OPTIMISING TRAFFIC DISTRIBUTION ON MOTORWAYS AND ARTERIALS: A GLOBAL COMPARISON OF RAMP-METERING ALGORITHMS

M.-C. ESPOSITO
Sétra (Service d'Etudes sur les Transports, les Routes et leurs Aménagements),
Ministry in charge of Transport, France
marie-christine.esposito@developpement-durable.gouv.fr
J. W. POLAK & R. KRISHNAN
Centre for Transportation Studies, Imperial College London, UK
j.polak@imperial.ac.uk, rajesh.k@imperial.ac.uk
M. PLEYDELL
telent Traffic Technology, UK
Pleydell Technology Consulting Ltd, UK
mark.pleydell@p-t-c.co.uk

ABSTRACT

The objective of this paper is to compare different ramp-metering algorithms in terms of the compromise they establish between delays to traffic on motorways and on arterial roads. Two different types of local ramp-metering were compared in a simulated environment: the ALINEA algorithm with a feedback philosophy and the Demand-Capacity algorithm with a feed-forward philosophy. The main conclusion of this work is that the combination of ramp-metering algorithm, green time policy and ramp queue management strategy should consider impacts on the entire road system, i.e., an integrated policy is necessary between motorway and arterial road operators while implementing traffic control policies. This work has also shown that the best integrated policy may be different depending on the traffic condition on the motorway and the arterials. A worthwhile direction for future research would be the development of an algorithm to identify the best ramp-metering algorithm during a given traffic situation.

1. INTRODUCTION

Congestion on motorways is a widespread phenomenon resulting in delays, reduced traffic safety and increased fuel consumption and air pollution. Congestion on motorways is caused by a wide range of factors including excess demand, incidents and accidents, queues on arterial roads that spill over onto the motorway or peaks in demand resulting from the platooned entry of vehicles from on-ramps. On-ramp metering aims to reduce the effects of these problems by regulating vehicular access to the motorway. Typically, ramp-metering is implemented using traffic signals at motorway on-ramps to control the rate at which vehicles enter the motorway. The signal timings can be set for achieving the required metering rate to optimise motorway flow and minimise congestion.

However, while reducing congestion on the motorway, ramp-metering may cause the traffic to spill over onto feeder arterial roads as the on-ramp queue length increases, especially when the flow on the motorway is high. Thus, when implementing ramp-metering, it is desirable to understand the nature of the trade-off between delays on motorways and arterial roads. This issue is all the more difficult to deal with when the motorway operator is different from the arterial road operator, and consequently these issues are not typically tackled. In France, national road operators are currently deploying such traffic control strategies and acting in consultation with other operators, especially local ones, cannot be easily done.

The objective of this paper is to compare different ramp-metering algorithms in terms of the compromise they establish between delays to traffic on motorways and on arterial roads. To ensure relevance to practice, the comparison is restricted to those algorithms that can be implemented within a typical signal controller device.

2. BACKGROUND

Three kinds of ramp-metering systems can be distinguished:

- static control [3] where beacons or physical barriers restrict the maximum entry rate of vehicles into the motorway.
- fixed time control implemented with ordinary traffic signals using a fixed metering rate based on historically averaged traffic conditions,
- traffic responsive strategies in which real-time motorway and ramp data are used to determine the metering rate.

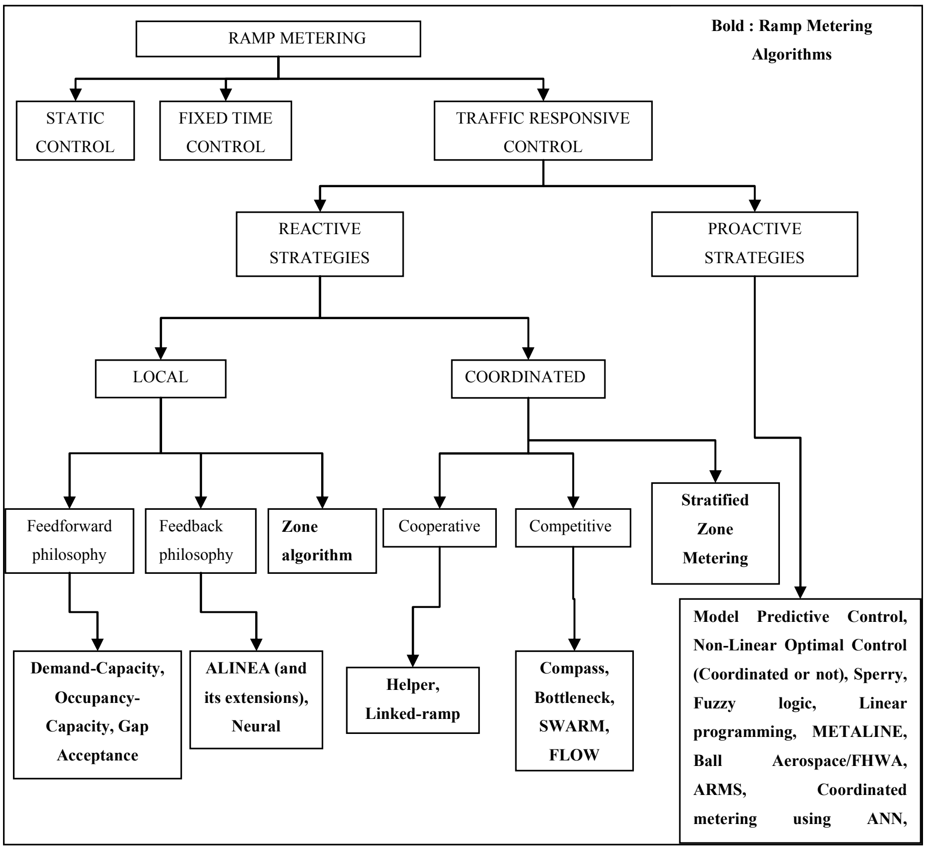


Figure 1 – Classification of Ramp-Metering Strategies

This paper focuses on traffic-responsive strategies. These strategies can be divided into two broad categories. Reactive strategies aim to maintain motorway conditions close to pre-determined desirable state, based on measurement of the traffic current state. Proactive strategies aim to achieve optimal traffic conditions based on measurement of the current state and prediction of the state [8].

Reactive strategies are usually linear algorithms whereas proactive strategies optimise a non-linear objective function based on a macroscopic traffic flow model that can take into account several aspects of network performance (e.g., total travel time over the freeway or environmental effects). Proactive strategies in principle have stronger theoretical foundations and greater flexibility in handling different types of metering constraints. However, their complex logic and the associated computational requirements currently limit the scope of their practical deployment but this constraint will reduce as micro-processors become faster, smaller and cheaper over time.

Reactive strategies ramp-metering can be further divided into two broad groups: local and coordinated strategies.

A coordinated traffic responsive ramp-metering plan works based on current traffic information but with individual ramps being metered jointly to optimise the motorway traffic flow. This approach was first implemented in the 1970's and has gradually spread to many freeway control systems [1]. A disadvantage of the coordinated strategy is its complexity and the cost to implement and maintain it due to its requirement for communications and a central computing facility.

