Ramp Metering Strategy Implementation: A Case Study Review

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Abstract: Ramp metering (RM) is a traffic management technique that aims at controlling the flow of traffic entering specific roadways tailored for fast-moving traffic containing separate multilane divided carriageways (such as motorways, highways, expressways, freeways, and turnpikes). The objective of RM is to minimize congestion on the main thoroughfare of the roadway. RM algorithms have evolved significantly since the 1960s and will continue to do so into the future. While the functionalities of the algorithms remain valid through time, the applications of the RM strategies are continually being updated. Unlike previous reviews that focused on the RM methodological aspect, this study details the recent literature regarding the implementation of RM strategies. The aim of this paper is to provide a global perspective on existing RM applications and the algorithms used, for future reference for both academics and practitioners. The paper provides an indicative historical context and characteristics for each reported project, as well as an overview of the evaluation of these schemes. Based on the current understanding of RM strategies, the paper discusses challenges and the potential future of RM technology. **DOI: 10.1061/JTEPBS.0000641.**

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Introduction

The investment into further capital infrastructure to increase the capacity of the road network to cater to greater traffic volumes is constrained economically and the phenomenon of induced traffic limits its effectiveness, and at times even exacerbates the congestion issue. An alternative approach involves optimizing the use of available infrastructure through various traffic and demand management techniques. In relation to motorways, the goal is to ensure full utilization of their capacity, and ramp metering (RM) is a traffic management technique that attempts to achieve this goal (Yuan 2008). It uses traffic signals to control the flow of traffic on-ramps entering a motorway, freeway, or other fast-moving traffic roadway in order to optimize the main thoroughfare while minimizing congestion. For the purpose of simplification, in the current paper we use the term *motorway* to identify a roadway with RM-controlled access.

The concept of RM stems from 1956, when the US government launched the Interstate Highway Program to cater to the growing need for people and goods to travel more efficiently. As demand, speed, and congestion increased, the value and safety of the network reduced (Jacobson et al. 2006). This phenomenon led to research into the understanding and mitigation of motorway congestion and safety concerns, which in turn led to a variety of methods to manage traffic demand on motorways. RM was one of the techniques resulting from this investigation.

RM originated within the US and since then has been implemented in over 30 cities within the US as a motorway management technique. RM was initially explored within Chicago, Detroit, and New York and has gradually been implemented throughout the rest of the country, with particularly high usage within Washington State and California. In Europe, RM systems have been applied widely to improve motorway travel conditions. The precise number of existing systems and metered ramps implemented has not been reported. However, literature indicates that a significant number of RM systems are operating in several European countries, including France, Germany, and the Netherlands (Middelham and Taale 2006).

One study (Haj-Salem et al. 2001) suggested that unlike in the US, in European countries, the integration of RM strategies within the traffic management centers faced a number of difficulties due to misunderstandings of the potential impacts such techniques have on the traffic conditions. The European governments, together with research institutions and private operators, have been involved in a number of projects where the main objective was to advance, promote, and harmonize RM control measures in order to improve

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safety and increase the efficiency of traffic flow. One of the studies was the European Ramp Metering Project (EURAMP) executed within the 6th European Research and Technological Development Framework Programme (Bielefeldt 2007; EURAMP 2014; Papageorgiou and Papamichail 2007).

The three key findings of the EURAMP project are as follows: (1) proof that considerable socioeconomic benefit can be gained from the operation of local RM; (2) a warning that the ramp delays can outweigh the travel time gains for the vehicles on the mainline motorway, if the metering is applied too harshly; and (3) proof that coordinated metering is superior to local metering strategies, and that substantial additional benefits can be gained from the coordination.

In this paper, we present case studies of 15 RM applications deployed worldwide that were reported in the literature. Each project is discussed in detail in the subsequent sections. Special attention is paid to the project findings, with a particular focus on the impacts of RM on the road network (e.g., effect on mainline speeds, travel time, delay, and number of crashes). All the projects report on performance in reference to initial objectives and highlight the positives of RM implementation. The benefits include: (1) increased mainline speeds, (2) decreased travel times, (3) reduced delays, (4) increased motorway capacity and throughput, (5) improved safety—reduction in accidents, (6) congestion reduction by managing traffic demand, (7) reduction in emissions and improved air quality, (8) reduction in fuel consumption and improvement in fuel economy, and last but not least, and (9) efficient use of capacity. The list of incurred costs includes: (1) disruption of the surrounding arterial network as a result of metering; (2) increased ramp delay and spillback; (3) equity (most travel time savings are obtained by users traveling longer distances along the motorway, while short distance travel on the motorway may result in greater travel times); (4) capital cost of installation, maintenance, enforcement and public education; and (5) mode shift toward private car use as performance of the mainline improves.

The reviewed documents include technical reports, journals, and conference papers. A semistructured approach was used starting from collecting studies from Google and Scopus, based on relevant keywords (ramp metering, ramp signals, motorway congestion management, on-ramp control, entrance control, and motorway traffic control), for the publication year range 1970–2020. The obtained studies were divided based on their relevance and topics and implementation locations. Country/state names are also added to the keywords to find some additional studies for particular locations. There were two main challenges in finding the references: (1) many scientific studies performed their proposed RM methods only in traffic simulations, and we could not find any evidence that they were used in real-world applications; and (2) for non-English-speaking countries, most of the implementation reports were in a language other than English. Therefore, this study is biased toward Western countries, while RM methods implementations are not limited to the only reviewed case studies.

Unlike previous reviews that focused on RM algorithms (Papageorgiou et al. 2003; Shaaban et al. 2016), the current study details the recent literature regarding the implementation of RM strategies. The goal is to provide practical insights on RM solutions useful to both academics and practitioners. The review focuses on real-world applications, highlighting available options and challenges of implementation and evaluation of RM.

The remainder of this paper is organized as follows. The next section provides an overview of RM case studies, focusing on implementation and effectiveness of the schemes, followed by a section discussing the challenges in implementing and evaluating RM solutions. The last section presents concluding comments and discusses future research directions.

RM Case Studies: Context and Results

RM strategies can be classified based on the method of control (Zhang et al. 2001). A method of control determines the scale and complexity of the RM strategy. Throughout the literature, it is evident that there are two general approaches: (1) fixed-time; or (2) traffic-responsive RM strategies. Both of these large categories include algorithms formulated to achieve goals specific to the method of control.

Fixed-time RM systems determine metering rates based on historical traffic conditions and are preset according to the time of day. Their drawback is the inability to react to the volatility of traffic flow that may occur due to fluctuations in demand or the presence of a disruption within a network (Scariza 2003).

The majority of implemented RM systems are based on traffic-responsive control methods, and thus they naturally became the main focus of the current work. Traffic-responsive systems use real-time data collected from loop-detector devices to determine the timings and activity of the metering (Jacobson et al. 2006). In this way, they adapt to the prevailing traffic conditions, allowing greater flexibility and ability to coordinate across a series of ramps for a motorway corridor. Traffic-responsive systems can be further classified into (1) isolated (local); and (2) coordinated (network-wide) (Zhang et al. 2001).

Isolated traffic-responsive metering attempts to resolve localized traffic management concerns. An advantage of these systems is that, unlike fixed-time systems, they have the ability to react to volatility in traffic flow.

Coordinated traffic-responsive metering aims to optimize the traffic flow along a metered stretch of a motorway considering a series of metered ramps. It coordinates the metering rates based on the traffic conditions of the mainline as well as those of the downstream ramps. The coordinated algorithms can be separated into three types: (1) cooperative, (2) competitive, and (3) integral.

Cooperative RM algorithms aim at initially satisfying the local traffic conditions at each on-ramp, and then at a global level minimize overall congestion within the mainline and adjacent arterial network (Aydos and O'Brien 2014; Papamichail and Papageorgiou 2008; Papamichail et al. 2010). This is an improvement to isolated RM; however, these algorithms balance between local and network-wide objectives in an ad hoc manner, resulting in instability (Zhang et al. 2001).

Competitive algorithms determine metering rates on a local and network-wide level. The most restrictive rate is utilized throughout the system (Zhang et al. 2001). This differs from the staged approach of cooperative algorithms, where the global system assists the local metering by providing a measure of the traffic conditions downstream of the ramp. Competitive algorithms may also consider queue lengths of ramps and impacts on the surrounding network when determining metering rates.

