimal control strategies, hierarchical control strategies and rule-based strategies \[1\].

Optimal-control based ramp metering strategies employ a macroscopic traffic flow model (e.g. METANET) which runs several times in an iterative way to produce optimal ramp metering flows over an optimization time horizon \[9\]. Hierarchical control strategies use a receding horizon (model predictive) approach, which consists of three layers: the estimation/prediction layer, the optimization layer and the direct control layer \[10\].

Rule-based strategies make their real-time decisions by checking appropriate heuristic rules and activating specific regulators or actions at individual on-ramps. Contrary to the previous two strategies, these strategies are actually implemented and operated. Several rule-based strategies, such as ACCEZZ algorithm, Zone algorithm, Helper algorithm, Bottleneck algorithm, Fuzzy logic algorithm and HERO algorithm, have been proposed and applied with mixed results \[1\]. The HERO algorithm incorporates local ALINEA regulators. When the queue of an on-ramp becomes larger than a predetermined threshold, then the burden of decreasing this queue is assigned to upstream on-ramps. This algorithm has been shown to reach the efficiency of more sophisticated optimal control schemes \[1, 4\].

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3 INTRODUCTION TO HERO/RWS ALGORITHM

Kotsialos et al. [10] have reported positive simulation results on the ring-road A10 by implementation of hierarchical coordinated strategy using the optimal control tool “AMOC”. However, to implement the control strategy in AMOC in practice is very complex and not yet operational. So, the Dutch ministry of transport developed a ramp metering coordination strategy (HERO/RWS algorithm) for the Dutch freeway network [3]. This algorithm incorporates local RWS controllers, thus creating a variant version of the standard HERO algorithm which uses ALINEA regulators. Nevertheless, the basic concepts of HERO and HERO/RWS are similar, namely rule-based control strategy.

In the HERO/RWS algorithm, individual RWS ramp metering systems are the basis to realize the coordination of multiple agents. Each Ramp-metering (“RM” used at acronym) in the coordinated network is an agent-based control system, which in principle operates isolated as long as no need exists for coordination.

When the queue on a certain on-ramp (referred to as “master” in the ensuing) exceeds some predefined threshold, HERO/RWS starts gradually recruiting upstream ramp metering controllers (so-called “slaves”) to support the metering task of the master. The reason for recruiting slave ramps is to enlarge the useable storage space that would otherwise be limited to the storage space available at the master ramp only. More specifically, it aims at preventing the queue on the master ramp from spilling back to urban intersections as well as limiting the number of vehicles onto the freeway. The underlying principle of the algorithm is to postpone the occurrence of congestion on freeways based on more storage space on the successive on-ramps, leading to higher freeway outflow and lower total travel times both on freeway and urban networks.

The working principle is described in the following, followed by a schematic control strategy shown in Figure 2:

Where, i denotes the concerning RM; j denotes the coordination route; k denotes the following upstream located RM; and n denotes the number of RMs in a certain coordination route.

- Local RWS-C (Code for RM controller is in C language) controllers are operated at each metered ramp for maximum local freeway mainstream throughput.
- During every control interval Tc, the current ramp queue lengths, maximum admissible queue lengths and control status are received from the local controls; based on these data, possible coordination actions are decided.
- When a ramp relative queue (current_queue[i]/max_queue[i], i ∈ [1, n-1]) exceeds a certain activation threshold value (activation_threshold[j]), it becomes a master (master[i], i ∈ [1, n-1]), and the HERO/RWS control strategy is activated. HERO/RWS starts gradually recruiting upstream metered ramps as slaves (slave[k], k ∈ [i+1, n]), up to a pre-specified maximum number of slaves (usually 4–6). (See the first and third steps presented in Figure 2.)

Slave ramps receive from HERO minimum desired ramp queue lengths to maintain, to virtually increase the available storage space needed at the master ramp to face the forming of congestion. As the demand increases, the queue of the master ramp may continue to increase; therefore, the HERO algorithm is updating the minimum queue length of each slave ramp each Tc such that the relative queues at each ramp are maintained close to each other. (See the fourth step presented in Figure 2.)

- The created cluster(s), each consisting of one master and several slave ramps, are dissolved if the relative queue of the master ramp falls below a deactivation threshold (deactivation_threshold[j]). (See the second step presented in Figure 2.)