Local control, on the other hand, calculates the metering rate based on prevailing traffic conditions in the vicinity of the ramp; typically, occupancy or flow data from detectors on the ramp and on the motorway are used as input. It was first implemented in the 1960's in the US and continues in many locations today [1]. The advantage of this approach is its relative simplicity and the ability to implement a local control plan. The disadvantage is the lack of coordination between metering on adjacent ramps in order to optimise the traffic flow on the motorway. As this paper focuses on those algorithms that can be implemented within a typical signal controller device, only local ramp-metering algorithms were considered. There are two main philosophies in local control.

2.1. Feed-forward philosophy

First, there are reactive traffic responsive algorithms which adjust metering rates after motorway congestion has already occurred. The main drawback of this approach is that it adjusts the metering rates only after motorway congestion has already occurred and in a rather simplistic manner.

- Demand-Capacity algorithm:

at each cycle k (k = 1, 2, 3...), metering rate r(k) is determined as:

$$r(k) = \begin{cases} q_{cap} - q_{in}(k) \; if \; o_{out} \leq o_{cr} \\ r_{min} \;\; otherwise \end{cases} \tag{1}$$

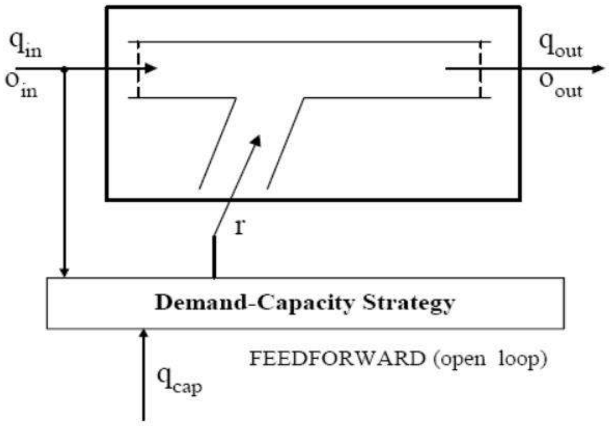


Figure 2 – Demand-Capacity strategy (source: [8])

The metering rate is calculated based on the traffic volume q_{in} upstream of the merge area and comparing this demand with the capacity q_{cap} of the bottleneck as determined by historical data. However, since traffic volume alone is insufficient to determine whether the motorway is congested or free-flowing, occupancy o_{out} measured from the downstream detector stations is also used. If the occupancy is above a preset threshold o_{cr} determined using historical data, congested flow is assumed to exist and the minimum metering rate

r_{min} is used. If not, the upstream volume is compared with capacity to determine the ramp-metering rate.

- Percent-Occupancy (PO) strategy:

The difference with the DC strategy lies into two points: the upstream demand is estimated using occupancy measurements and congestion is detected by the upstream detector. It then only needs one detector overall. The final form of the PO strategy is depicted in figure 3. The critical value of the upstream occupancy is specified by use of historical data and the transition value is found by trial-and-error in accordance to the historical on-ramp demand. The formula of the metering rate is ([7]):

at each cycle k: $r(k) = K_1 - K_2 o_{in}(k-1)$ (2)

where K_1 and K_2 are two constants respectively the capacity flow and a constant based on slope of a straight line approximation of the uncongested part of the fundamental diagram.

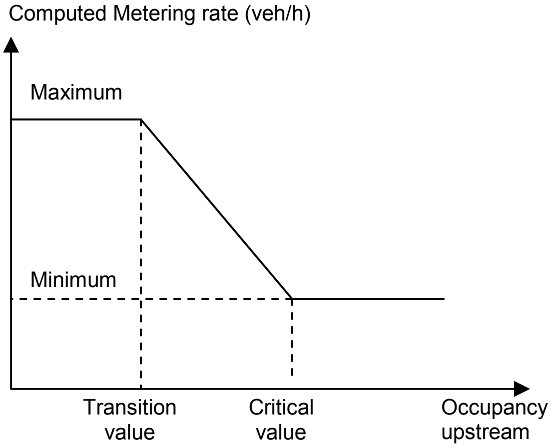


Figure 3 – Percent-Occupancy strategy (source: [3])

- Demand-Capacity INRETS:

This strategy is a modified version of the DC described above [3]. It utilises measurements from three mainstream detector stations in order to better estimate the degree of congestion and react accordingly. Under free-flowing conditions and under severe congestion conditions, this strategy reacts in the same way as DC. There are however a series of (typically two) intermediary traffic situations where the ramp-metering rate is calculated by use of the following equation:

$$r(k) = \beta q_{in}(k) - q_{out}(k) \quad (3)$$

So, the capacity utilised in the DC strategy is now replaced by the actually measured downstream volume and a parameter β is utilised taking the values 1 for rather slight congestion and 0.9 for stronger congestion.

- Gap acceptance control:

It sets metering rates based on occupancy measurements taken upstream of the ramp during the previous period and the ramp signals turn green in response to the detection of an available gap in the merging lane on the freeway such that the ramp vehicle has adequate time to accelerate and merge into the gap. However, this method assumes constant gap between vehicles and no lane changing between the upstream detector and the ramp, which are hypothesis that should be discussed [6].

2.2. Feedback philosophy

These are ramp-metering algorithms that try to avoid motorway congestion before it occurs. This approach is theoretically more robust than feed-forward systems [7], and is based on downstream measurements as opposed to upstream measurements. The main example of this approach is ALINEA ("Asservissement LINéaire d'Entrée Autoroutière" meaning "Linear Overriding Control of Motorway On-Ramp"). ALINEA adjusts the metering rate to keep the occupancy downstream of the on-ramp at a pre-specified level, called the occupancy set-point $\hat{o}$ (typically, set equal or slightly lower than the critical occupancy o_{cr}, the occupancy at capacity) according to the formula given below:

$$r(k) = r(k-1) + K_R(\hat{o} - o_{out}(k-1)) \tag{4}$$

where, r(k) is the metering rate at cycle k, K_R *a regulation parameter and* $o_{out}(k-1)$ *the measured downstream occupancy.*

The use of occupancies rather than volumes is justified by the fact that the same traffic volume may appear for non-congested and for congested traffic conditions due to the inverse U-shape of the fundamental diagram (figure 4).

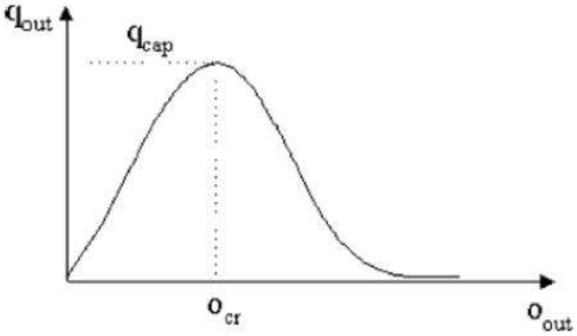


Figure 4 – The fundamental diagram (source: [9])

As it is one of the most commonly used algorithms, it has been extended in many studies to try to optimise its performance and several improvements exist.

