

# ALINEA Local Ramp Metering

## Summary of Field Results

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Asservissement Linéaire d'Entrée Autoroutière (ALINEA), a local feedback ramp-metering strategy, has had multiple field applications, and more applications are planned in several European countries. The main features of ALINEA are presented and the field results achieved to date at both single and multiple ramps of the Boulevard Périphérique in Paris and at the A10 West motorway in Amsterdam are summarized. The reported results indicate easy application, flexibility, and high efficiency of ALINEA. Planned implementations are outlined.

In the presence of recurrent or nonrecurrent congestion, freeway traffic flow may drop below capacity, resulting in underuse of the expensive infrastructure. At the same time, congestion may reduce exiting-traffic volumes at off-ramps, increasing overall travel time. A proposal to ameliorate this situation uses lights to meter traffic freeway on-ramps. This control measure aims at limiting access to the freeway mainstream so as to achieve and maintain capacity flow and avoid or reduce congestion. Moreover, ramp metering affects the route-choice behavior of drivers and may be employed as a dynamic assignment tool to encourage use of corridor networks.

Ramp-metering control strategies have been proposed at several levels of sophistication (1) but the majority of implemented systems are of the local, traffic-responsive type. Asservissement Linéaire d'Entrée Autoroutière (ALINEA) was the first local ramp-metering control strategy to be based on straightforward application of classical feedback control theory (2). This paper summarizes the main features of ALINEA and focuses on its past, present, and future field implementations in several European countries. Because the field implementations addressed in this paper are numerous, summarized results are given for each. Detailed results may be found in the provided references.

### LOCAL RAMP METERING

#### Ramp-Metering Problems

Figure 1 depicts schematically the motorway mainstream and the on-ramp. The following quantities are defined:

- $q_{out}$  and  $q_{in}$  are the measurable mainstream traffic volumes (vph) downstream and upstream of the ramp, respectively.
- $o_{out}$  and  $o_{in}$  are the measurable mainstream occupancy rates downstream and upstream of the ramp, respectively.

- $r$  is the measurable on-ramp traffic volume (vph) that may be controlled using ordinary traffic lights, on either a one-car-per-green basis or a  $n$ -cars-per-green basis (with  $n > 1$ ), or on the basis of a fixed traffic cycle subdivided into green and red phases of controllable duration.

- $\delta$  is the distance between Sites 1 and 2.

A simple model relating  $q$  and  $o$  at a given site is provided by the well-known fundamental diagram  $q = Q(o)$  having the typical shape of an inverted U, where  $o = o_{cr}$  is the critical occupancy resulting in maximum (or capacity) flow  $q_{cap} = Q(o_{cr})$ . It is the main aim of a ramp-metering installation to control  $r$  to keep the downstream mainstream flow  $q_{out}$  near a set value  $\hat{q}$ , that is,  $\hat{q} = q_{cap}$ . Alternatively, one may attempt to regulate  $o_{out}$  to a set value  $\hat{o}$ , that is,  $\hat{o} = o_{cr}$ .

#### Constraints

All control strategies calculate suitable ramp volumes  $r$ . In the case of traffic-cycle realization,  $r$  is converted to a green-phase duration  $g$  by use of

$$g = (r/r_{sat})C \quad (1)$$

where  $C$  is the fixed traffic-cycle duration and  $r_{sat}$  is the ramp capacity flow (or saturation flow) that may be fixed or estimated in real time, on the basis of ramp flow measurements filtered over some past cycles. The green-phase duration  $g$  is constrained by  $g \in [g_{min}, g_{max}]$ , where  $g_{min} > 0$  to avoid ramp closure, and  $g_{max} \leq C$ .

In the case of an  $n$ -cars-per-green realization, typically a constant-duration green light permits exactly  $n$  vehicles to pass. The ramp volume  $r$  is controlled by varying the red phase duration between a minimum and a maximum value.

If the queue of vehicles on the ramp becomes excessive, interference with surface street traffic may occur. This may be detected with suitably placed detectors, leading to an override of the regulator decisions to allow more cars to enter the motorway and the queue to diminish.

These specifications and constraints apply in the same way to all control strategies.

#### Popular Control Strategies

The following popular strategies are based on a feedforward disturbance rejection principle that may render them particularly sensitive and not sufficiently accurate (2).

The demand-capacity strategy used extensively in the United States (3,4) is based on measuring  $q_{in}$  and comparing it with  $q_{cap}$ . However, because the value of traffic volume alone is insufficient

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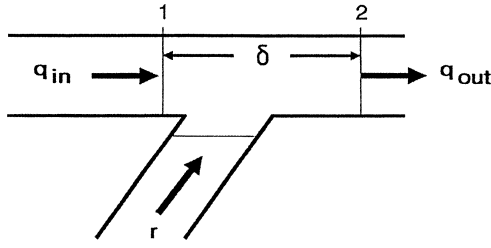


FIGURE 1 Local ramp-metering variables.

to determine whether the motorway is congested or free flowing, the occupancy  $o_{out}$  also is used according to the following scheme applying at each period  $k = 1, 2, 3, \dots$  (e.g., every minute):

$$r(k) = \begin{cases} q_{cap} - q_{in}(k) & \text{if } o_{out} \leq o_{thres} \\ r_{min} & \text{otherwise} \end{cases} \quad (2)$$

where  $r_{min}$  is a minimum ramp-volume value and  $o_{thres}$  is a threshold of occupancy.