To facilitate the coordinated control, a CVMS (Central Traffic Signal Control Management System) controller is used to communicate and coordinate with each local controller. This coordination controller reads data from each ramp metering controller. A more detailed description of the HERO/RWS algorithm can be found in [11].
HERO is already regarded as the most promising approach for large-scale field application of coordinated ramp metering [1]. The features of this control concept are simple, real-time operable and efficient. The HERO/RWS algorithm will be assessed using a microscopic simulation environment. The details of the proposed research methodology and the case study are described in the next sections.

4 ASSESSMENT METHODOLOGY

VISSIM [12] is a microscopic simulation tool in which external traffic control algorithms can be implemented and tested. In this study, HERO/RWS is tested in VISSIM for the Amsterdam A10-west network.

In VISSIM 5.00, ramp metering and its coordinated control have been realised via the external control interface [13]. The effects of the HERO/RWS algorithm (scenario 2) are compared to the situation without ramp metering controllers (no-control case as reference, null scenario) and the situation with individual ramp metering controllers (non-coordinated case, scenario 1). Since VISSIM is a stochastic model, ten simulation runs are performed to get an average result, each with different random seeds. This appears to be sufficient to get representative and reliable results [11].

For the purpose of this study, we focus on impact assessment. In the following, the first three criteria are related to network level impact. The last six are related to individual level impact [11].

- Total time spent (TTS) by all vehicles in the network (freeway & urban road)
- Average travel time for each vehicle in the network
- Total distance traveled in the network
- Total throughput of the main surveyed stretch (see case study)
- Speed contour plot of the related freeway stretch
- Average travel time on the main surveyed stretch
- Mean speeds of segments on the main surveyed stretch
- Average delay time on each on-ramp
- Usage (throughput) of each on-ramp

5 CASE STUDY

A simulation model is built to simulate the HERO/RWS performance in the Amsterdam A10-West network, where the existing four ramp meters are located, as shown in Figure 3. The main research stretch is restricted to the freeway section from S105 to the Coentunnel (see yellow oval in Figure 3). The main study area from S105 to S101 is divided into four segments, each of which contains one ramp metering controller. The afternoon peak period between 15:30 and 18:00 has been chosen as the simulation period. The first half hour is regarded as warming-up. Fixed-time control is adopted for the urban intersections. More details of model assumptions and modelling are described in [11].

Fig 3. Simulation model of Amsterdam A10-West.

In the model, four RWS-C controllers are used for ramp metering and one for coordination. However, RWS-C controllers cannot read speed data from VISSIM, which is an essential aspect of the control algorithm. Therefore, the “CCol” controller has been used for speed detection in VISSIM. The data communication between CCol and RWS-C controller as well as that within the same (RWS-C) type controllers (HERO/RWS and Individual Ramp Metering) is realized via so-called linking cables provided by the control interface (VriVissim-Vialis[13]). The iterative simulation runs with external controllers are realised through the VISSIM COM (Component Object Model) interface and the external control program Matlab. Meanwhile, Matlab is also used for processing the raw-data derived from simulation. The complete simulation environment is shown in Figure 4.

Fig 4. VISSIM simulation environment (Blue lines indicate data streams; Green lines indicate control streams).
6 EXPERIMENT AND DISCUSSION

Based on empirical data collected by double inductive loop detectors, calibration and validation of the model has been performed for the main study stretch in order to reproduce similar traffic conditions (flow and speed) compared to the OD (Origin-Destination) matrix [11]. For impact assessment, three scenarios have been tested in VISSIM. The integrated results are presented in Table 1. Although the overall performance in HERO/RWS network is the best among the three scenarios, the results at the system-level are not statistically significant.

The changes on the freeway section are much more significant. In scenario 1 and scenario 2, the average travel time on the freeway decreases by 24.15% (scenario 1) and 25.67% (scenario 2), respectively. The average travel time in scenario 2 is 10 seconds less than that in scenario 1, which is a 2.00% improvement. The coordinated control is the main reason to account for the positive effect, both for the freeway and for the whole traffic network. Moreover, the mean speeds on the first two segments of the freeway are improved. This is probably the main contribution to the decrease in average travel time. In scenario 2, the improvement of the mean speed on segment 1 is even higher than 50% compared to the no-control case. This improvement is caused by the fact that the inflows are metered at on-ramps to limit the flow on freeway.