- MALINEA:

Oh and Sisiopiku [5] suggests that the downstream measurements alone may lead to errors due to dual possible modes on the upstream of the ramp (congested and uncongested). They then propose the algorithm MALINEA to deal with this issue, that is to say, introducing an upstream measurement-based ramp-metering model. MALINEA helps deal with another issue as well, the fact that the optimal detector location can be difficult to determine. MALINEA then measures the upstream occupancy o_{in} and accepts as parameters a regulator parameter K, the slope of the curve relating the downstream and upstream occupancies A and the time lag between the upstream and downstream measurements n. The equation is the following:

$$r(k) = r(k-1-n) + \frac{K}{A}[\hat{o}(k+n) - o_{in}(k-1)] \tag{5}$$

based on the relationship: $o_{in}(k) = A\, o_{out}(k)$ (6)

MALINEA demonstrates superior performance when compared to ALINEA using several measures of effectiveness in a simulated environment. However, many issues were reported and more testing was needed [5].

- UP-ALINEA:

Smaragdis and Papageorgiou [8] suggest a similar idea in their model called UP-ALINEA. The reason for this use is also to be able to use upstream measurements previously implemented to use DC or PO strategies. Here, the relationship between upstream and downstream estimate measurements is given by:

$$\tilde{o}_{out}(k) = o_{in}(k)\left[1 + \frac{q_{ramp}(k)}{q_{in}(k)}\right]\frac{\lambda_{in}}{\lambda_{out}} \tag{7}$$

where λ_{in} *and* λ_{out} *are respectively the number of mainstream lanes upstream and downstream of the ramp and* q_{ramp} *and* q_{in} *are respectively the measured ramp flow entering the freeway and the measured upstream flow.*

Thus, UP-ALINEA is given by: $r(k) = r(k-1) + K_R\left(\hat{o} - \tilde{o}_{out}(k-1)\right)$ (8)

with $\tilde{o}_{out}(k-1)$ *given by the previous equation.*

In the same paper, Smaragdis and Papageorgiou [8] states that Oh and Sisiopiku [5] had considered *A* constant but it depends on the ratio $\frac{q_{ramp}}{q_{in}}$ that is not constant. However, the results of UP-ALINEA compared with ALINEA in different simulation scenarios are not significantly better.

- FL-ALINEA:

They also introduced algorithms that use flow-based set values and not occupancy-based that are not readily related to the classic traffic flow variables.
Indeed, it may be easier to specify set values for flows than for occupancies [8]. A flow-based version of ALINEA is then:

$$r(k) = \begin{cases} r(k-1) + K_F[\hat{q} - q_{out}(k-1)] \;\; if \; o_{out}(k-1) \leq o_{cr} \\ r_{min} \; otherwise \end{cases} \tag{9}$$

The upper part of the equation attempts to stabilise the flow q_{out} around the set value $\hat{q}$ as long as the occupancy is undercritical because under this condition, the flow is determined in a unique way. When the occupancy is overcritical, the rate should be fixed to a minimum. This last case should not be used very often not to irritate the drivers and to avoid this, the set value $\hat{q}$ should not be close or equal to q_{cap}. If so, FL-ALINEA is not recommended. Furthermore, q_{cap} might not be known in reality and the algorithm might target a value that is not attainable in real traffic. Hence, Smaragdis and Papageorgiou [8] do not recommend it as a flow-maximising ramp-metering strategy.

- UF-ALINEA:

They also tried to combine the previous two in Upstream-Flow Based ALINEA.
The equation to operate flow-based ALINEA based on measurements collected upstream of the ramp is:

$$r(k) = \begin{cases} r(k-1) + K_F[\hat{q} - \tilde{q}_{out}(k-1)] \;\; if \; \tilde{o}_{out}(k-1) \leq o_{cr} \\ r_{min} \; otherwise \end{cases} \tag{10}$$

with $\tilde{q}_{out} = q_{in} + q_{ramp}$ and $\tilde{o}_{out}(k) = o_{in}(k)\left[1 + \frac{q_{ramp}(k)}{q_{in}(k)}\right]\frac{\lambda_{in}}{\lambda_{out}}$ (11)

This algorithm is very similar to the DC strategy (if $K_F = 1$, $q_{ramp}(k-1)=r(k-1)$ and $\hat{q} = q_{cap}$) and then share some of its weaknesses.

- AD-ALINEA (Adaptative ALINEA):

In 2004, the same authors along with Kosmatopoulos [9] proposed algorithms that allow the automatic tracking of the critical occupancy to help maximise the mainstream flow.

Whenever the downstream flow maximisation is the goal of ALINEA, the set value $\hat{o}$ should be set equal to the critical occupancy o_{cr} which must be known before ALINEA can be applied to this end. However, this value may change in real time, especially in a more comprehensive network-wide strategy. In their paper, their approach is to design an estimation algorithm that utilises real-time measurements $q_{out}(k-1)$ and $o_{out}(k-1)$ and attempts to produce estimates $\tilde{o}_{cr}(k)$ of the currently prevailing critical occupancy, for which the freeway flow q_{out} is maximised. The produced estimates are subsequently used as set values by the ordinary ALINEA strategy (figure 5).

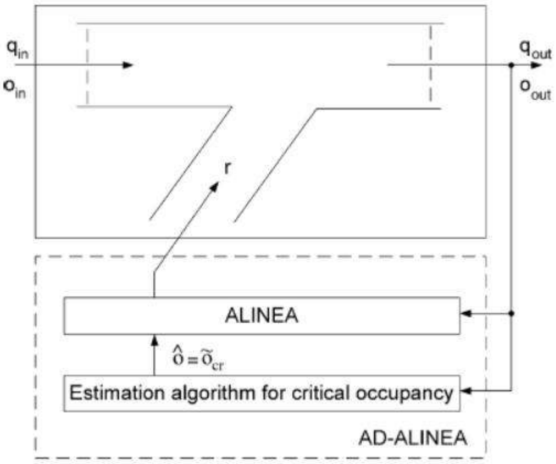


Figure 5 – Basic structure of AD-ALINEA (source: [9])

- AU-ALINEA:

As for UP-ALINEA, it could be useful to have an upstream version of AD-ALINEA [9]. The same approach is adopted as for UP-ALINEA in this case, using the same equations to obtain the measurements and then the procedure is the same as in AD-ALINEA.

2.3. Queue management strategy

The previously discussed ramp-metering strategies, in general, use ramp-queue override tactics to avoid the build-up of long queues on the ramp that result in congestion in the arterial road network: if the queue on the ramp becomes excessive, the running traffic responsive strategy is replaced by the fixed-time strategy.

Another queue management strategy is X/Q, which was developed as an extension to ALINEA termed ALINEA-Q [8], which balances the motorway flows with the queue length on-ramp. Video detectors rather than Inductive Loop Detectors (ILDs) can be used to obtain an estimate of the ramp queue length. Using this estimate, a queue metering rate is computed at the next time step so that the queue length stays close to its set value *w* as follows:

$$r'(k) = -\frac{1}{T}[\hat{w} - w(k)] + d(k-1) \tag{12}$$

where, w(k) is the current measured queue length (vehicles), d(k-1) is the measured demand flow entering the ramp (and using the approximation d(k)≈d(k-1)) and r'(k) is the flow entering the freeway.

Since there is no reason to apply a ramp-metering strategy when the freeway demand is low, as this would provoke an unnecessary queue formation, the final ramp-metering rate *R(k)* will be:

$$R(k) = max\{r(k), r'(k)\} \tag{13}$$

where, r(k) is the ramp-metering rate decided by any of the previously described ramp-metering strategies.