The occupancy strategy (3,4) in use in the United States essentially is based on the same philosophy as the demand-capacity strategy, but it relies on occupancy-based estimation of  $q_{in}$ , which may, under certain conditions, reduce the corresponding implementation cost.

### ALINEA Strategy

The ALINEA strategy calculates at each period  $k = 1, 2, \dots$  (e.g., every minute):

$$r(k) = r(k-1) + K_R[\hat{o} - o_{out}(k)] \quad (3)$$

where  $K_R > 0$  is a regulator parameter (2,5). In field experiments, it was found that ALINEA is not very sensitive to the choice of the regulator parameter  $K_R$ . A value of  $K_R = 70$  vph was found to yield excellent results at many different sites. The value of  $r(k-1)$  appearing in Equation 3 should be set equal to the measured actual ramp volume in the last period (i.e., not equal to the calculated ramp volume in the last period) (2,5).

Note that both the demand-capacity and the occupancy strategies react to excessive occupancies  $o_{out}$  only after a threshold value is reached, and in a rather crude way, whereas ALINEA reacts smoothly even to slight differences,  $\hat{o} - o_{out}(k)$ , and thus may prevent congestion in an elegant way, stabilizing traffic flow at a high throughput level. It has been proved (2,5) that if  $q_{in}$  is constant, ALINEA leads asymptotically to  $o = \hat{o}$ , whereas for time-varying  $q_{in}$ , ALINEA acts as a smoothing filter.

ALINEA requires only one mainstream detector station for  $o_{out}$  downstream of the ramp entrance. The measurement location should be such that congestion, originating from excessive on-ramp volumes, is visible in the measurements.

Measurement of  $r(k)$  also may be necessary, such as for real-time estimation of  $r_{sat}$  or for use in Equation 3. However, ALINEA also is applicable directly to the green- or red-phase duration, which circumvents the need to estimate  $r_{sat}$  and measure  $r$ . In fact, combining Equations 1 and 3, instead of Equation 3 the feedback law is obtained:

$$g(k) = g(k-1) + K_R[\hat{o} - o_{out}(k)] \quad (4)$$

where  $K_R = K_R C / r_{sat}$ . Equation 4 has not been tested extensively in the field as yet.

The set value  $\hat{o}$  in Equation 2 is provided by the user. This set value may be changed any time and thus ALINEA may be embedded directly into a hierarchical control system with set values of the individual ramps being specified in real time by a superior coordination level or by an operator. The main reason for regulating occupancy, rather than volume, is that traffic volume may have the same values for both light and congested traffic. An additional advantage in the case  $\hat{o} = o_{cr}$ , regulation to capacity flow, is that the critical occupancy  $o_{cr}$  appears to be less sensitive to weather conditions and other influences compared with the capacity  $q_{cap}$  of a motorway stretch (6).

## FIELD IMPLEMENTATION AT A SINGLE RAMP

### Boulevard Périphérique

The first field implementation of ALINEA, along with a detailed comparison with other ramp-metering strategies, was at the on-ramp Brancion of the internal (westbound) Boulevard Périphérique in Paris (7,8). The downstream detector station measuring  $o_{out}$  was placed 40 m downstream of the ramp. Ramp-metering implementation is based on a fixed cycle  $C = 40$  sec with variable duration of the green and red phases. With an estimated critical occupancy  $o_{cr} = 31$  percent, a slightly undercritical set value of  $\hat{o} = 29$  percent was chosen for ALINEA and was kept constant over the experimentation period to achieve capacity flow downstream of the on-ramp. Several ramp-metering strategies were applied over a period of one month each, and 13 typical days (without incidents) per strategy were selected for comparison. The evaluation criteria included total travel time (TTT) on the mainstream; total waiting time (TWT) at the ramp; total time spent (TTS = TTT + TWT); total travel distance (TTD); mean speed (MS = TTD/TTS); and mean congestion duration (MCD), which is the accumulated period of time during the morning peak in which the measured occupancy is higher than  $o_{cr} = 31$  percent. Table 1 displays a summary of the comparative results for the period 7:00 a.m. to 10:00 a.m. It becomes apparent that ALINEA leads to maximum improvement of all evaluation criteria, which provided a first strong motivation for further implementation.