Integral algorithms focus on specific objectives and develop the metering rates and control methods with the goal of achieving those objectives. In general, the considered objectives are travel time minimization for the mainline or throughput maximization along the mainline. RM rates are determined by optimizing the objective considering constraints such as maximum allowable ramp queue, bottleneck capacity, and other important factors affecting traffic conditions external to the mainline (Gokasar et al. 2013). The study by Zhang et al. (2001) suggests that integral

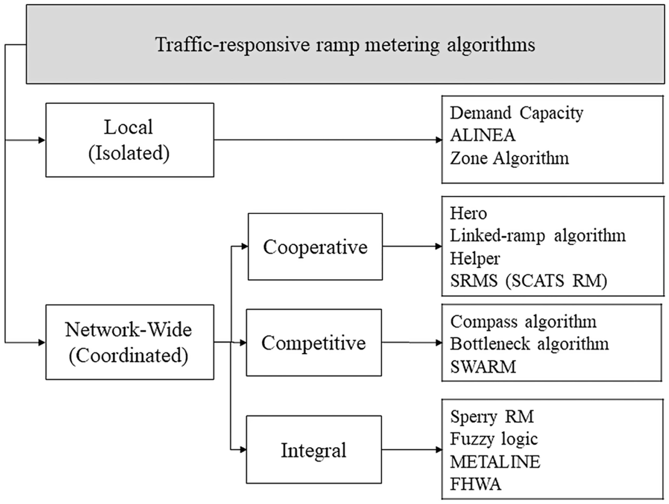

Fig. 1. Classification of traffic-responsive RM algorithms.

algorithms are the most appealing because of the theoretical foundation and capability of handling various types of metering and modeling constraints. However, the increased complexity results in a computational burden, and performance is heavily dependent on fine-grained input data. Fig. 1 provides an overview of the traffic-responsive RM algorithms that have been proposed and implemented globally.

In the rest of this section, we review several real case study applications in different countries based on the more often used RM system. At each subsection, we first provide a brief summary from the main concept of the method, followed by some case studies. A summary of all the analyzed case studies is gathered in Tables 1 and 2, which contain information on the site [i.e., used system—e.g., Asservissement Linéaire d'Entrée Autoroutière (ALINEA), system-wide adaptive RM (SWARM), etc.—country, city, project name, etc.], the motorway test network (i.e., motorway name, identification, etc.), what the system was tested/compared against, the practical impact of RM implementation, and the source of reference, all if available.

Table 1. Case studies of RM applications reported in the literature

Project	Motorway test network	Used system	Other tested systems	Summary of impact of RM implementation	Sources
Paris, France	Périphérique, A6 Île-de-France	Adaptive ALINEA	Classic ALINEA CS-ALINEA VC-ALINEA	The traffic-responsive feedback control strategies are clearly superior to fixed-time control Implementation of the ALINEA family control systems improved the traffic congestion in range of 10%–17% Results from implementation of HERO in A6 showed a clear improvement over the uncoordinated ALINEA	Muhurdarevic et al. (2006), Papageorgiou et al. (1990a, b), Papamichail et al. (2010)
Tel Aviv, Israel	Ayalon motorway (Road No. 20)	Classic ALINEA	No-control strategy	The system's capacity increased by up to 950 vehicles/h upstream of the ramp TTD values in the system were higher by 3.3% TTTS was reduced by 2.6% on average over the whole tested time period	Papageorgiou et al. (1990a, b)
Birmingham, England	M6 near Birmingham	Classic ALINEA	Merge control ACDC	Journey time reduced for mainline traffic of 13% across all sites where RM was implemented during the morning peak period Increase in traffic volume ranging from 1% to 30% was observed by individual measured sites	Hayden et al. (2009), Highways Agency (2007, 2008)
Gauteng, South Africa	BSH	Classic ALINEA	No-control strategy	Traffic volumes during the peak period increased by 2.2%, whereas the increased during the peak hour is 8.5% The effect of RM on travel times for the main traffic stream was minor	Vanderschuren (2006)
Munich, Germany	A94 Munich, A9 Nuremberg/Berlin, and A8 East Salzburg	Adaptive ALINEA Fuzzy logic	Classic ALINEA	TTTS was 1.4% and 0.6% lower for classic ALINEA in comparison to the adaptive ALINEA and ACCEZZ, respectively Clear conclusions could not be identified regarding system's performance during potential congestion events	Papageorgiou et al. (1990a, b)
Amsterdam, Netherlands	A-10 West ring road, Delft-Zuid on-ramp to the A13	Fuzzy logic	RWS strategy ALINEA	The fuzzy logic strategy increased by 5% the overall mainline capacity, which led to higher speeds and lower travel time	Middelham and Taale (2006), Papageorgiou et al. (1997), Taale et al. (1996)
Seattle, Washington	I-5, I-90, I-405	Fuzzy logic	FLOW Bottleneck Zone metering	With fuzzy metering 8.2% reduction in I-90 mainline congestion The I-405 mainline congestion was 1.2% worse with fuzzy metering than with bottleneck metering	Chu et al. (2004), Taylor and Meldrum (2000)

Table 2. More case studies of RM applications reported in the literature

Project	Motorway test network	Used system	Other tested systems	Summary of impact of RM implementation	Sources
Melbourne, Australia	M1 Motorway	ALINEA HERO (STREAMS)	Fixed-time meters	Average flow improved by 4.7% and 8.4% during morning and evening peaks, respectively Average speed improved by 35% and 58.6% during AM and PM peaks, respectively	Papamichail et al. (2010)
Brisbane, Australia	M1/M3 Motorway	ALINEA HERO (STREAMS)	Fixed-time meters	7% increase in travel speeds in AM peak (from 70 to 75 km/h) 4% increase in throughput (150 vehicles/h)	Faulkner et al. (2014)
Los Angeles, California	Westbound Route 210	SWARM	Demand-capacity control (SATMS) and occupancy control (SDRMS and TOS)	Increase in mainline speed by 11% during the AM peak Decreased travel time by 14% Reduced mainline occupancy by 13% Reduced motorway delay by 17%	Chu et al. (2004), MacCarley et al. (2002), Monsere et al. (2008), Pham et al. (2002), Zhang et al. (2001)
Denver, Colorado	I-25, I-225, I-270	Helper	No-control strategy	Mainline speed increased by 16% (from 69 to 80 km/h) The overall rate of accidents decreased by 20% between 1983 and 1989 18% increase in peak volume in mainline	Lipp et al. (1991)
Minneapolis, Minnesota	I-494, I-94, I-35E, I-35W	SZM	Fixed-time meters Zone metering	9% reduction in through traffic of motorways 14% reduction in motorway speeds, increasing travel times Depreciation of travel time reliability with greater standard deviations of travel times measured	Lau (1997), Levinson and Zhang (2006), Xin et al. (2004)
Toronto, Canada	QEW, Highway 401, Highway 403	COMPASS	No-control strategy	Substantial improvements in travel time and decrement in accident rates achieved during its first two years of operation	Morala et al. (2008)
Auckland, New Zealand	Mahunga Drive, Rimu Road, Highway 20	SRMS	Fixed-time meters	8% increase in throughput flow 25% improvement in speed for average and congestion periods An average 22% reduction of crashes was reported	NZ Transport Agency (2014), O'Brien (2014), O'Brien and McCombs (2007)

ALINEA Family

The well-known feedback RM algorithm ALINEA is a discrete, closed-loop occupancy control algorithm based on feedback control theory. In the core of the original ALINEA algorithm (Papageorgiou et al. 1991), a feedback control system adjusts the RM rate in order to keep the downstream occupancy rate less than a certain occupancy threshold. ALINEA can be applied to local RM or used as a key component in a coordinated RM system. Theoretical analysis shows that ALINEA may result in poorly damped closed-loop behavior in the cases where bottlenecks propagated further downstream from the merging area. Different versions of ALINEA have been proposed in previous studies to address this issue (Ferrara et al. 2018). Some versions of the model replaced the flow rates upstream and downstream (Smaragdis et al. 2004), and some enhanced the core controller of the algorithm (Wang et al. 2014). For details on the ALINEA algorithm and the method's extensions, please refer to Frejo and De Schutter (2018), Kan et al. (2016), Kontorinaki et al. (2019), Papageorgiou et al. (2003), Stylianopoulou et al. (2020), and Zhao et al. (2019).

Paris, France

In 1990 and early 1991, METALINE and ALINEA were implemented on three on-ramps of the internal southern part of Boulevard Périphérique. METALINE is the integral coordinated system version of ALINEA. METALINE extends ALINEA to the linear quadratic control type by calculating two gain matrices. The original motivation of the study was the fact that the Boulevard Périphérique was underutilized during peak-hour congestion. The study area included 6 km of motorway, including three metered ramps and two nonmetered ramps. The models were validated on the basis of real traffic flow measurements selected under a broad spectrum of traffic conditions. The morning peak period was studied for 10 days using each algorithm, with results showing mainline speeds increasing for both. This 10-day-long study remains the only field implementation of METALINE in the Paris area. The results showed that METALINE and ALINEA perform similarly under normal conditions, but in the case of nonrecurring incidents METALINE outperforms ALINEA (Papageorgiou et al. 1997).

Within the framework of the EURAMP project, a number of field trials were designed and executed on the A6 motorway located south of Île-de-France, Paris (the project was initiated in 2004). The tested RM strategy was ALINEA, implemented independently at each of the four controlled ramps. The performance of ALINEA was compared with a base case when no control was implemented. The results indicated that the benefits of the RM were higher under nonrecurrent congestion with low waiting time on the ramps.

In addition to the classic ALINEA algorithm, two other variants were tested: variable cycle (VC-ALINEA) and coordinated strategy

(CS-ALINEA). The latter constitutes an adaptation of ALINEA heuristic RM coordination (HERO). In comparison with the no-control strategy, all three ALINEA algorithms proved their superiority (Bielefeldt et al. 2007; Haj-Salem et al. 2001).