By selecting the maximum of both values, this combined strategy helps to keep a high ramp flow, thanks to the ramp-metering strategy, when the freeway demand is low and the

ramp queue regulator delivers a low ramp flow *r'(k)*. If the freeway cannot accommodate the ramp demand without getting congested, the ramp-metering strategy will calculate low ramp flow rates *r(k)* while the queue regulator will deliver higher ramp flow rate *r'(k)* to prevent the queue length from exceeding w.
This queue-management strategy, can be combined with any other ramp-metering algorithms producing *r(k).* Another commonly used queue-management strategy is the override tactic. The override tactic uses occupancy from an on-ramp upstream ILD to detect when the queue duration exceeds a given value using a preset occupancy threshold, and applies an overriding metering rate.

2.4. Green-time policy

A given metering rate estimated by a ramp-metering algorithm can be achieved using a number of different green-time policies. The "one-car-per-green policy" is commonly used, where a single car is let into the motorway during each green stage of the ramp-metering signal and the metering rate is adjusted by varying the frequency of green stages. Another popular policy is full-traffic-cycle, where the cycle time of the ramp-metering signal is fixed, and the duration of the green stage determines the metering rate.

3. METHODOLOGY

3.1. Study of ramp-metering strategies and policies

The two main local ramp-metering philosophies, feedback and feed-forward philosophies, are studied in this paper by testing ALINEA and Demand-Capacity algorithms respectively.

- Green policies:
The metering rate estimated by these algorithms (formulas 4 et 1 respectively) is implemented using two green policies: one-car-per-green and full traffic cycle.
Traffic lights are operated on the basis of a traffic cycle *c* (sec) equal to:

$$c = G + A + R + A' \tag{14}$$

where G is the green phase (sec), A is the amber phase (sec), R is the red phase (sec) and A' is the red-amber phase (sec).

For a given *G* and *c*, the implemented ramp flow may be estimated from: $r = S.\frac{G}{c}$ where *S* (veh/h) is the ramp saturation flow typically equal to $\lambda_r.1800\ veh/h$ where λ_r denotes the number of metered merging ramp lanes.

- One-car-per-green policy:

In this policy, the green time in stage 1 (G_1) is fixed to 2 seconds. The cycle time will vary according to the value of the green time of stage 2 (G_2), which is the unknown. The formulas can then be deduced to compute the green time in stage 2 (G_2).

ALINEA:

$$G_2(k) = \frac{1}{\frac{1}{G_2(k-1)+12} + K_R(\hat{o} - o_{out}(k-1))} - 12 \tag{15}$$

Demand-Capacity:

$$G_2(k) = \begin{cases} \dfrac{1}{q_{cap} - q_{in}(k)} - 12 \; if \; o_{out}(k-1) \leq o_{cr} \\ \dfrac{1}{r_{min}} - 12 \;\; otherwise \end{cases} \tag{16}$$

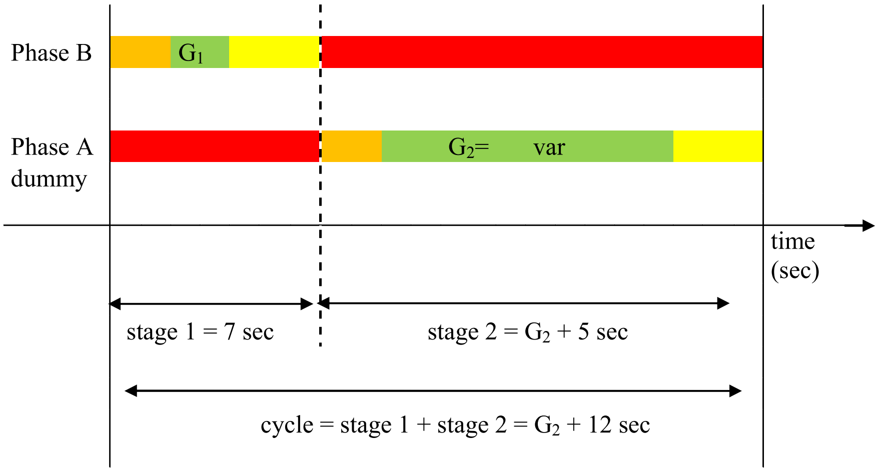


Figure 6 – Traffic Signal Cycle Graph for one-car-per-green policy

- Full-traffic cycle policy:

In this policy, both the green time of stage 1 and 2 are varying. The cycle time *T* is fixed (either 30 or 60 sec). Here, the green time of stage 1 needed to be determined and the green time of stage 2 was then deduced.

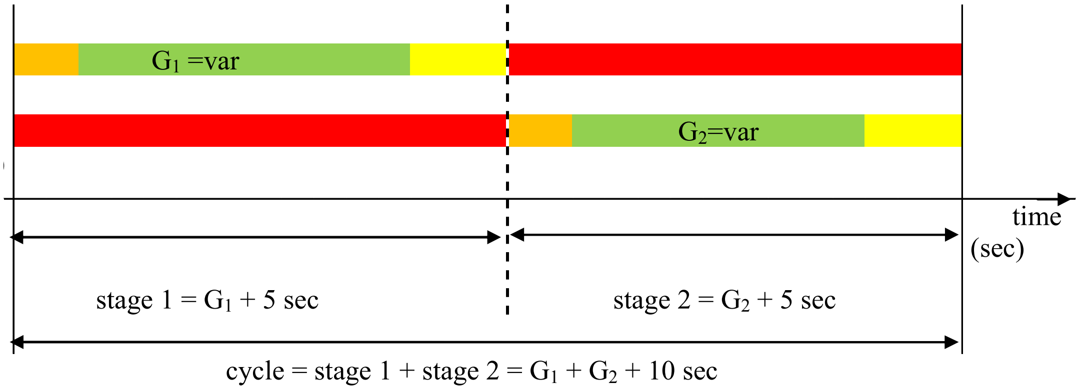


Figure 7 – Traffic Signal Cycle Graph for full-traffic cycle policy

ALINEA:

$$G_1(k) = G_1(k-1) + \frac{K_R T}{S}\left(\hat{o} - o_{out}(k-1)\right) \tag{17}$$

$$G_2(k) = T - 10 - G_1(k) \tag{18}$$

Demand-Capacity:

$$G_1(k) = \begin{cases} \left(q_{cap} - q_{in}(k)\right)\dfrac{T}{S} \; if \; o_{out}(k-1) \leq o_{cr} \\ r_{min}\,\dfrac{T}{S} \;\; otherwise \end{cases} \tag{19}$$

$$G_2(k) = T - 10 - G_1(k) \tag{20}$$

- Queue-management strategies:
Two different queue-management strategies, the X/Q algorithm and the override tactic, are used in conjunction with these two local ramp-metering algorithms. The formulas of green times for the X/Q algorithms can be derived from formulas 15 to 20.

3.2. Evaluation using a simulation model

The effects of the different ramp-metering strategies discussed in this paper were evaluated on Junction 6 of the M8 motorway in Scotland, which links Glasgow and Edinburgh (M8J6). This is a typical UK motorway junction with an arterial road (A73) connecting with M8 through a roundabout with on-ramps to the motorway in either direction (figure 8). The evaluation was performed using a micro-simulation model of M8J6. The model was not subject to a detailed calibration. However, the issue of calibration is not relevant to the objective of this study, which focuses on the relative impact various ramp-metering algorithms have on motorway, ramp and arterial road traffic. However, it should be noted that the magnitude of impacts shown in this paper may not match the actual ones if the same ramp metering algorithms were to be implemented on the ground. This does not invalidate the results of this study.