Another field test was conducted at the same ramp in September and October 1991 within the DRIVE Project CHRISTIANE (V1035) (9). The local ramp-metering strategies to be compared were ALINEA and the WJC strategy, which was developed by Wooton & Jeffreys Consultants for the U.K. Department of Transport and is operational at several entry ramps on the M6 as it passes through the West Midlands Conurbation in England (10). The WJC strategy uses speed and flow information from downstream of the metering ramp to determine the appropriate capacity limit. The capacity limit is varied according to the prevailing speed and flow conditions on the main carriageway by comparison with a capacity matrix on a second-by-second basis. This real-time estimated capacity limit is used in way similar to  $q_{cap}$  in Equation 2. Overall, the WJC strategy is quite complex and its implementation requires calibration (based on collected data) of the capacity matrix to a  $35 \times 35$  dimensional array and of four further threshold parameters. The calibration of the capacity matrix for the reported implementation was carried out by Wooton & Jeffreys Consultants using internal software developed for this purpose.

For the comparative evaluation, 7 typical days (7:00 a.m. to 10:00 a.m.) were selected for each strategy. As a result, it was found

TABLE 1 Comparative Results at Boulevard Périphérique (Paris)

CONTROL STRATEGY	TTS		TTD		MS		MCD	
	veh · h	% change	veh · km	% change	km/h	% change	min	% change
NO CONTROL	421	—	16463	—	39	—	108	—
ALINEA	354	−15.9	16980	3.1	48	23.1	53	−50.9
DEMAND-CAPACITY	407	−3.3	15143	−8.0	37	−5.1	108	0.0
OCCUPANCY	438	0.4	15673	−4.8	36	−7.7	103	−4.6

that ALINEA decreases TTS by 6.8 percent and increases TTD and MS by 0.4 percent and 7.8 percent, respectively, compared with the WJC strategy.

#### Amsterdam A10 West Motorway

The second implementation of ALINEA at a single ramp was within the DRIVE Project CHRISTIANE (V1035) at the Coentunnel ramp (S101) of the A10 West Motorway in Amsterdam (11). ALINEA and the RWS strategy (a variant of the demand-capacity strategy) were applied in weekly alternation in October and November 1990 during the evening peak period. The downstream detector station measuring  $o_{out}$  is placed 400 m downstream of the ramp. Ramp-metering implementation is based on the one-car-per-green principle. By inspection of measured flow-occupancy diagrams, the critical occupancy was estimated to be a little less than 20 percent; hence a slightly undercritical set value of  $\delta = 18$  percent was chosen for ALINEA and was kept constant over the experimentation period to achieve capacity flow downstream of the on-ramp. Table 2 summarizes the main findings of this field comparison. In contrast to the Paris site, the evaluation here is based on 5-min samples, hence the modified dimensions in Table 2. These numbers “prove that the ALINEA algorithm gives better results as compared with the RWS algorithm. ALINEA gives significantly higher speeds and traffic volumes on the A10, upstream of the ramp, higher speeds in the bottleneck, a lower waiting time on the ramp, shorter times spent

and travelling times on the A10 and in the total system, and a higher total service of the system as a whole” (11).

#### FIELD IMPLEMENTATION AT MULTIPLE RAMPS

##### Boulevard Périphérique

In 1990 and early 1991 ALINEA was applied at three on-ramps (Italie, Chatillon, and Brançon) of the internal Boulevard Périphérique in Paris. Figure 2 depicts a schematic representation of the test site. The three controlled ramps were within a 6-km motorway stretch. Two further on-ramps, A6 and Orleans, were included within this stretch but were not metered. Because the main inflows into the motorway stretch, namely the mainstream and the A6, are not controlled, the controllability of the traffic flow in the stretch via ramp metering is rather limited. This field trial was conducted within the DRIVE Project CHRISTIANE (V1035) (12). The goals of this field trial were the following:

- To assess the efficiency of ALINEA when applied to multiple ramps;
- To assess the coordinated ramp-metering strategy METALINE;
- To compare ALINEA, METALINE, and no control situations;
- To verify (or otherwise) the simulation results that had been obtained for this same site earlier (13,14).

TABLE 2 Comparative Results at A10 West (Amsterdam)

CONTROL STRATEGY	TTS		TTD		MS	
	veh · h 5 min	% change	veh · km 5 min	% change	kph	% change
RWS STRATEGY	9.16	—	347	—	37.9	—
ALINEA	8.58	−6.3	352	1.3	41.0	8.2