Across all the ALINEA strategies, CS-ALINEA improved the motorway traffic the most. It reduced the delays on the on-ramps by distributing the ramp flows among the on-ramps so that all the queues were diminished and the total sum of all on-ramp delays was decreased. In addition, while maintaining the system's capacity, the travel times reduced by 0.9%, 3.5%, and 4.6% in comparison to no-control, classic ALINEA, and VC-ALINEA, respectively. The cost-benefit ratio of implementation of CS-ALINEA was calculated to be 8.8.

Munich, Germany

Another RM study within the EURAMP project was completed for the motorway near Munich in Germany. The study involved reviewing the performance of classic ALINEA, adaptive ALINEA, and adaptive and coordinated control of entrance ramps with fuzzy logic (ACCEZZ). The data was gathered during winter 2005 and spring 2006 across the five-hour afternoon peak period. Due to the fact that during the time of study traffic volumes did not increase, and congestion was not present, only minor differences in the performance of the algorithms were observed. The differences noted for different hours and different strategies eventually canceled each other out in the overall comparison. For example, the total travel time spent (TTTS) was 1.4% and 0.6% lower for classic ALINEA in comparison to the adaptive ALINEA and ACCEZZ, respectively. Consequently, clear conclusions could not be identified regarding the system's performance during potential congestion events. It also showed that a RM system is appropriate under congestion conditions (Bielefeldt et al. 2007).

Tel Aviv, Israel

Ayalon Highway (i.e., Road No. 20) is the busiest highway in Israel. It serves 750,000 vehicles a day and the traffic volumes on its busiest section exceed 140,000 vehicles a day. The project was initiated in 2004 and the data was gathered in the spring of 2006. Similar to the Munich case study, the time interval of interest was a five-hour-long afternoon peak period. The objective of the study was to contrast ALINEA with a no-control strategy. The congestion conditions were severe at the section of motorway assessed due to geometrical design and high traffic volumes: up to 8,000 vehicles/h present on the mainline of the motorway, while 1,400 vehicles/h used the on-ramp. ALINEA managed to increment the average ramp time from 15 to 59 s, never reaching 90 s. Also, ALINEA reduced downstream travel times by 2.4% and upstream travel times by between 6.7% and 8.5%, with the greatest improvements observed immediately upstream of the ramp. In absolute terms, due to implementation of ALINEA, the system's capacity increased by up to 950 vehicles/h upstream of the ramp (Bielefeldt et al. 2007). The comparison with the no-control strategy also showed that the total traveled distance (TTD) values in the system were higher by 3.3% and the net TTTS was reduced by 2.6% on average over the whole tested time period. Ramp queues dissipated more quickly when ALINEA was used in contrast to the situation when the no-control strategy was used. The study also focused on measuring fuel consumption and emission levels, both of which reduced by 1%–1.5% in the presence of metering. The noted levels of emissions when using ALINEA differed for inorganic gases (NOx) and hydrocarbons (HC) and were equal to 0.3% and 2.4%, respectively. In addition, the investment costs and system operating costs were estimated. The comparison presented monetary benefits of operating ALINEA over the no-control strategy with a cost-benefit ratio of 7.6, resulting in a break-even point of 6 months. Like in all the other test cases within the EURAMP project, the safety assessment study, although conducted, was not conclusive (Bielefeldt et al. 2007).

Birmingham, England

The first RM was trialed on M6 near Birmingham in 1986. RM was initially introduced on the southbound access slip road at Junction 10 and later extended to the northbound and some other junctions in this motorway. With the positive evaluation of the project, the Highways Agency increased the number of RM over 30 sites in the UK by 2000 (Highways Agency 2007). The before and after study assessed three main indicators; journey times, traffic speeds and traffic flows. The field data was collected from loop detectors located at every 500m and journey times along the mainline carriageway (Highways Agency 2008). Overall, journey time reduced for mainline traffic by 13% across all sites during the morning peak period. Moreover, an increase in traffic volume ranging from 1% to 30% was observed by individual measured sites. Despite the success of the implemented RM system, some potential improvements have been proposed in Hayden et al. (2009). This study used a microsimulation model to evaluate different RM algorithms such as ALINEA, merge control, and AINEA cascaded with demand capacity (ACDC). In comparison to existing RM, ACDC resulted in lowering of travel times due to reduction of underlying traffic volumes. Also, the merge control approach resulted in the lowest journey time compared to the other tested approaches.

Gauteng, South Africa

The application of RM was a part of the Intelligent Transport System launched as the Gauteng Motorway Improvement Project (GFIP) by the South African National Roads Agency (SANRAL). The project aimed to improve the congested conditions on the road system of South Africa's economic hub in 2007 (Vanderschuren 2006). The Ben Schoeman Highway (BSH) connects Johannesburg to Pretoria and is the busiest road in South Africa. The capacity of the motorway is almost 6,600 vehicles/h, of which on average 5% are heavy vehicles. The BSH corridor is the main motorway where the RMs were introduced. The introduction of RM on the BSH provided better utilization of road capacity. Traffic volumes during the peak period have increased by 2.2%, whereas the increase during the peak hour is 8.5%. Furthermore, the safety risk decreased, whereas the headway distribution was almost identical to the base case headway distribution. The effect of RM on travel times for the main traffic stream was minor (Vanderschuren 2006).

Fuzzy Logic

Fuzzy logic seems to be well established for RM. Because a fuzzy controller can handle nonlinear systems with unknown models, the approach has an advantage over classical controllers for the RM problem (Vukanovic and Ernhofer 2006). In fuzzy controllers, the imprecision and uncertainty are handled by defining the input variables as fuzzy sets rather than as crisp values. Therefore, the measured data (e.g., speed, flow) is first fuzzified and fed to RM controller. The controller determines the action by using set of predefined logic rules. The fuzzy logic rules incorporate human expertise in a manner to control extreme traffic situations. At the end, outputs are defuzzified to obtain the real RM rates. Having tested different fuzzy logic control strategies in some real-world applications, it can be said that the traffic situation improved at the mainline, especially at the merging areas. For details on the fuzzy logic algorithm, please refer to Bogenberger and Keller (2001) and Xu et al. (2013).

Seattle, Washington

Washington State DOT (WSDOT) implemented a bottleneck algorithm, FLOW, in 1981 as a component of a motorway management strategy. The metering was conducted on the I-5 north of the Seattle Central Business District and included 17 southbound ramps (metered during the morning peak) and five northbound ramps (metered during the evening peak). Though the primary goal of the metering was motorway management, in 1986 metering was also used on the SR-520 as a local traffic calming measure to discourage users from traveling through paths near residences and schools. The metering generated a delay, creating diversions from these ordinarily used paths. An evaluation of the initial 22 ramps was conducted, comparing the efficacy of the system between 1981 and 1987.

Insufficiencies such as high ramp delays, queue length volatility, and lack of coordination between ramps from the FLOW implementation resulted in the development of a new algorithm based on the concepts of fuzzy logic theory. These insufficiencies were highlighted by Chu et al. (2004) in a study that compared a number of leading algorithms using microsimulation tools. The study indicated that the performance of bottleneck and zone algorithms were inferior relative to system-wide coordinated techniques.

WSDOT commissioned a study to formulate and evaluate the benefits of using an algorithm that accounts for heuristic-based decision-making in conjunction with purely quantitative metrics. The study compares the fuzzy logic algorithm to FLOW and is detailed in Taylor and Meldrum (2000). It shows that the development, implementation, and optimization of the fuzzy logic algorithm on all 126 ramps at the time of the study were an achievement, as this form of algorithm had never previously been implemented. The benefits of the fuzzy logic algorithm were due to both the inclusion of downstream inputs and the fuzzy controller's use of smooth graduated control in a preventative manner. An online performance comparison with the local metering on the I-90 and the bottleneck metering on the I-405 provided the following results: (1) on the I-90 site, fuzzy logic metering resulted in lower mainline occupancies, higher throughput volumes, and slightly higher queues than local metering; (2) on the I-405 site, fuzzy logic metering resulted in slightly higher mainline occupancies, slightly higher throughput volumes, and significantly reduced queues; and (3) in a system-wide perspective, the fuzzy logic RM algorithm improved travel time and resulted in higher throughput.

In effect, the fuzzy logic algorithm was implemented in 1999 and is currently being utilized in Seattle across the 126 ramps throughout the region as a critical component of the motorway management scheme.

Amsterdam, Netherlands

In 1989, the first RM system in the Netherlands was installed near the Coentunnel on the A-10 West ring road around Amsterdam. The objective of the project was to improve the traffic on the A10-West, because significant congestion was caused by the large number of vehicles using the on-ramp trying to avoid the congestion before reaching the Coentunnel. Positive performance of this system led to two other deployments: the Delft-Zuid on-ramp to the A13 in the direction of Rotterdam and Zoetermeer. In 2005, in the Netherlands, 54 ramps were equipped with the RM devices. On 10 of the locations a comparison study of different available algorithms was completed. The algorithms included the Dutch RWS strategy (European demand-capacity theory), the ALINEA strategy, and the algorithm based on fuzzy logic (Taale et al. 1996).

The comparison of the RWS strategy and ALINEA showed that ALINEA provides comparable or better results. ALINEA increased the total service of the motorway and the on-ramp. However, when fuzzy logic was contrasted with ALINEA and the RWS strategy, it was clearly the best performing of the three. The fuzzy logic strategy gave better results with respect to capacity increment (5%), which led to higher speeds and lower travel times (Middelham and Taale 2006).