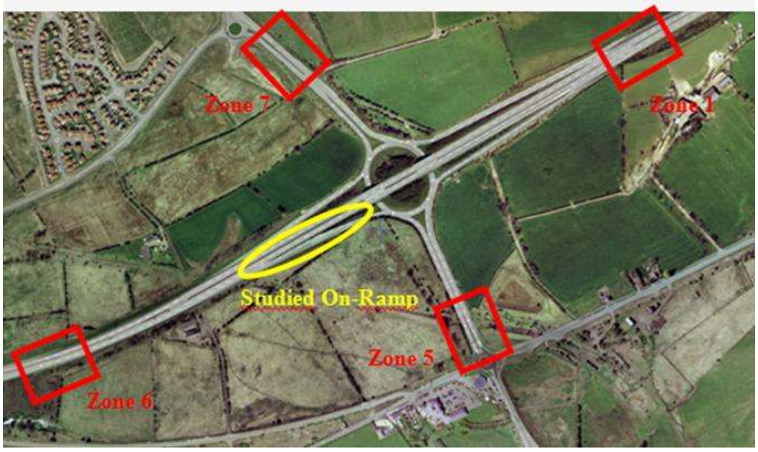


Figure 8 – Microsimulation model zoning system.

3.3. Integration of algorithms within the microsimulation model

The microsimulation model has an SNMP interface that can be used by custom software to interact with a running simulation model. A high-level Java API, that acts as a wrapper around the native SNMP API, has been developed at the Centre for Transport Studies, Imperial College London. The ramp-metering algorithms used in this study were implemented in Java and they were integrated within the microsimulation model using the Java API.

3.4. Measures of Effectiveness (MOEs)

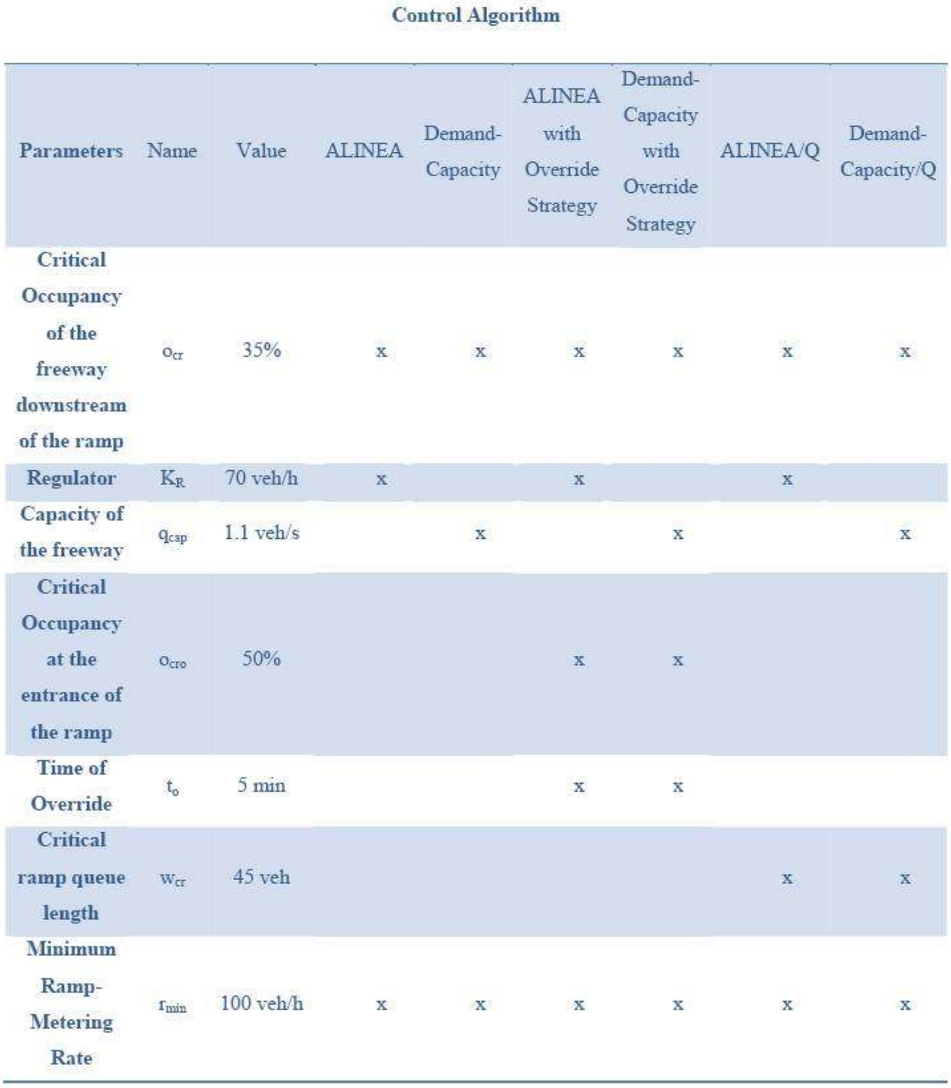
The goal of this study is to evaluate the impact of the ramp-metering algorithms on both motorway and arterial streets. The evaluations were carried out for three impact domains; the whole network, the motorway network alone, and the ramp and arterial road network alone. For each impact domain, both the average travel time and the throughput (total number of vehicles that passed through the system) were measured. In addition, a metric called Generalised Total Travel Time per Vehicle (GTTTV) was defined as the ratio between average travel time and the number of vehicles (sec/veh). The GTTTV metric will help determine if decrease in travel time is achieved by reducing the throughput of the ramp system.

3.5. Parameters of the algorithms

Table 1 shows all the different parameters that need to be calibrated. Four parameters influence the performance of ALINEA [2]:

- Desired occupancy $\hat{o}$: it can be equal to or around the occupancy at capacity; usually the values range between 0.18 and 0.31,
- Regulator K_R: this regulator, used for adjusting the constant disturbances of the feedback control is found to yield good results in real-life experiments when it is set to 70 veh/hour; a lot of studies [1] found that the results are insensitive when this parameter is varied within a wide range of values,
- Location of the downstream detector: ideally, the detector should be placed at a location where the congestion caused by the excessive traffic flow originating from the ramp entrance can be detected; in reported implementations, the detector was located between 40 and 500 m downstream of the ramp,
- Update cycle of the ramp-metering rate: usually the values range between 40 sec and 5 min.