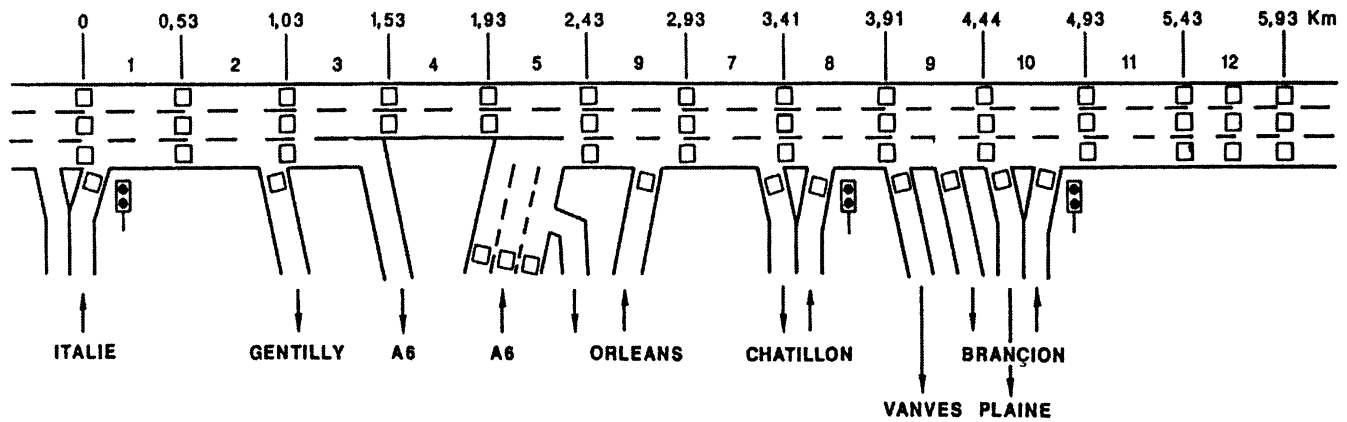


FIGURE 2 Test site with multiple ramps at Boulevard Périphérique.

METALINE is a coordinated generalization of ALINEA whereby the metered on-ramp volumes are calculated from

$$\mathbf{r}(k) = \mathbf{r}(k-1) - \mathbf{K}_1[\mathbf{o}(k) - \mathbf{o}(k-1)] - \mathbf{K}_2[\mathbf{O}(k) - \hat{\mathbf{O}}(k)] \quad (5)$$

where

- $\mathbf{r} = [r_1 \dots r_m]^T$  is the vector of  $m$  controllable on-ramp volumes (here  $m = 3$ );
- $\mathbf{o} = [o_1 \dots o_n]^T$  is the vector of  $n$  measured occupancies along the motorway (here  $n = 13$ );
- $\mathbf{O} = [O_1 \dots O_m]^T$  is the vector of  $m$  measured occupancies, typically those immediately downstream of the controlled ramps (note:  $\mathbf{O}$  is a subset of  $\mathbf{o}$ );
- $\hat{\mathbf{O}} = [\hat{O}_1 \dots \hat{O}_m]^T$  is the vector of  $m$  corresponding set values; and
- $\mathbf{K}_1 \in R^{m \times n}$ ,  $\mathbf{K}_2 \in R^{n \times n}$  are two gain matrices.

The general methodology behind METALINE and the way of deriving suitable gain matrices are detailed elsewhere (13,14). ALINEA and METALINE were tested via simulation, and the corresponding conclusions included the following statement: "Coordinated on-ramp control (METALINE) is superior to local feedback control (ALINEA) in case of unexpected incidents. Both feedback control strategies lead to roughly the same results under normal conditions" (13,14).

For the field implementation of both ALINEA and METALINE the utilized (constant) occupancy set values  $\hat{o}_i$  and  $\hat{O}_i$ , respectively, again were chosen to be slightly undercritical to achieve roughly capacity flow for the corresponding motorway locations. The occupancy set values may be changed in real time; however, this was not thought necessary for this particular field implementation. In fact, a real-time change of set values may be performed by a superior strategic coordinating control level that addresses a whole motorway, a motorway ring, or a motorway network. This task was outside the scope of the field implementations reported in this paper. Nevertheless, this task is fully compatible with ALINEA and METALINE because both allow real-time change of the occupancy set values.

For the field evaluation, 10 typical days (without incidents) per strategy were selected and the average performance of each strategy for the period 7:00 a.m. to 10:00 a.m. is displayed in Table 3. The criteria of Table 3 consider the entire 6-km motorway stretch including the controlled ramps. The results given in Table 3 and the overall findings of the field study confirmed to a large extent the simulation results of Papageorgiou and Papageorgiou et al. (13,14) [see INRETS report (12) for details]. In particular, the statement cited earlier is confirmed for normal traffic conditions. For obvious reasons, a statistically reasonable comparison of the incident-responsive behavior of different strategies in the field is a delicate matter.