HERO

HERO is based on ALINEA method principles. The algorithm uses real-time measurements, but without doing real-time calculations (Kristeleit et al. 2016). Each RM is independently controlled using ALINEA. Once congestion is observed on the mainline, the critical RMs—including the closest ones—are prioritized and called master ramps. The master ramps continue controlling RM at local level while the other upstream RM rates are reduced as long as the congestion dissipated. For details on the HERO algorithm, please refer to Bélisle et al. (2019} and Papamichail and Papageorgiou 2008).

Melbourne, Australia

In early 2008, VicRoads started a pilot project in Melbourne and implemented the ALINEA/HERO system (on the STREAMS platform) on six on-ramps along the M1 motorway (also known as the Monash motorway) (Burley and Gaffney 2010). It is a major urban six-lane dual carriageway linking Melbourne's Centre Business District with the southeastern suburbs, and one of Australia's busiest motorways. The motorway was utilized by 160,000 vehicles per day, comprised of 20% commercial vehicles, experiencing 3–8 h of congestion a day (Samad and Annaswamy 2011).

The on-ramps were previously operating on a fixed-time-of-day ramp signaling system. Later, 64 coordinated RMs were deployed as part of a major upgrade to the Monash-City Link-West Gate motorway. The project budget was $AUD 1.93 billion, from which approximately $AUD 100 million was devoted to intelligent transport systems (ITS) (Vong and Gaffney 2009). The performance of the system was evaluated and showed that the average flow improved by 4.7% and 8.4% during the morning and evening peaks, respectively. Furthermore, the average speed improved by 35% and 58.6% during the morning and evening peaks, respectively. The economic evaluation was based on travel time savings and vehicle operating costs. The economic benefit was estimated to be $AUD 94,000 per day per RM (Papamichail et al. 2010; Samad and Annaswamy 2011).

Brisbane, Australia

On September 2011, the Department of Transport and Main Roads (DTMR) implemented the HERO system and related infrastructure upgrades on six on-ramps over a stretch of 17 km along the M1/M3 Motorway (Pacific Motorway/South East Motorway). The on-ramps had been operating on a fixed/time-of-day ramp signaling system for the past 20 years. The motorway was utilized by 120,000 vehicles per day, and was comprised of majority commuters (3% heavy vehicles was used in the economic analysis) (Faulkner et al. 2014).

The capital cost covered infrastructure upgrades, research and development, software licenses, deployment and configuration, and training. The installation and configuration took approximately five months. The infrastructure upgrades comprised signal lanterns, new close-circuit television (CCTV) systems, and loop detectors on the mainline and within the ramps. Other specific factors about this pilot project were as follows: (1) tight changes to cycle time were imposed (min/max of 4.8–6 s), (2) average cycle time changed from 4.8 s during fixed-rate system to 5.4 s with HERO, and (3) the scope of the study was limited to on-ramp control, and no arterial coordination was mentioned; as such, congestion continues to exist, particularly at off-ramps downstream of on-ramps.

Three types of performance evaluations were conducted by comparing measurements from May–August 2011 (before HERO) to May–August 2012 (after HERO). All indicators showed a significant improvement compared to the previous fixed-time system. As the period corresponding to the before scenario was during the upgrade of facilities, it is not clear if on-road construction had any impact on traffic (Faulkner et al. 2014). Ramp delays were measured on the on-ramps and no net increment was observed. Economic benefits analysis indicated that the main benefit was based on an average speed increase of 5 km/h, which was found during the morning peak period only (Faulkner et al. 2014).

SWARM

SWARM, similar to other coordinated algorithms, includes a bilevel control system: local level and network level. The local controller estimates RM rates based on predicted links' density using a Kalman filter. The network controller adjusts RM rates to minimize deviation of current and desired density values. One of the advantages of the SWARM algorithm is the capability of cleaning the measured data in case of faulty traffic sensors. Moreover, SWARM is able to predict congestion in advance, and estimates optimized RM rates in an active control manner. At the same time, if the algorithm predictors are not well calibrated, the high reliability of the SWARM algorithm on the traffic prediction (rather direct measured traffic data) can be the largest drawback of this method. For details on the SWARM algorithm, please refer to Bogenberger and Keller (2001).

Los Angeles, California

The California DOT (Caltrans) has employed different forms of RM since 1968. Currently, there are three major systems in place (Chu et al. 2009): (1) the San Diego RM system (SDRMS), deployed in Sacramento, Fresno, San Bernadino and Riverside, and San Diego areas; (2) the semiactuated traffic management system (SATMS), deployed in Los Angeles and Orange County; and (3) the traffic operations system (TOS), deployed in the San Francisco Bay area.

The metering algorithms in these systems are local area traffic-responsive control operated according to real-time detector data and preset metering plans (Chu et al. 2009). SATMS is based on demand-capacity control. Both SDRMS and TOS are based on occupancy control. The SWARM algorithm has been tested and implemented in parts of southern California—Orange, Los Angeles, and Ventura Counties—during the late 1990s and continues to be assessed.

A study by MacCarley et al. (2002) indicated that the implementation within Orange County was not appropriately monitored. However, the implementation and evaluation of the algorithm was far more successful within the Los Angeles and Ventura Counties (Pham et al. 2002). In excess of 1,200 ramps contain meters within the network. The SWARM system was compared against the pretimed and local traffic-responsive RM systems considering morning peaks of Route 210, including 20 controlled ramps.

Portland, Oregon

The Oregon DOT (ODOT) first implemented RM in the Portland metropolitan area in 1981 along a 10-km section of I-5 between Portland and the Washington state line. Portland's original RM strategy employed a fixed-time algorithm that determined the activity of the ramp as well as the metering rate based on historical data (Ahn et al. 2007). The original strategy was evaluated and the effectiveness of the strategy was evident, with a 40-km/h increase in travel speeds along the I-5 14 months after installation (Bertini et al. 2005a, b). As a result, the RM system expanded throughout Portland's network, and currently, Portland contains 138 metered on-ramps (Ahn et al. 2007).

In 2005, a SWARM algorithm was implemented in stages in the Portland metropolitan area to improve and coordinate the fixed-time RM strategy. The studies by Bertini et al. (2005a, b) utilized the loop-detector data provided by the Portland Oregon Regional Transport Archive Listing (PORTAL) to provide an assessment of the impact of metering on traffic flow parameters and concepts. In particular, Bertini et al. (2005a, b) offered directions for the hardware and software that needed to be implemented for the successful continuation of the data collection efforts of PORTAL.

Ahn et al. (2007) studied the deployment of the SWARM algorithm across six major corridors during the morning and afternoon peak hours. The study describes a before and after evaluation of the RM comparing SWARM and the fixed-time system. Similar to the Minnesota cessation of RM, Ahn et al. (2007) conducted a shut-off experiment for a two-week-long period on the 11.3-km OR-217 corridor (including 12 on-ramps) to perform the comparison. Overall, SWARM resulted in higher metering rates, which reduced delays on the on-ramps. However, the motorway delay increased. Definitively determining the cause of the motorway delay was difficult as the bottleneck discharge rate within the mainline was not measured within the data set.

Stratified Zone Metering

Stratified zone metering (SZM) is the modified version of the zone algorithm in that the delay on ramps is reduced and a strict maximum delay boundary is applied to each RM. In the SZM method, the mainline is divided into multiple zones based on the location of critical bottlenecks in the motorway. Ideally, each zone starts with a free-flow area and ends in a congestion area. The algorithm aims to find a balance between each zone's density and RM rates. Metering rates are determined in a manner to handle traffic volume entering the zone (inflow) and traffic volume leaving the zone (outflows) in each iteration. For more details on the SZM algorithm, please refer to Geroliminis et al. (2011), Karim (2015), and Lau (2001).

Minneapolis/St. Paul, Minnesota

The Minnesota DOT (MnDOT) uses RM as a motorway management technique for 340 km of motorway in the Twin Cities metropolitan area. MnDOT first implemented RM in 1969, and since then approximately 430 RMs have been installed to manage congestion and improve safety. The implementation of RM has been deemed a success as a consequence of the staged implementation on a segment-by-segment and motorway-by-motorway basis over time, strict attention to priority entry control, and motorway-to-motorway connector metering (Lau 1997).

Initially MnDOT successfully implemented fixed-time meters during 1970 and 1971. Notwithstanding, further investment into the system resulted in the transition to use the zone algorithm. The zone algorithm was effective in reducing motorway congestion and accident rates (Arnold 1998; Bogenberger and May 1999; Zhang et al. 2001). However, the on-ramp delays experienced were in excess of 4 min, resulting in public disapproval and leading to the cessation of the metering strategy for a 6-week period in 2000. Several studies (Levinson and Zhang 2006; Xin et al. 2004) were conducted during the absence of the metering to evaluate the impact of the metering strategy.

A study by Zhang and Levinson (2010) further utilized this unique situation of the short-term closure to study the impact of RM on the capacity of bottlenecks. The authors hypothesized a series of relationships between RM and bottleneck capacity and tested these hypotheses using the traffic data across two equal periods with and without the presence of RM. The results indicated that RM could increase capacity by delaying the presence of a bottleneck, allowing for increased traffic volumes.