The speed contour plots derived from the three scenarios illustrate the traffic performance on the freeway graphically, as shown in Figure 5a, b and c. What is worth mentioning here is that the congestion in scenario 2 occurred later than that in the null scenario and scenario 1, as indicated with vertical lines. As shown in plot 5c, during the first half hour from 16:00 to 16:30, the queue’s growth rate (shockwave speed) is lower than in the previous two cases. In the congested area, the overall speed indicated in plot 5c is higher than that in plot 5b. This is again evidence for the benefits from the HERO/RWS coordinated control, by enlarging storage space to postpone congestion.

Due to the amelioration of traffic conditions, the total throughput of the freeway in the two control cases increases, as presented in Table 1, with 5.49% and 5.69% improvement compared with the null scenario. That means the outflow of the freeway increases.

The following discussion focuses on local traffic around the main area related to the so-called equity. The term “equity” used here has two meanings. First of all, the focus is on the fairness between the freeway traffic and the underlying traffic. Since DTM measures have a large impact on the whole transport system and do more than just solve local problems, it is absolutely necessary to have a policy with well-defined goals for the total application area. The objective of the DTM measures for the A10 is to keep the ring-road running [3]. That means that the control scheme should give priority to the freeway traffic. The HERO/RWS control strategy turns out to be unfair to the travelers on the urban network in terms of fairness. The resulting total delay time for the traffic using the four on-ramps in scenario 2 increases by 2.59% compared to scenario 1. Nevertheless, the new control scheme meets the objective of Amsterdam by inducing more local delay and reducing delay on the freeway. Second, the equity is needed for the drivers using on-ramps. In non-coordinated control, it is unfair that a huge delay occurs at S101. HERO/RWS orders the slave ramp metering to start control earlier than scenario 1. Consequently, the queues formed at upstream on-ramps occur earlier as well. The HERO/RWS algorithm distributes delay in a more balanced way within a coordination control string, by activating upstream located ramp meters and thus inducing more delay there.

In summary, the HERO/RWS network outperforms the no-control and non-coordinated control networks, showing its potential effects. It is able to postpone congestion on the freeway at the expense of inducing more unfair local delay. Nevertheless, HERO/RWS improves the equity requirement for each on-ramp within a coordination control string.
7 CONCLUSIONS AND RECOMMENDATIONS

The VISSIM simulations performed in this study show that HERO/RWS coordinated ramp metering control may have positive effects compared to a local agent-based control strategy. For the considered case, the improvement on average travel time on the freeway in the HERO/RWS network is 2.00% compared to non-coordinated control, and 25.67% compared to the reference case (no ramp-metering control). The congestion on the freeway can be postponed effectively. Meanwhile, the HERO/RWS coordination control is in accordance with the control objectives established for this region. Although it may induce more delay on the underlying network (2.59% increment on total delay time for the traffic using the four on-ramps) compared with the local control case, it turns out to provide less congestion, higher mean speeds and lower travel time spent on the freeway. Furthermore, the HERO/RWS algorithm distributes the delay in a more balanced way over consecutive on-ramps.

The proposed HERO/RWS algorithm incorporates local RWS controllers. This kind of feed-forward control is generally known to be sensitive to various disturbances and thus has a low accuracy. In addition, the RWS strategy targets a pre-fixed capacity value which may lead to further efficiency degradation due to the inherent uncertainty of freeway capacity. ALINEA control could be introduced at local level for further improvement. Furthermore, the application of the HERO/RWS algorithm is limited to the four existing ramp metering systems. These reasons could account for the small percentage of improvement.

Future generalizations of the HERO/RWS algorithm will entail the coordination between the coordinated ramp meters and the adjacent urban intersection controllers. Additionally, research is needed on the effect of the HERO/RWS algorithm on route choice behavior as well as the departure time choice. Further improvements can be expected if other additional DTM measures, such as route guidance, are included in a coordinated way. Moreover, the prioritization of certain on-ramps within coordination control strings, with respect to the control objectives of Amsterdam, should be taken into consideration.

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