TABLE 3 Comparative Results at Multiple Ramps (Boulevard Périphérique)

CONTROL STRATEGY	TTS		TTD		MS	
	veh·h	% change	veh·km	% change	kph	% change
NO CONTROL	3819	—	95489	—	25	—
ALINEA	3621	−5.2	96786	1.4	26.7	6.8
METALINE	3637	−4.8	95391	−0.1	26.2	4.8

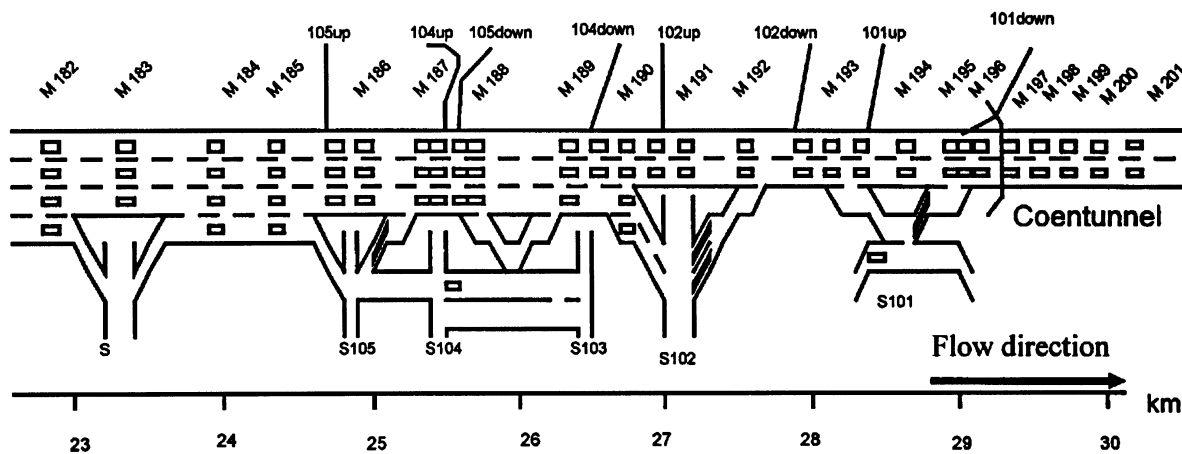


FIGURE 3 Test site with multiple ramps at A10 West.

The overall results given in Table 3 may be broken down to address three substretches, one for each controlled ramp. In this case, ALINEA provides mean speed changes of 4.6 percent, -1.4 percent, and 21.2 percent for the three subsystems (Italie, Chatillon, and Brançon) compared with the no-control case, whereas the corresponding changes for METALINE are 1.9 percent, -3.5 percent, and 19.1 percent. The reason for reduced ramp-metering performance at the Italie and Chatillon ramps is the very frequent activation of the excessive queue constraint because of the strong, uncontrolled inflows from the mainstream and A6 and the short length of both ramps, particularly Chatillon.

Nevertheless, the overall improvement obtained from metering three low-demand ramps in a 6-km motorway stretch in the presence of two strong uncontrolled inflows is remarkable.

#### Amsterdam A10 West Motorway

In the spring and fall of 1994 ALINEA and the RWS strategy were applied at four consecutive ramps of the A10 West Motorway in Amsterdam using the one-car-per-green principle. Figure 3 depicts a schematic representation of the test site with the controlled on-ramps S101, S102, S104, and S105. Constant, slightly undercritical occupancy set values for the corresponding motorway locations were used again for ALINEA implementation. A third situation, the NULL situation, is characterized by applying the RWS strategy to S101 only. Typically, during the evening peak period, congestion forms at the Coentunnel and extends to S105 and beyond. This field