Table 1 – Parameter values of ramp-metering algorithms



Control Algorithm

Parameters	Name	Value	ALINEA	Demand-Capacity	ALINEA with Override Strategy	Demand-Capacity with Override Strategy	ALINEA/Q	Demand-Capacity/Q
Critical Occupancy of the freeway downstream of the ramp	o_{cr}	35%	x	x	x	x	x	x
Regulator	K_R	70 veh/h	x		x		x	
Capacity of the freeway	q_{cap}	1.1 veh/s		x		x		x
Critical Occupancy at the entrance of the ramp	o_{cro}	50%			x	x		
Time of Override	t_o	5 min			x	x		
Critical ramp queue length	w_{cr}	45 veh					x	x
Minimum Ramp-Metering Rate	r_{min}	100 veh/h	x	x	x	x	x	x

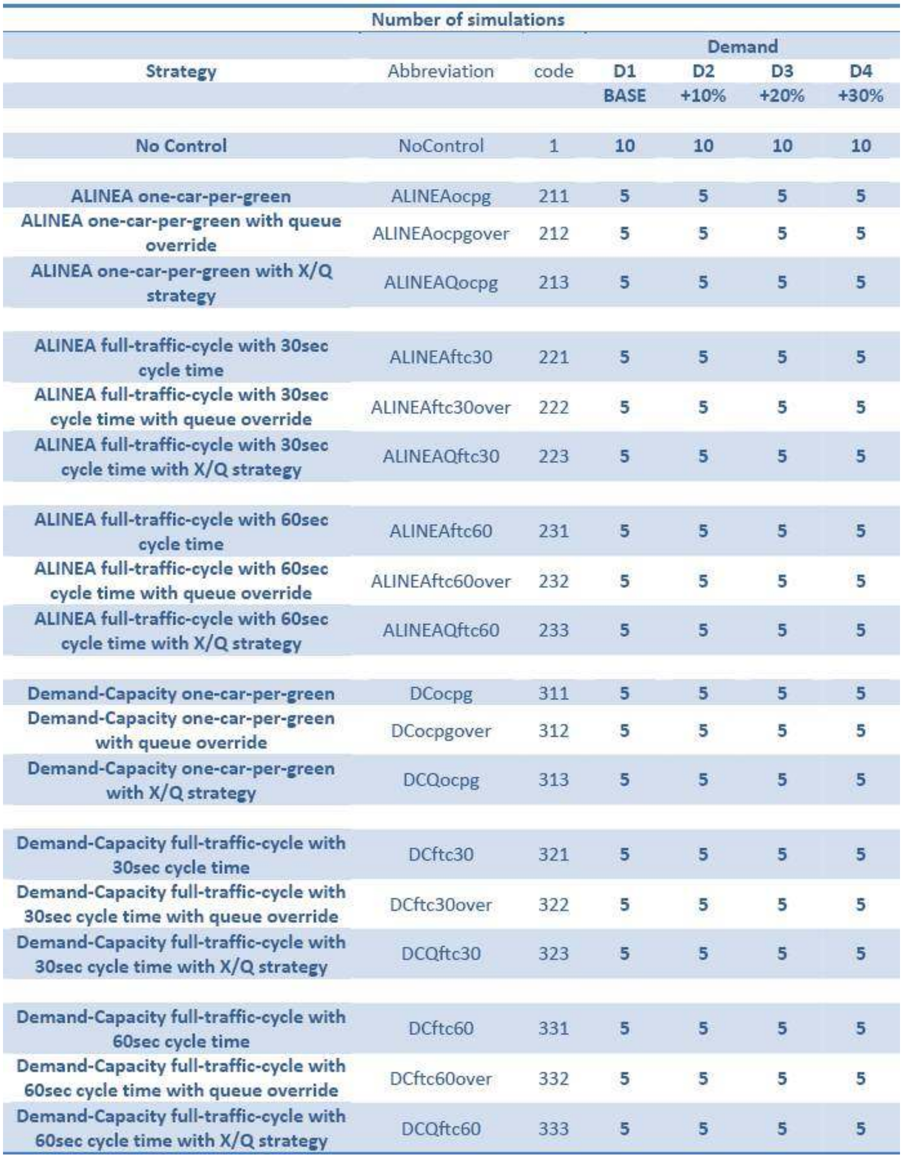
The parameter values given in Table 1 were used in this study, which were determined based on a combination of the information available from the academic literature as explained above and engineering judgement. The critical occupancy (*o_{cr}*) was found to be equal to 35% based on the ILD output from the microsimulation model; so a set point $\hat{o}$ of

30% was chosen. The update cycle of the ramp-metering rate depends on the ramp-metering policy adopted. The cycle time varies for the one-car-per-green policy. For fixed-cycle-time policy, cycle times of 30 sec and 60 sec were used; larger cycle times will result in longer delays for vehicles on the ramp. The detector was placed immediately downstream of the ramp merge point on the motorway.

In order to make the comparison between the two algorithms easy, the same parameter values were used for the Demand-Capacity (DC) algorithm, where applicable. The desired occupancy value in DC algorithm was the same as the critical occupancy value used in ALINEA. In DC algorithm, the capacity q_{cap} had to be determined, which is not required for ALINEA. The minimum metering rate was set at 100 veh/hour to have a flexible one-car-per-green policy for both DC and ALINEA. The same downstream detector was used for both ALINEA and DC algorithms, and additionally an upstream used for the DC algorithm.

An ILD was placed 60m downstream of ramp-entrance to detect queues in the ramp for the queue management strategy. The location of this ILD will enable ramp queues to be detected before they spill back into the arterial road. A critical occupancy value of 50% was used to define ramp queues [1], and the time of override was set to 5 minutes. To apply the X/Q algorithm, two additional detectors had to be placed to measure the queue length. They were set at the entrance and exit points of the ramp. The microsimulation model would not allow the use of video detectors.

Table 2 – Summary of simulation runs



Number of simulations						
			Demand			
Strategy	Abbreviation	code	D1	D2	D3	D4
			BASE	+10%	+20%	+30%
No Control	NoControl	1	**10**	**10**	**10**	**10**
ALINEA one-car-per-green	ALINEAocpg	211	**5**	**5**	**5**	**5**
ALINEA one-car-per-green with queue override	ALINEAocpgover	212	**5**	**5**	**5**	**5**
ALINEA one-car-per-green with X/Q strategy	ALINEAQocpg	213	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 30sec cycle time	ALINEAftc30	221	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 30sec cycle time with queue override	ALINEAftc30over	222	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 30sec cycle time with X/Q strategy	ALINEAQftc30	223	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 60sec cycle time	ALINEAftc60	231	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 60sec cycle time with queue override	ALINEAftc60over	232	**5**	**5**	**5**	**5**
ALINEA full-traffic-cycle with 60sec cycle time with X/Q strategy	ALINEAQftc60	233	**5**	**5**	**5**	**5**
Demand-Capacity one-car-per-green	DCocpg	311	**5**	**5**	**5**	**5**
Demand-Capacity one-car-per-green with queue override	DCocpgover	312	**5**	**5**	**5**	**5**
Demand-Capacity one-car-per-green with X/Q strategy	DCQocpg	313	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 30sec cycle time	DCftc30	321	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 30sec cycle time with queue override	DCftc30over	322	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 30sec cycle time with X/Q strategy	DCQftc30	323	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 60sec cycle time	DCftc60	331	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 60sec cycle time with queue override	DCftc60over	332	**5**	**5**	**5**	**5**
Demand-Capacity full-traffic-cycle with 60sec cycle time with X/Q strategy	DCQftc60	333	**5**	**5**	**5**	**5**

It was decided to test the algorithms for the demand levels D1 (base) to D4, with 10% demand increase at each level. This will help evaluate the ramp-metering algorithms during different traffic levels, ranging from light traffic (D1) to congested (D4).