The results of the evaluation studies conducted in academia and practice (MnDOT) emphasize the benefits of the metering system in place. As a result of an evaluation study conducted in 2002 by MnDOT and as an effort to improve public perception and performance of the RM strategies, MnDOT implemented a SZM algorithm. The SZM considers multiple layers of segments/zones of a motorway, so zones can be considered in isolation and also be grouped and coordinated in a hierarchical structure. Accordingly, SZM accounts for the performance of the mainline as well as the delays and impacts on the ramps and surrounding network.

Helper

The Helper algorithm locally computes its metering rates based on the upstream mainline occupancy and the queue length measured on the ramp. If a long queue length appears on a ramp, the corresponding RM is considered as a critical RM, and some constraints are applied to downstream and upstream RM rates. If the adjacent RMs become critical ramps as well, the request is sent to the next closest RMs. The Helper algorithm is considered robust, but its calibration is sophisticated. For more detail on the Helper algorithm, please refer to Kristeleit et al. (2016) and Lipp et al. (1991).

Denver, Colorado

A RM pilot project was conducted during 1981 on a section of the northbound I-25 consisting of five on-ramps (Corcoran and Hickman 1989). A local traffic-responsive algorithm was implemented at each of the ramps where each meter selects one of six available metering rates based on localized upstream mainline occupancy (Corcoran and Hickman 1989; Lipp et al. 1991). This system was evaluated periodically between 1981 and 1983. The effects of the project measured two weeks, one month, three months, and 18 months into the operation of the scheme.

The benefits of the project led to the expansion of the system in 1984 with the implementation of a centralized computer system and a coordinated algorithm, Helper (Lipp et al. 1991), and the implementation of metering to a number of other ramps on the I-25, I-225, and I-270 and the Sixth Avenue Motorway.

In late 1988 and early 1989, a comprehensive evaluation of the original metered section of five ramps on the I-25 was conducted. The measured speeds reduced from the value of 85 km/h obtained in the 1983 study to 80 km/h. However, this remained far greater than the premetering speed of 69 km/h. Accident levels remained at a similar level as experienced in 1983. Nonetheless, these results indicate a significant improvement of conditions, as volumes between 1983 and 1989 have increased by over 20%. The fact that the accident rates and travel speeds have been maintained indicates reaching greater throughput and safety of the motorways (Corcoran and Hickman 1989). Currently, the Denver RM system is actively utilized on the I-25, I-225, I-270, Sixth Avenue Motorway (US-6), and C-470.

COMPASS

COMPASS is a coordinated and competitive algorithm that looks up predetermined RM rates determined by the local mainline occupancy. The rates are determined by the downstream mainline occupancy and the upstream mainline volume. An offline optimization selects the most appropriate RM rates based on system-wide data. Traffic spillback is considered by overriding restrictive rates that increase the metering rate as the queue threshold is exceeded. For more detail on the COMPASS algorithm, please refer to Lam et al. (1993) and Morala et al. (2008).

Toronto, Canada

The traffic control system projects became operational in 1975. The project was initially implemented on 42 ramps on Queen Elizabeth Way (QEW) linking Toronto with the Niagara Peninsula and Buffalo, New York. The broad aims for the project were increasing the efficiency of the motorway and nearby arterial service at the traffic peak period and minimizing the collision rate on the mainline. The project included installation of CCTV and loop-detector surveillance systems, microprocessor-based RM controls, and variable message signs. The traffic control system managed the metering rate periodically based on current traffic flow conditions on the mainline and entrance ramps to maximize throughput. According to the assessment of the effectiveness of the QEW, substantial improvements in travel time and a decrease in accident rates were achieved during its first two years of operation. Building on the success of this project, the Ontario Ministry of Transportation (MTO) implemented a state-of-the-art motorway traffic management system known as COMPASS. COMPASS has been in operation since 1990 and extends to Highway 401 in the greater Toronto area, Highway 403 and QEW in the Golden Horseshoe area, Highway 417 in the Ottawa area, and Highway 402 in Sarnia (Morala et al. 2008).

The Sydney Coordinated Adaptive Traffic System RM System

The Sydney Coordinated Adaptive Traffic System (SCATS) is the core functionality of the SCATS RM system (SRMS) method. The accumulated occupancy error between calibrated critical occupancy and measure occupancy is calculated to adjust RM rates. SRMS consists of four major modules: (1) data fusion of multiple traffic sources, (2) bottleneck location identification, (3) coordinated response of several ramps simultaneously, and (4) integration with arterial traffic signals. The latter module makes the SRMS less dependent on the manual operator once traffic spill backs to adjacent arterials of the motorway. For more detail on the SRMS algorithm, please refer to Amini et al. (2016, 2015a, b); Aydos and O'Brien (2014), and Kristeleit et al. (2016).

Auckland, New Zealand

New Zealand was the first country in Australasia to deploy coordinated RM, with the majority of work completed in Auckland during 2006–2008 (Aydos and O'Brien 2014). As part of the Travel Demand Management program, the New Zealand Transport Agency (NZTA) deployed 84 RMs, with 33 additional RMs planned for the Western Ring Route between Manukau and Albany as it was being built. The estimated cost of the project was $NZ 20–100 million (NZ Transport Agency 2014).

A before and after report was completed in 2013 for projects undertaken between 2005 and 2010. The sites included in this assessment only considered RM sites where the traffic impact could be primarily attributed to the RM deployment. A cost-benefit analysis of the RM implementation project was conducted based on the benefits identified by O'Brien (2014). The results indicated an average annual savings of $AUD 2 million per ramp meter. The direct benefits of the RM were assessed including: (1) throughput, (2) average speeds, (3) annual delay savings, and (4) crash reductions.

Challenges in Implementing and Evaluating RM

There are many challenges regarding both implementation and evaluation of RM strategies. Effective implementation of RM systems requires careful consideration of the local and network-wide traffic management implications. The primary aims for RM are reduction in traffic congestion and the improvement of safety on a motorway. However, these objectives are dependent on the following factors (Jacobson et al. 2006; Yang et al. 2020):

- Geographic extent of the RM system—determination of which motorway (or sections of motorway) should be metered;
- RM method of control—determination of whether a local or system-wide approach is suitable and if pretimed or traffic-responsive control methods should be utilized;
- RM algorithm—determination of specific logic used to calculate the metering rates for each of the ramps;
- Queue management/ramp volume control—understanding how the metering rate will be affected by ramp queues and determining a method to manage the presence of the queues; and
- Informational signage for public awareness of the system.

Prioritizing and accounting for all of the aforementioned factors is a challenge in itself. One of the vital steps in effective implementation of a RM strategy is selection of a metering approach and algorithm. Sound understanding of the approaches that are currently in operation is essential in assessing feasible options. Therefore, we provide an overview of real-life projects organized per type of algorithm in the section "RM Case Studies: Context and Results."

Furthermore, it is also imperative to identify or develop key performance indicators to measure the effectiveness and efficiency of RM strategies. Section "RM Case Studies: Context and Results," and in particular Tables 1 and 2, indicates that there is no universal and systemic evaluation approach consistently used across projects. Every project reports on different measures and uses different before-after evaluation methodology: (1) field evaluation; or (2) simulation-based evaluation.

As with MacCarley et al. (2002) and Haj-Salem et al. (2001) described in the section "RM Case Studies: Context and Results," the field evaluation study considers the performance of the network before and after RM implementation and is based on assessment of available field data. The test sites are selected to ensure that there is adequate data available and to isolate the impact of RM as much as possible. The advantage of this type of study is that: (1) safety analysis can be completed using changes in crash rates (Corcoran and Hickman 1989), (2) the assumptions that would be made for simulation-based analysis are avoided (e.g., growth rates, driver behavior, etc.), and (3) the analysis process is a significantly easier task than the development of a simulation model (Haj-Salem et al. 2001). A disadvantage is that the impact of geometric upgrades to capacity cannot be easily disentangled.

The simulation-based studies are typically conducted with microscopic and mesoscopic simulation software (Amini et al. 2016, 2015a, b; Karim 2015; Mitkas and Politis 2020; Scariza 2003). The advantage of this type of evaluation is that: (1) the direct comparison of different RM algorithms is possible, and (2) it does not include the variability that might be observed in the data from the field (e.g., day-to-day demand changes), offering a consistent base for comparison. However, as highlighted in the sections "Birmingham, England" and "Paris, France," simulation modeling involves a series of behavioral assumptions that can mask the potential advantages and disadvantages of RM. For example, it is challenging that a simulation captures the complex phenomena of capacity drop, which is directly linked to the congestion that RM intends to dissipate. The specification and analysis of the relation between the RM and the capacity drop is still an open research question and a limitation of simulation studies.

The RM evaluation process is based on the operational data collected either by the ITS equipment located in the system (in the case of field evaluation) or as a result of running a simulation scenario (in the case of simulation evaluation). Both data collection and analysis need to be carefully coordinated. The quality, type, and amount of information to collect has to be well thought through, because they are essential for assessment against the generic evaluation aspects and specific objectives of the project. Also, the selection, duration, and frequency of data collection are of critical importance, because the traffic behaves differently during peak hours, holidays, and weekends (RMS 2013).