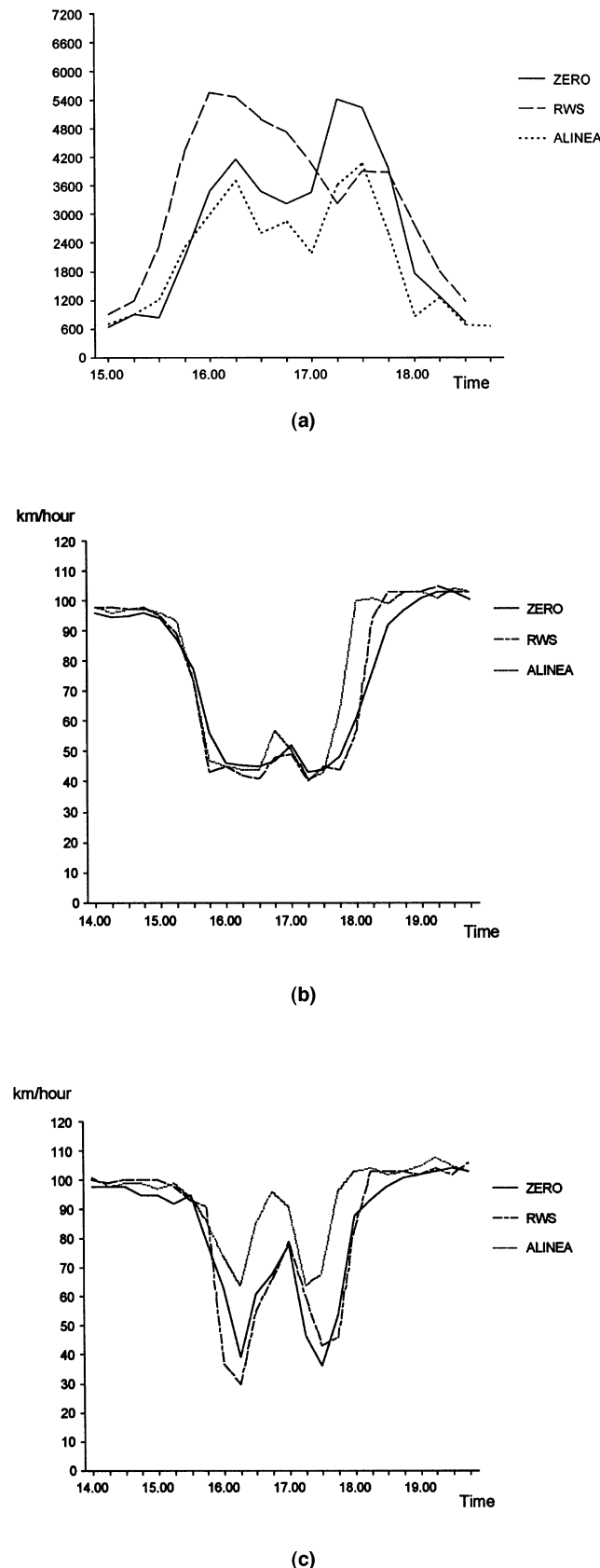
trial was conducted within the DRIVE II Project EUROCOR (V2017) (15,17). The main goal of this field trial was to test and compare the efficiency of ALINEA and the RWS strategy when applied to multiple ramps and to compare both with the NULL situation. Moreover, the coordinated ramp-metering strategy METALINE was developed and tested by simulation for this site (16), but its field implementation and assessment have been delayed because of organizational reasons. For the field evaluation, 5, 4, and 3 typical days were selected for NULL, RWS, and ALINEA, respectively, during the evening peak 2:00 p.m. to 8:00 p.m. Besides the usual loop data, measurement materials include license-plate registration on the on-ramps S101, S102, S104, S105, and S106, as well as on the mainstream inflow just upstream from S106 (Kilometer 23.3) and at the exit of the Coentunnel (Kilometer 30.6), to determine the travel times from all entry points of the A10 West until the end of the Coentunnel; and observations of queue lengths at the on-ramps and the surface streets that feed the on-ramps.

The evaluation results may be summarized as follows:

- Travel-time losses are suffered at the on-ramps (because of ramp metering or congested mainstream traffic or both) and on the mainstream (because of congestion). Table 4 depicts the average cumulative vehicle-hours lost between 3:00 p.m. and 7:00 p.m. on the whole system including the on-ramps. The results given in Table 4 are broken down by time of day in Figure 4(a). It may be seen that ALINEA reduces the travel-time losses over the whole evening peak period.
- These results are underlined by the measured average speeds at different mainstream locations. Figure 4(b) and 4(c) depict the

TABLE 4 Performance Criteria for Multiple Ramps (A10 West)

CONTROL STRATEGY	TIME LOST (3:00 p.m. - 7:00 p.m.)		TTD (2:00 p.m. - 8:00 p.m.)	
	veh-h	% change	veh-km	% change
NULL	682	—	159463	
RWS STRATEGY	925	35.6	159946	0.3
ALINEA	554	-18.8	161223	1.1



**FIGURE 4** Travel time losses (a), and average measured speeds at S102-down (b) and S104-down (c).

average-speed histograms at the measurement sites S102-down and S104-down, respectively.

- The time and space extension of the evening peak congestion is reduced considerably in the case of ALINEA, as is evident in the results [Figure 4(b) and 4(c)] and in the iso-speed diagrams (15,17), which are not provided here for space reasons.

- TTD increases slightly in the case of ALINEA (Table 4).
- The average mainstream traffic volumes during the highest peak (4:00 p.m. to 6:00 p.m.) are 4,273 vph, 4,244 vph (−0.7 percent), and 4,442 vph (+4 percent) for NULL, RWS, and ALINEA, respectively.
- No particular traffic problems caused by ramp metering could be observed on the surface streets.

As stated in the literature, “[W]ithin each situation, the data for the different days are comparable. The good performance of the ALINEA strategy and the poor performance of the RWS strategy are a constant throughout the days for each of the situations. The same holds for the NULL-situation. The good or poor results therefore cannot be accounted to non-representative days” (15,17).

## EVALUATION IN CORRIDOR CONTEXT

Some system operators hesitate to apply ramp metering because of the concern that congestion may be conveyed from the motorway to the adjacent street network. In fact, a ramp-metering application designed to avoid or reduce congestion on motorways may have both positive and negative effects on the adjacent road network traffic. On-ramp queues may motivate drivers to use a road link route instead of a motorway route, which may result in an additional load for the road subnetwork. Conversely, reduced recurrent congestion on motorways may attract more drivers to use a motorway path, which eventually will reduce traffic problems on the road network.