Since micro-simulations are stochastic in nature, it is desirable to consider the output of multiple model runs. A quick analysis showed that the values of MOEs stabilised after averaging over 5 simulation runs in most cases. Hence, it was decided to carry out 5 replications of the simulation runs at each of the demand levels, for each ramp-metering algorithm/queue management strategy/green-policy combination. The summary of simulation runs carried out is shown in Table 2 (this table also shows the abbreviations used for the algorithms in this document). The simulations lasted 3 hours and 30 minutes with a burn-in period of 15 minutes during which no measurements were made.

4. RESULTS

This section presents the effect ramp-metering has on the motorway, the arterial road, the ramp and the whole system, based on the simulation study described above.

4.1. Motorway

The algorithm that resulted in the best performance on the motorway is DCocpg, as shown in Figure 9 and Table 3. DCocpg is robust across all demand levels. It is also clear that one-car-per-green policy is the best for the motorway. ALINEA works better at higher demand levels; ALINEAocpg is better than DCocpg for D4. Lastly, the choice of the ramp-queue-management strategy does not have an effect on motorway traffic when one-car-per-green policy is used; this is because even if the metering rate is high, no more than one vehicle enters the motorway at any given time, minimising disruptions to the motorway traffic.

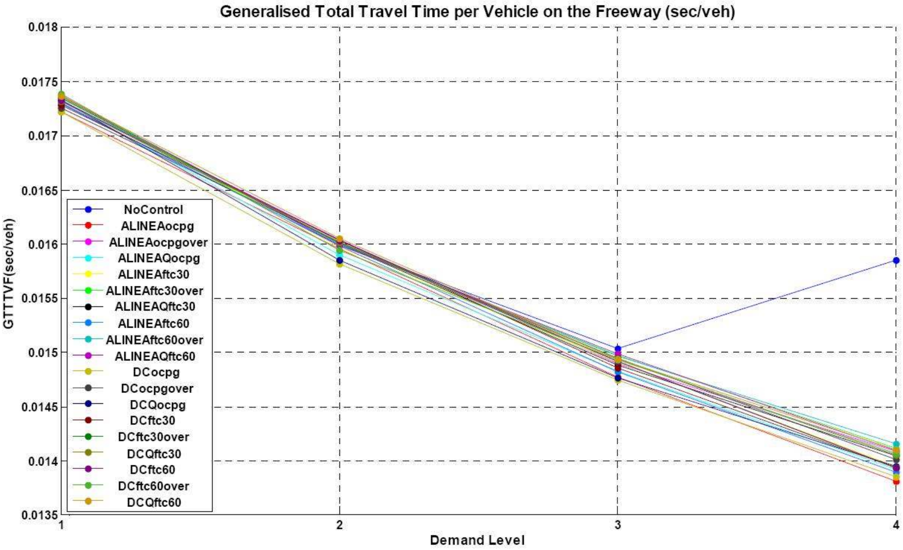


Figure 9 – Results of GTTTVF (sec/veh)

4.2. Arterial Road

Using a ramp-queue-management strategy improves arterial road performance when a full-traffic-cycle green-policy is used to achieve the desired metering rate. Hence, use of a ramp-queue-management strategy is recommended in conjunction with ramp-metering. A one-car-per-green green-strategy works better at high demand levels rather than low demand levels. This can be intuitively explained by the fact that a constant release of vehicles from the ramp reduces the queue build-up on the ramp.

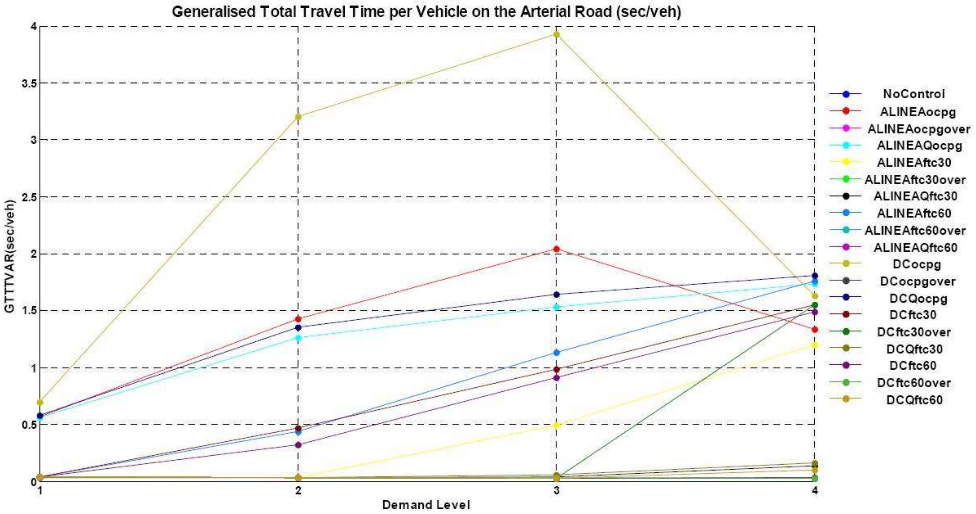


Figure 10 – Results of GTTTVAR (sec/veh)

4.3. Ramp

Not surprisingly, having no ramp-metering results in the best on-ramp performance. If ramp-metering is implemented, then a ramp-queue management policy is necessary to limit the impacts on the ramp. Indeed, as shown in Figure 4, the most robust strategies for the ramp, except for NoControl are ALINEAQftc60 and ALINEAftc30over as the variation according to the demand is low and the GTTTVR value is the lowest. The one-car-per-green policy is not effective for the ramp, except when the demand is very high.

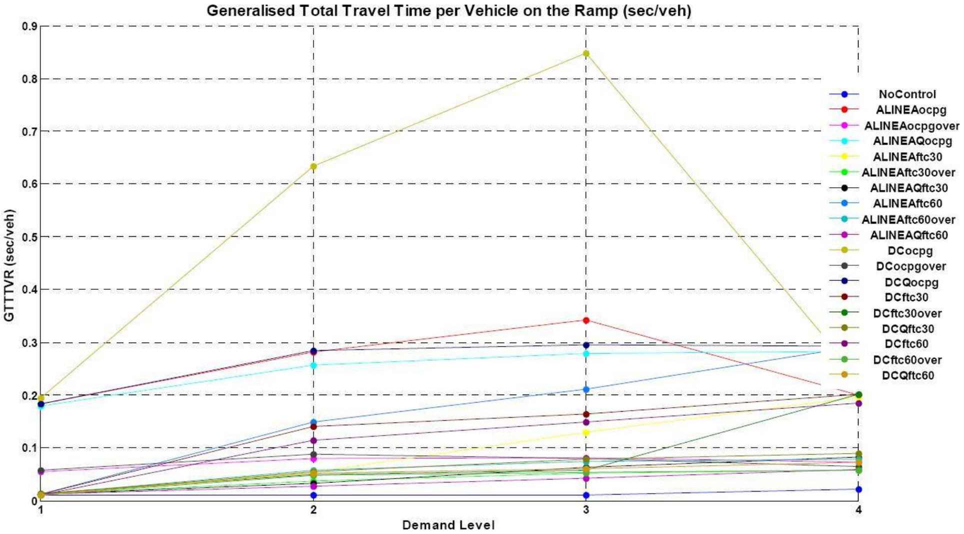


Figure 11 – Results of GTTTVR (sec/veh)

4.4. Whole System

Now that the impacts of ramp-metering at different local scales are examined, its effect on the whole system is evaluated in this section. Indeed, the algorithms that result in the best motorway performance are also the ones that result in worst on-ramp and arterial road performance, as one would expect. Hence, the algorithms that provide the best balance between the motorway, arterial and on-ramp performance need to be identified.