The consolidated list of measures reported across all the reviewed projects, presented in Tables 1 and 2, is extensive. However, the majority of the measures were mentioned only once and for one project, reducing the ability to compare between projects. A large number of performance measures can be calculated to assess the impact of a RM system. Based on the review, it is evident that a comprehensive set of measures that every project should consistently report on needs to be defined and followed in practice. Thus, to be able to clearly identify both drawbacks and benefits of a specific implementation project, on the basis of comparison to the other known case studies, the following components are necessary: (1) a definition of a limited, but significant, set of measures; and (2) consistent data collection and reporting of these measures. Currently, the most commonly reported measures are travel speed (km/h), traffic volumes and throughput (vehicles/h/lane), travel time on the mainline (vehicles $\times$ h) and the crash rates. In addition, there is a need for a general holistic methodology, offering guidance for data collection and analysis, which when used consistently would allow for comparison of different projects with one another and in effect facilitate identification of the best implementation strategies for particular cases.

The majority of reviewed studies focused on the traffic performance of RM systems when evaluating different options, often ignoring important factors that are more difficult to quantify (e.g., resources required to acquire in-house expertise). A comprehensive methodology should involve the following:

1. Continued data collection;
2. Definition of a list of measures used for evaluation; and
3. In RM evaluation:
   - Cost estimation;
   - Benefit estimation, including field evaluation (based on collected real-life data) and simulation evaluation (based on collected simulation results), if possible; and
   - Cost-benefit analysis to understand overall economic value.

It is important to conduct a cost-benefit analysis of the major factors influencing the choice of RM systems. The importance of the cost-benefit analysis is reflected by the number of projects that have completed and reported such analyses (Austroads 2020). However, the execution of the cost-benefit analysis of a RM system is a challenging task considering that there are a large number of variables and aspects to consider. Depending on the policies of the agency that develops the system, different aspects and objectives receive varying levels of focus. Such contextual differences have resulted in a spectrum of cost-benefit evaluation methodologies that differ from project to project.

Complexity in the quantification of costs and benefits necessitates engineering judgement in order to define the inputs to an analysis. Furthermore, the case study review indicates that not all the costs and benefits are captured in the final appraisal, indicating the scope for inconsistency in such assessment methodologies. As an example, costs associated with ITS infrastructure development tend to be omitted, though there are instances where upgrades to available infrastructure are necessary. In a similar fashion, costs associated with training staff are also not considered. These costs have been considerable in the deployment of systems in Brisbane and Melbourne (Faulkner et al. 2014; Papamichail et al. 2010). In addition to RM strategies, other changes to the system such as infrastructure upgrades to the mainline and ramps of a network can also assist in the alleviation of congestion, making it difficult to disentangle benefits associated with the strategies alone. Thus, when conducting a cost-benefit analysis, these aspects need to be considered on a project-specific basis that is consistent to offer a platform for comparison.

Similarly, subjectivity involved when identifying, quantifying, and estimating different costs and benefits might add to the problem. Many costs and benefits are nonmonetary in nature and require an assignment of a monetary value for purposes of the overall project evaluation. The assigned monetary value is forecasted or estimated on the basis of past experiences and expectations. The latter may be biased. In effect, the subjective measures can potentially result in misleading results of the cost-benefit analysis.

The literature review, as documented in the section "RM Case Studies: Context and Results," also indicates that one of the most significant shortcomings in RM development is the limited understanding of the network-wide costs and benefits for users and transport authorities alike. A majority of studies evaluated RM strategies considering mainline performance in isolation to the impact on the surrounding arterial network. The evaluation methods have generally involved using field data assessments, simulation exercises, and/or capacity assessments. The inability to capture wider economic benefits is one of the main weaknesses of the cost-benefit analysis.

Disruptive technologies, especially sensor-based technology and information provision, can be leveraged to improve the implementation and evaluation of RM schemes. Data collection forms the foundation of calibrating RM systems and, more importantly, evaluating the performance of the implemented systems. Currently, standard data collection practice involves using in situ methods that require physical sensing apparatus such as inductive loops, weigh-in motion (WIM) sensors, and video image processing systems (VIPS) (Ni 2015). These systems are expensive to install and maintain, limiting network-wide utilization. This aspect has been a barrier to completing before and after studies within the RM domain, limiting the extent of evaluating such systems. Smart phone data, in-vehicle Bluetooth, and global positioning system (GPS) devices have formed a new option for traffic data collection through a means of participatory sensing (Burke et al. 2006), supplementing the existing sources. User locations, travel patterns, route selection, travel time, and vehicle speeds can all be collected from this format of crowd-sourced smartphone data, providing an alternative avenue for data collection and evaluation of RM projects.

The new data collection methods help network operators to understand the real traffic state before or after RM implementation. With traditional traffic measurement methods, including loop detectors and human surveys, the number of measured traffic sites was limited, and simultaneous measurement of the entire corridor was almost impossible. However, the new data collection methods and their integrations with artificial intelligence (AI) image processing provide the opportunity to measure various traffic attributes such as traffic volumes, speeds, and queues in a reasonable time and at a reasonable cost.

Overall, the comparison of various RM projects on the basis of results from the cost-benefit analysis remains a challenge.

Conclusions and Future Directions

The current survey of the global implementation of RM strategies provides practical insights on the challenges and opportunities for researchers and practitioners. The quantity of literature and the scale of implementation highlight the wide interest in the area and the potential for further development and research into the topic of RM.

In the current paper, information has been gathered from a variety of sources to develop a comprehensive understanding of RM systems deployed globally. This task constitutes the first step toward understanding of the solutions that are currently in place globally and the existing evaluation approaches. Future research and applications must lead toward a comprehensive methodology for RM systems evaluation to improve consistency and robustness of the application.

The review of outcomes obtained from the field deployments of RM shows that there have been many benefits derived from RM, including the reduction of motorway congestion, reduced travel times, redistribution and balance of network traffic, and enhanced road safety conditions. The opportunities, however, also bring various challenges. There are also a number of costs associated with RM, including the development of ramp queues, the degradation of surrounding arterial networks, and the equitable deployment of systems. These costs and benefits are affected by the method of control and the algorithm utilized at a particular site, highlighting the importance of the implementation procedure and the evaluation approach toward any RM deployment.

The overall evaluation of the particular RM strategy is a major challenge in itself. The current methodologies of evaluation of RM systems include: (1) the assessment and comparison of both the benefits of the evaluated RM system and the impacts and associated costs, i.e., cost-benefit analysis (the most desirable outcome is when the costs are clearly and significantly overweight by the benefits); (2) the identification and assessment of existing impacts of the evaluated RM system on both surface streets and transit operations; (3) the assessment of the attitudes and opinions of the community toward the evaluated RM system; and (4) a comparison of the evaluated RM system against other RM systems, either implemented in different geographical locations or deploying different algorithms.

Some of the key gaps that call for further attention in future studies are recognized and highlighted below.

Sytematic Approach for RM Evaluations

The observed evaluation methodologies themselves are varied and case-specific. This further indicates that there is a need for a systemic approach to estimating the advantages and disadvantages of the feasible RM systems. Methodologies must be developed to capture the impacts of RM on the arterial network, wider economic and social implications, and measures of equity across the community.

Using Advanced Multisource Traffic Data

Smartphone applications and real-time online information provision stemming from disruptive technologies can provide details of traffic congestion events guiding route choice. In addition, this technology can be used to inform motorists regarding the presence of RM across the network and educate drivers on the need and benefits of the metering scheme. Such initiatives could potentially enhance the benefits of RM while concurrently removing the disadvantages associated with societal perceptions of these systems. The aforementioned opportunities will be further enhanced through the adoption of connected and autonomous vehicles. The vehicle-to-vehicle and vehicle-to-infrastructure connectivity can be used to enforce RM compliance, optimizing the benefits of the system.

Education and Information Provision

Another key finding in the review of RM projects is the lack of education and information provision surrounding the implementation of metering. This aspect has been noted in deployments within Auckland and Minnesota in particular, where public perception has affected the functionality and value of the system.

Other Aspects of RM Implementations

Researchers and practitioners can also further develop the quantification of supplementary aspects such as health benefits (e.g., effects of reduced stress when merging), user satisfaction and compliance, and effects of network upgrades (e.g., ramp geometry, ITS improvements such as TV cameras or variable message signs). These factors have not been mentioned in the reviewed papers but are important aspects that have been identified in concluding statements of implementation reports.

In summary, the metering approach and algorithm are vital components in the effective implementation of a RM strategy. Accordingly, a sound understanding of the approaches currently present is essential in developing evaluation criteria to assess the feasible RM options. It is also essential to understand existing metrics that have been used to measure the effectiveness and efficiency of RM strategies. There is a clear message across all the reviewed case studies that RM strategies are a viable traffic management technique that tends to enhance the performance of the road network. Accordingly, the review presented in this study can provide a foundation for the further development of the RM technology and the improved implementation of RM strategies.

Data Availability Statement

No data, models, or code were generated or used during the study.