Which one of these two competitive aspects will dominate for a given application may depend on several factors, including the network’s structure and capacity, the particular origin-destination demands, the time of day, and the efficiency of the applied ramp-metering strategy.

To enhance the understanding of the ramp-metering effect in the corridor context, a comprehensive field trial was conducted within the DRIVE II Project EUROCOR (V2017) at the southern Corridor Périphérique in Paris (Figure 5). The Corridor Périphérique consists of two parallel beltways around the city of Paris and the connecting radial streets. The outer motorway belt is the Boulevard Périphérique and the inner signal-controlled arterial is the Boulevard des Maréchaux. The motorway part of the test site comprises 9 on-ramps and 11 off-ramps, and the street network within the test site comprises 36 mostly signal-controlled intersections. Three on-ramps (Italie, Chatillon, and Brançon) are equipped with ramp-metering installations. Loop-detector data were collected from both Boulevard Périphérique and Boulevard des Maréchaux with and without ALINEA application to assess the ramp-metering impact on the whole corridor. The detailed results (17,18) may be summarized in the following paragraphs.

Drivers perceive the corridor network as an entity. For medium to long trips they appear to prefer use of the motorway, which offers (under average nonincident peak-hour traffic conditions) 50 percent higher speeds than the parallel arterial. Nevertheless, some drivers may divert toward the parallel arterial in response to perceived excessive congestion on the motorway (real-time diversion).

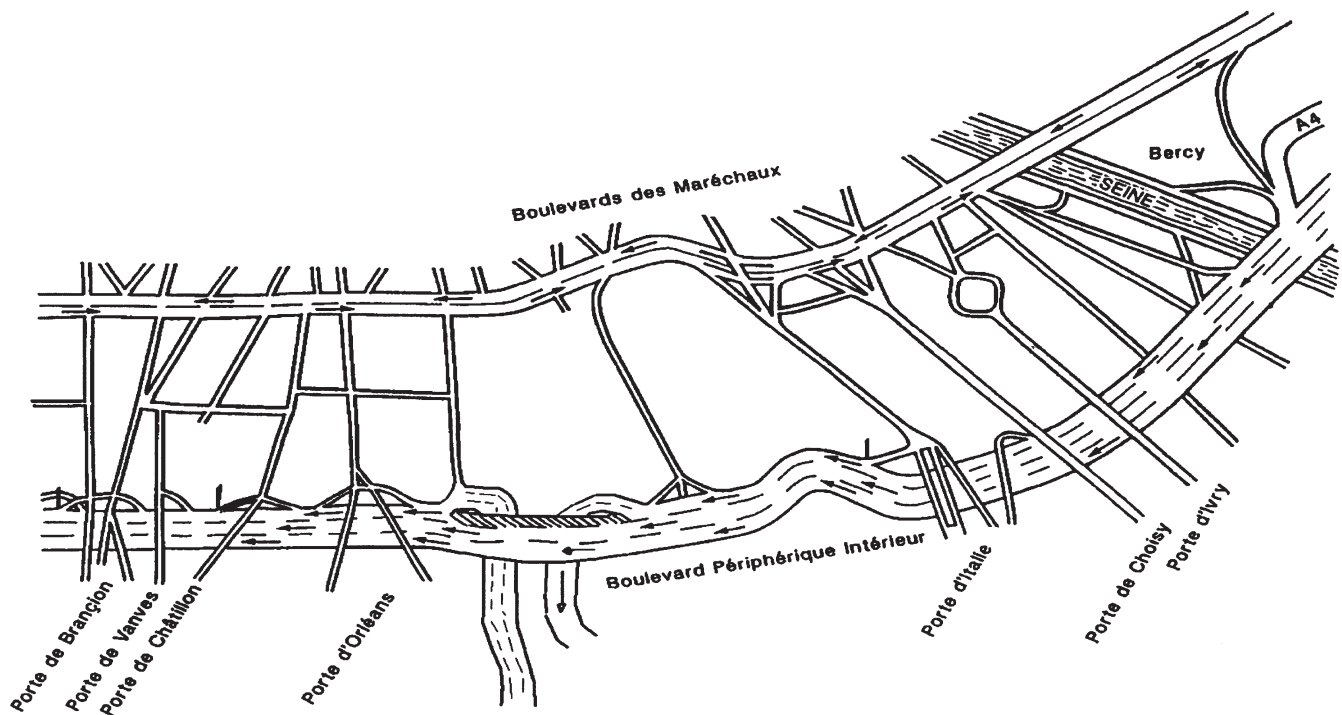


FIGURE 5 The southern Corridor Périphérique in Paris.

The demand in vehicle kilometers on the particular site of Corridor Périphérique is distributed roughly 2:1 between Boulevard Périphérique and Boulevard des Maréchaux, respectively.