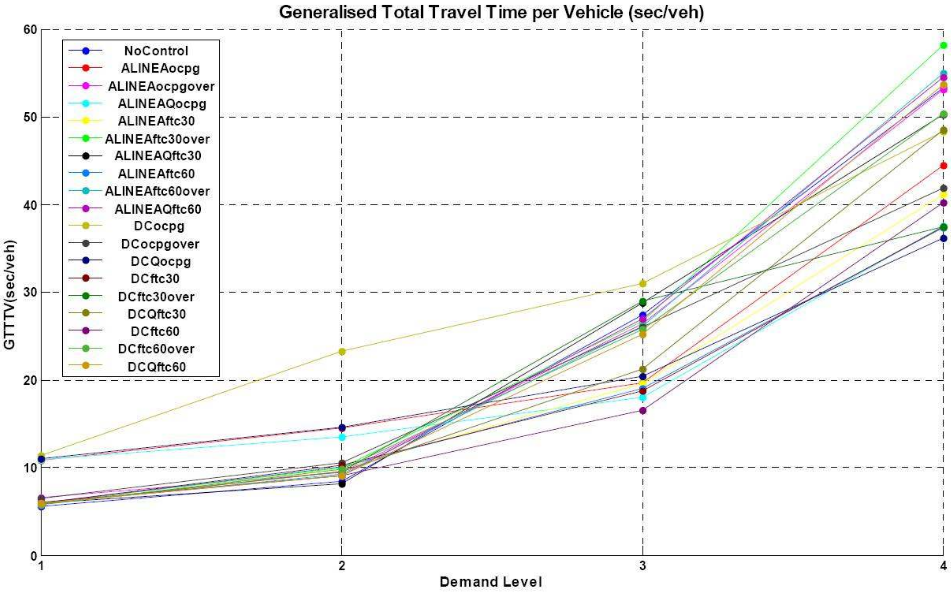


Figure 12 – Results of GTTTV (sec/veh)

Firstly, it is clear that the difference in performance between different algorithms are more apparent when the whole system is considered, as can be inferred from Figure 5. Some of the algorithms, such as DCocpg, do not work well at the system level regardless of the demand level because of the huge ramp queues they inflict. Some of the algorithms, such as DCQocpg and ALINEAQocpg, do not work well at low demand levels but provide very good performance at high demand levels. It is also clear that one-car-per-green policy works best for both ramp-metering algorithms at high demand levels. The difference in performance between DC and ALINEA is not as great as one would expect given the findings from the literature review. In the literature reviewed for this study, the X/Q queue-management-strategy was not even considered with the DC ramp-metering strategy. However, this is the strategy that worked the best during congested conditions, at demand level 4. Lastly, it is clear that a single algorithm does not provide the best performance across all demand levels.

5. CONCLUSION

The objective of this paper was to compare different ramp-metering algorithms in terms of the compromise they establish between delays to traffic on motorways and arterial roads. To ensure relevance to practice, the comparison was restricted to those algorithms that can be implemented within a typical signal controller device. Two different types of local ramp-metering were compared: ALINEA algorithm with a feedback philosophy and Demand-Capacity algorithm with a feed-forward philosophy. The algorithms were programmed in Java and tested within an S-PARAMICS micro-simulation model of Junction-6 on the M8 motorway in Scotland. It should be kept in mind that a simulation environment does not work exactly the same as the real world where Inductive Loop Detectors (ILDs) can fail and result in imperfect data. The more complex an algorithm, the more traffic detectors it needs, and more susceptible it is to equipment failures, in addition to being more expensive.

This work has shown that focusing on a single road type is insufficient when analysing the impact of ramp-metering algorithms. Evaluations of ramp-metering schemes should consider its impact on the motorway, arterial roads and the ramp itself.

The second point is that the use of a queue management policy in conjunction with ramp-metering is extremely important. Despite the criticism of queue-management strategies in the academic literature due to their tendency to create unstable flows, they are effective in reducing congestion on the arterial road.

The one-car-per-green policy produces bad overall results for low demand levels. This is because this policy does not allow the vehicles to enter the motorway even when the demand is low. When the demand is high, the one-car-per-green policy works better since it avoids the build-up of queues associated with fixed-cycle-time green-policy.

ALINEA and Demand-Capacity algorithms have similar performance, despite evidence to the contrary in academic literature. Lastly, no single algorithm provides the best performance across all demand levels.

For the demand levels considered, the most robust algorithm is Demand-Capacity with one-car-per-green green-strategy and X/Q ramp-queue-management strategy. However, this algorithm performs badly at low demand levels. Considering that different algorithms are effective during different demand levels, this is a potential topic for future research. Strategies such as time-tabled switching between ramp-metering algorithms or dynamic switching based on traffic conditions could be explored. Indeed, a new algorithm could be developed that could identify the best ramp-metering algorithm for a given traffic situation. However, all future approaches would do well to jointly consider their effect on the motorway and the arterial road network.

Such approaches are the ones considered when defining the sets and rules of traffic control strategies implementation. Indeed, the Sétra, head service of the scientific and technical network of the French Ministry in charge of Transport, is currently leading a study in order to define such methods.

REFERENCES

1. K. Bogenberger, A. D. May, (1999). “Advanced Coordinated Traffic Responsive Ramp Metering Strategies”, *California Partners For Advanced Transit And Highways.* Berkeley.
2. L. Chu, H. X. Liu, W. Recker, H. M. Zhang, (2001). “Development of A Simulation Laboratory for Evaluating Ramp Metering Algorithms”. *Transportation Research Board*, 81th Annual Meeting.
3. H. Hadj-Salem, J.-M. Blosseville, M. Papageorgiou, (1990). “ALINEA: a local feedback control law for on-ramp metering; a real-life study”. *Road Traffic Control, Third International Conference on.*
4. E. Kosmatopoulos, M. Papageorgiou, D. Manolis, J. Hayden, R. Higginson, K. McCabe, N. Rayman, (2006). “Real-Time Estimation of the Critical Occupancy for a Maximum Motorway Throughput”. *Transportation Research Record: Journal of the Transportation Research Board*, 1959, pp. 65-76
5. H.-U. Oh, V.P. Sisiopiku, (2001). “A Modified ALINEA Ramp Metering Model”. Transportation Research Board, 80th Annual Meeting
6. R. Pearson, J. Black, J. Wanat, (2001). “CALCCIT: Ramp Metering”, available from <http://www.calccit.org/itsdecision/serv_and_tech/Ramp_metering/ramp_metering_report.htm>
7. J. Skariza, (2003). “Evaluation of Coordinated and Local Ramp Metering Algorithms using Microscopic Traffic Simulation”, *Massachussetts Institute of Technology*, MSc Transportation, 108p
8. E. Smaragdis, M. Papageorgiou, (2003). “A Series of New Local Ramp Metering Strategies”. *Transportation Research Record*, 1856, pp. 74-86
9. E. Smaragdis, M. Papageorgiou, E. Kosmatopoulos, (2004). “A flow-maximizing adaptive local ramp metering strategy”. *Transportation Research Part B*, 38, pp. 251–270