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References

Ahn, S., R. Bertini, B. Auffray, J. Ross, and O. Eshel. 2007. "Evaluating benefits of systemwide adaptive ramp-metering strategy in Portland, Oregon." *Transp. Res. Rec.* 2012 (1): 47–56. https://doi.org/10.3141/2012-06.

Amini, N., C. Aydos, H. Grzybowska, K. P. Wijayaratna, V. Dixit, and S. T. Waller. 2016. "Network-wide evaluation of the state-of-the-art coordinated ramp metering solutions." In *Proc., Transportation Research Board 95th Annual Meeting*, 1–19. Washington, DC: Transportation Research Board.

Amini, N., C. Aydos, K. Wijayaratna, H. Grzybowska, and T. Waller. 2015a. "A network wide evaluation of the SCATS ramp metering system using microsimulation." In *Proc., 37th Australasian Transport Research Forum*. Sydney, Australia: Australasian Transport Research Forum.

Amini, N., H. Grzybowska, K. Wijayaratna, and S. T. Waller. 2015b. "Systemic evaluation of the HERO-based ramp metering algorithm using microsimulation: Demonstration analysis using a Sydney motorway." In *Proc., 2015 IEEE 18th Int. Conf. on Intelligent Transportation Systems*, 2287–2292. New York: IEEE.

Arnold, E. D., Jr. 1998. *Ramp metering: A review of the literature*. Charlottesville, VA: Virginia DOT.

Austroads. 2020. *Guide to traffic management Part 4: Network management strategies*. Sydney, Australia: Austroads.

Aydos, J. C., and A. O'Brien. 2014. "SCATS ramp metering: Strategies, arterial integration and results." In *Proc., 17th Int. IEEE Conf. on Intelligent Transportation Systems (ITSC)*, 2194–2201. New York: IEEE.

Bélisle, F., L. Torres, P. Volet, D. K. Hale, and A. Avr. 2019. "Evaluating the HERO ramp-metering algorithm with San Diego's integrated corridor management system model." *Transp. Res. Rec.* 2673 (12): 354–366. https://doi.org/10.1177/0361198119858078.

Bertini, R. L., S. Hansen, A. Byrd, and T. Yin. 2005a. "PORTAL: Experience implementing the ITS archived data user service in Portland, Oregon." *Transp. Res. Rec.* 1917 (1): 90–99. https://doi.org/10.1177/0361198105191700111.

Bertini, R. L., S. Hansen, S. Matthews, and A. Delcambre. 2005b. "PORTAL: Implementing a new generation archived data user service in Portland, Oregon." In *Proc., 12th World Congress on Intelligent Transport Systems*. San Francisco: ITS America.

Bielefeldt, C., et al. 2007. "EURAMP (European Ramp Metering Project). Deliverable 6.3: Evaluation results." Accessed December 17, 2007. http://researchrepository.napier.ac.uk/id/eprint/1989/.

Bogenberger, K., and H. Keller. 2001. "An evolutionary fuzzy system for coordinated and traffic responsive ramp metering." In *Proc., 34th Annual Hawaiian Int. Conf. on System Sciences*, 10. New York: IEEE. https://doi.org/10.1109/HICSS.2001.926333.

Bogenberger, K., and A. D. May. 1999. "Advanced coordinated traffic responsive ramp metering strategies." In *California partners for advanced transit and highways*. UCB-ITS-PWP-99-1. Berkeley, CA: Univ. of California, Berkeley.

Burke, J. A., D. Estrin, M. Hansen, A. Parker, N. Ramanathan, S. Reddy, and M. B. Srivastava. 2006. "Participatory sensing." In *Proc., ACM SenSys Workspace World-Sensor-Web*. Boulder, CO: ACM SenSys.

Burley, M., and J. Gaffney. 2010. *Managed freeways: Freeway ramp signals handbook*. Kew, VIC, Australia: Network and Asset Planning, VicRoads.

Chu, L., H. X. Liu, W. Recker, and H. M. Zhang. 2004. "Performance evaluation of adaptive ramp-metering algorithms using microscopic traffic simulation model." *J. Transp. Eng.* 130 (3): 330–338. https://doi.org/10.1061/(ASCE)0733-947X(2004)130:3(330).

Chu, L., W. Recker, and G. Yu. 2009. *Integrated ramp metering design and evaluation platform with Paramics*. Tech. Rep. No. UCB-ITS-PRR-2009-10. Berkeley, CA: California PATH program Institute of Transportation Studies Univ. of California, Berkeley.

Corcoran, L. J., and G. A. Hickman. 1989. "Freeway ramp metering effects in Denver." In *Proc., 59th Annual Meeting, Institute of Transportation Engineers Meeting*. San Diego: Institute of Transportation Engineers.

EURAMP (European Ramp Metering Project). 2014. "Deliverable D.3 evaluation results. Version: 1.0." Accessed October 8, 2007. http://www.transport-research.info/web/projects/project/.

Faulkner, L., F. Dekker, D. Gyles, I. Papamichail, and M. Papageorgiou. 2014. "Evaluation of HERO-coordinated ramp metering installation at M1 and M3 freeways in Queensland, Australia." *Transp. Res. Rec.* 2470 (1): 13–23. https://doi.org/10.3141/2470-02.

Ferrara, A., S. Sacone, and S. Siri. 2018. "An overview of traffic control schemes for freeway systems." In *Freeway traffic modelling and control*, 193–234. New York: Springer.

Frejo, J. R. D., and B. De Schutter. 2018. "Feed-forward ALINEA: A ramp metering control algorithm for nearby and distant bottlenecks." *IEEE Trans. Intell. Transp. Syst.* 20 (7): 2448–2458. https://doi.org/10.1109/TITS.2018.2866121.

Geroliminis, N., A. Srivastava, and P. Michalopoulos. 2011. "A dynamic-zone-based coordinated ramp-metering algorithm with queue constraints for Minnesota's freeways." *IEEE Trans. Intell. Transp. Syst.* 12 (4): 1576–1586. https://doi.org/10.1109/TITS.2011.2164792.

Gokasar, I., K. Ozbay, and P. Kachroo. 2013. "Coordinated feedback-based freeway ramp metering control strategies C-MIXCROS and D-MIXCROS that take ramp queues into account." In *Advances in dynamic network modeling in complex transportation systems*, 67–88. New York: Springer.

Haj-Salem, H., P. Poirier, J.-F. Heylliard, and J.-P. Peynaud. 2001. "Alinea: A local traffic responsive strategy for ramp metering. Field results on A6 motorway in Paris." In *Proc. Intelligent Transportation Systems*, 106–111. New York: IEEE.

Hayden, J., R. Higginson, M. Hall, and S. Ubhi. 2009. "Improvements to ramp metering system in England: VISSIM modelling of improvements." In *Proc., 16th ITS World Congress and Exhibition on Intelligent Transport Systems and Services*. Stockholm, Sweden: ITS America.

Highways Agency. 2007. *Ramp metering: Summary report*. Tech. Rep. No. 5053147-04-02141. Bristol, UK: Highways Agency Publications.

Highways Agency. 2008. *Ramp metering: Operational assessment*. Tech. Rep. No. 505314704-02-027. Bristol, UK: Highways Agency Publications.

Jacobson, L., J. Stribiak, L. Nelson, and D. Sallman. 2006. *Ramp management and control handbook*. Washington, DC: United States Federal Highway Administration.

Kan, Y., Y. Wang, M. Papageorgiou, and I. Papamichail. 2016. "Local ramp metering with distant downstream bottlenecks: A comparative study." *Transp. Res. Part C: Emerging Technol.* 62: 149–170. https://doi.org/10.1016/j.trc.2015.08.016.

Karim, H. K. 2015. "Exploratory analysis of ramp metering on efficiency, and safety of freeways using microsimulation." Ph.D. dissertation, Dept. of Civil, Environmental and Architectural Engineering, Univ. of Kansas.

Kontorinaki, M., I. Karafyllis, and M. Papageorgiou. 2019. "Local and coordinated ramp metering within the unifying framework of an adaptive control scheme." *Transp. Res. Part A: Policy Pract.* 128 (Oct): 89–113.

Kristeleit, T. P., B. Bracher, K. Bogenberger, and R. L. Bertini. 2016. *Ramp metering-algorithms and implementations: A worldwide overview*. Research Rep. No. 59. Munich, Germany: Univ. of Munich.

Lam, J., J. Kerr, P. Korpal, and C. Rayman. 1993. "Development of COMPASS—An advanced traffic management system." In *Proc., VNIS'93-Vehicle Navigation and Information Systems Conf.*, 200–203. New York: IEEE.

Lau, D. 2001. *Minnesota Department of Transportation: Stratified metering algorithm*. Minneapolis, MN: Minnesota DOT.

Lau, R. 1997. *Ramp metering by zone—The Minnesota algorithm*. Minneapolis, MN: Minnesota DOT.

Levinson, D., and L. Zhang. 2006. "Ramp meters on trial: Evidence from the Twin Cities metering holiday." *Transp. Res. Part A: Policy Pract.* 40 (10): 810–828.

Lipp, L. E., L. J. Corcoran, and G. A. Hickman. 1991. "Benefits of central computer control for Denver ramp-metering system." *Transp. Res. Rec.* 1320 (1): 3–6.

MacCarley, A. C., S. Mattingly, M. McNally, D. Mezger, and J. Moore. 2002. "Field operational test of integrated freeway ramp metering/arterial adaptive signal control: Lessons learned in Irvine, California." *Transp. Res. Rec.* 1811 (1): 76–83. https://doi.org/10.3141/1811-09.

Middelham, F., and H. Taale. 2006. "Ramp metering in the Netherlands: An overview." In *Proc., 11th IF AC Symp. on Control in Transportation Systems*, 267–272. Delft, Netherlands: Delft Univ. of Technology.

Mitkas, D.-Z., and I. Politis. 2020. "Evaluation of alternative ramp metering scenarios on freeway on-ramp with the use of microscopic simulation software Vissim." *Transp. Res. Procedia* 45: 483–490. https://doi.org/10.1016/j.trpro.2020.03.042.

Monsere, C. M., R. L. Bertini, S. Ahn, and O. Eshel. 2008. *Using archived ITS data to measure the operational benefits of a system-wide adaptive ramp metering system*. Tech. Rep. No. 01135250. Washington, DC: Federal Highway Administration.

Morala, E., M. Eng, P. Eng, H. Wong, and K. Wong. 2008. "Systems architecture for the next generation COMPASS software." In *Proc., Annual Conf. of the Transportation Association of Canada*. Toronto: Transportation Association of Canada.

Muhurdarevic, Z., H. Condie, E. Ben-Shabat, O. Ernhofer, H. Hadj-Salem, and I. Papamichail. 2006. "Ramp metering in Europe—State-of-art and beyond." In *Proc., 5th Int. Conf. on Traffic and Transportation Studies (ICTTS)*. Xi'an, China: International Conferences on Traffic and Transportation Studies.

Ni, D. 2015. *Traffic flow theory: Characteristics, experimental methods, and numerical techniques*. Boston: Butterworth-Heinemann.

NZ Transport Agency. 2014. "Ramp signaling." Accessed December 21, 2014. http://www.nzta.govt.nz/projects/rampsignalling/.

O'Brien, A. 2014. *SCATS ramp signalling—Safety and operational outcomes in Auckland NZ*. Wellington, New Zealand: IPENZT Transport Group, Wellington.

O'Brien, A., and P. McCombs. 2007. "Auckland adaptive ramp metering project." In *Proc., ITE Annual Meeting and Exhibit*. Pittsburgh: Institute of Transportation Engineers.

Papageorgiou, M., J.-M. Blosseville, and H. Hadj-Salem. 1990a. "Modelling and real-time control of traffic flow on the southern part of Boulevard Périphérique in Paris: Part I: Modelling." *Transp. Res. Part A: General* 24 (5): 345–359. https://doi.org/10.1016/0191-2607(90)90047-A.

Papageorgiou, M., J.-M. Blosseville, and H. Hadj-Salem. 1990b. "Modelling and real-time control of traffic flow on the southern part of Boulevard Périphérique in Paris: Part II: Coordinated on-ramp metering." *Transp. Res. Part A: General* 24 (5): 361–370. https://doi.org/10.1016/0191-2607(90)90048-B.

Papageorgiou, M., C. Diakaki, V. Dinopoulou, A. Kotsialos, and Y. Wang. 2003. "Review of road traffic control strategies." *Proc. IEEE* 91 (12): 2043–2067. https://doi.org/10.1109/JPROC.2003.819610.

Papageorgiou, M., H. Hadj-Salem, and J.-M. Blosseville. 1991. "ALINEA: A local feedback control law for on-ramp metering." *Transp. Res. Rec.* 1320 (1): 58–64.

Papageorgiou, M., H. Hadj-Salem, and F. Middelham. 1997. "ALINEA local ramp metering: Summary of field results." *Transp. Res. Rec.* 1603 (1): 90–98. https://doi.org/10.3141/1603-12.

Papageorgiou, M., and I. Papamichail. 2007. *Handbook of ramp metering. Deliverable 7.5*. Brussels, Belgium: EURAMP.

Papamichail, I., and M. Papageorgiou. 2008. "Traffic-responsive linked ramp-metering control." *IEEE Trans. Intell. Transp. Syst.* 9 (1): 111–121. https://doi.org/10.1109/TITS.2007.908724.

Papamichail, I., M. Papageorgiou, V. Vong, and J. Gaffney. 2010. "Heuristic ramp-metering coordination strategy implemented at Monash Freeway, Australia." *Transp. Res. Rec.* 2178 (1): 10–20. https://doi.org/10.3141/2178-02.

Pham, H., et al. 2002. *SWARM study final report on W/B Foothill Freeway (W/B LA-210)*. Sacramento, CA: California DOT.

RMS (Roads and Maritime Services). 2013. *Traffic model ling guidelines*-Sydney, Australia: RMS.

Samad, T., and A. E. Annaswamy. 2011. "The impact of control technology." In Vol. 31 of *Proc., IEEE Control Systems Society*, 26–27. New York: IEEE.

Scariza, J. R. 2003. "Evaluation of coordinated and local ramp metering algorithm using microscopic traffic simulation." Ph.D. dissertation, Dept. of Civil and Environmental Engineering, Massachusetts Institute of Technology.

Shaaban, K., M. A. Khan, and R. Hamila. 2016. "Literature review of advancements in adaptive ramp metering." *Procedia Comput. Sci.* 83: 203–211. https://doi.org/10.1016/j.procs.2016.04.117.

Smaragdis, E., M. Papageorgiou, and E. Kosmatopoulos. 2004. "A flow-maximizing adaptive local ramp metering strategy." *Transp. Res. Part B: Methodol.* 38 (3): 251. https://doi.org/10.1016/S0191-2615(03)00012-2.

Stylianopoulou, E., M. Kontorinaki, M. Papageorgiou, and I. Papamichail. 2020. "A linear- quadratic-integral regulator for local ramp metering in the case of distant downstream bottlenecks." *Transp. Lett.* 12 (10): 723–731. https://doi.org/10.1080/19427867.2019.1700005.

Taale, H., J. Slager, and J. Rosloot. 1996. "The assessment of ramp metering based on fuzzy logic." In *Proc., 3rd ITS World Congress*. Brussels, Belgium: European Road Transport Telematics Implementation Coordination Organization.

Taylor, C. E., and D. R. Meldrum. 2000. *Evaluation of a fuzzy logic ramp metering algorithm: A comparative study among three ramp metering algorithms used in the greater Seattle area*. Olympia, WA: Washington State DOT.

Vanderschuren, M. 2006. "Intelligent transport systems for South Africa: Impact assessment through microscopic simulation in the South African context." Ph.D. thesis, TRAIL Research School, Univ. of Twente.

Vong, V., and J. Gaffney. 2009. "Monash-CityLink-West Gate upgrade project: Implementing traffic management tools to mitigate freeway congestion." In *Proc., 2nd Int. Symp. on Freeway and Tollway Operations*. Washington, DC: Transportation Research Board.

Vukanovic, S., and O. Ernhofer. 2006. "Evaluation and field implementation of the fuzzy logic based ramp metering algorithm ACCEZZ." In *Proc., 2006 IEEE Intelligent Transportation Systems Conf.*, 437–441. New York: IEEE.

Wang, Y., E. B. Kosmatopoulos, M. Papageorgiou, and I. Papamichail. 2014. "Local ramp metering in the presence of a distant downstream bottleneck: Theoretical analysis and simulation study." *IEEE Trans. Intell. Transp. Syst.* 15 (5): 2024–2039. https://doi.org/10.1109/TITS.2014.2307884.

Xin, W., P. Michalopoulos, J. Hourdakis, and D. Lau. 2004. "Minnesota's new ramp control strategy: Design overview and preliminary assessment." *Transp. Res. Rec.* 1867 (1): 69–79. https://doi.org/10.3141/1867-09.

Xu, J., X. Zhao, and D. Srinivasan. 2013. "On optimal freeway local ramp metering using fuzzy logic control with particle swarm optimization." *IET Intel. Transport Syst.* 7 (1): 95–104. https://doi.org/10.1049/iet-its.2012.0087.

Yang, G., Z. Wang, Z. Tian, L. Y. Zhao, and H. Xu. 2020. "Geometric design of metered on-ramps: State-of-the-practice and remaining challenges." *Transp. Lett.* 12 (9): 649–658. https://doi.org/10.1080/19427867.2019.1677067.

Yuan, Y. 2008. "Coordination of ramp metering control in motorway networks." Unpublished Master's thesis, Transport & Planning Dept. of Faculty of Civil Engineering and Geo-Science, Delft Univ. of Technology.

Zhang, L., and D. Levinson. 2010. "Ramp metering and freeway bottleneck capacity." *Transp. Res. Part A: Policy Pract.* 44 (4): 218–235.

Zhang, M., T. Kim, X. Nie, W. Jin, L. Chu, and W. Recker. 2001. Vol. 95616 of *Evaluation of on-ramp control algorithms*. Berkeley, CA Berkeley: Institute of Transportation Studies, University of California.

Zhao, L., Z. Li, Z. Ke, and M. Li. 2019. "Distant downstream bottlenecks in local ramp metering: Comparison of fuzzy self-adaptive PID controller and PI-ALINEA." In *Proc., CICTP 2019*, 2532–2542. Reston, VA: ASCE.