Ramp metering reduces the recurrent congestion in space and time and increases the mean speed on the motorway, along with a slight increase in the served demand. In this way, diversion from the motorway to the parallel arterial decreases, and consequently traffic conditions on the parallel arterial are ameliorated.

The particular results obtained for Corridor Périphérique indicate amelioration in TTS, achieved by application of ALINEA, as compared with the no-control case, by -8.1 percent, -6.9 percent, and 20 percent for Boulevard Périphérique (including the ramps), Boulevard des Maréchaux, and the radial streets, respectively. The amelioration in TTS for the overall corridor amounts to -5.9 percent. This result is quite impressive considering the limited extent of

ramp-metering measures. In fact, only three on-ramps are under control, and the three most important inflows (mainflow entrance, A4, and A6 ramps) are uncontrolled.

Figure 6 depicts the average TTS histograms for Boulevard Périphérique (including the ramps), Boulevard des Maréchaux, and the radial streets with and without ALINEA, based on data from 5 and 6 incident-free days of no control and ALINEA application, respectively. Figure 6 demonstrates the significant impact of ramp metering on each component of the corridor network. For the motorway, the TTS histogram of ALINEA clearly is below the no-control histogram in the peak-hour period 7:00 a.m. to 10:00 a.m., with a maximum improvement of some -20 percent around 8:30 a.m. This amelioration is due to retarding of recurrent congestion on the motorway by means of ramp metering. For the parallel arterial, an apparent amelioration in the ALINEA case occurs in the period 8:00 a.m.

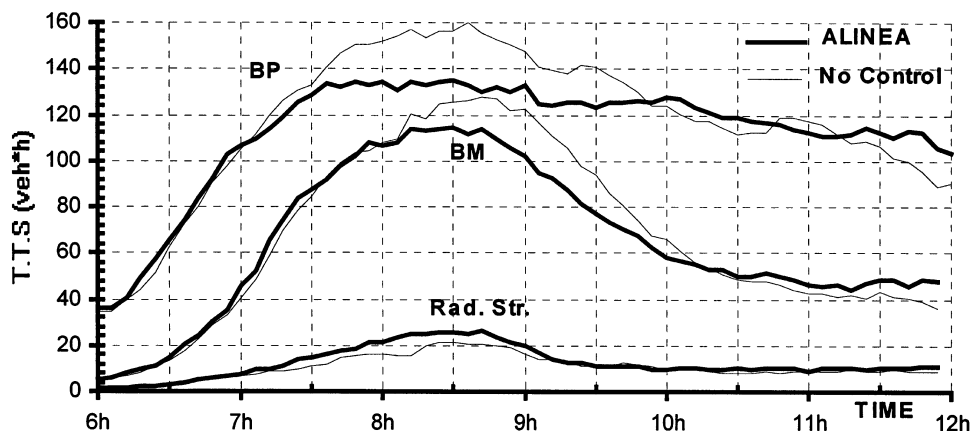


FIGURE 6 Average TTS histograms without incidents.

to 10:00 a.m., with maximum improvement of some –20 percent around 9:00 a.m. It appears that there is a diversion of motorway drivers toward the parallel arterial after 8:00 a.m. due to strong motorway congestion. This diversion is decreased in the ALINEA case because of reduced motorway congestion and this is the reason the amelioration of traffic conditions appears in Figure 6 in the parallel arterial histograms. For the radial streets, Figure 6 shows a deterioration occurring in the ALINEA case, which, however, concerns only 5 percent of the overall corridor load.

The benefits of ramp metering on traffic conditions on the motorway, the adjacent road network, and the whole corridor are even higher if nonrecurrent congestions caused by incidents are included in the evaluation. An enlarged evaluation, based on 14 days of data for ALINEA including 20 incidents, and 14 days of data for the no-control case including 19 incidents, was conducted, and the corresponding TTS histograms are depicted in Figure 7. The corresponding TTS ameliorations of ALINEA compared with the no-control case are –11.6 percent, –10 percent, and 7.4 percent for Boulevard Périphérique, Boulevard des Maréchaux, and the radial streets, respectively, with a respective increase of TTD by 7.6 percent, 4.2 percent, and –8.2 percent. Thus, for the overall corridor, ALINEA leads to a decrease of TTS by –10.8 percent despite the increased TTD of 6 percent compared with the no-control case.

It must be emphasized that the reported positive evaluation results of ramp-metering action are closely related to the utilized control strategy ALINEA. Less efficient ramp-metering strategies that may fail to improve traffic conditions significantly on the motorway or that may be too restrictive (thus underloading the motorway) probably will fail to reach the level of amelioration of corridor traffic conditions reported here.

## PLANNED IMPLEMENTATIONS

In France the importance of efficient ramp-metering strategies for a sensible improvement of motorway network traffic conditions is becoming clear. Immediate plans, partly within the DRIVE III Project DACCORD, include ALINEA implementation at some six consecutive ramps of the A6 motorway in the Paris direction and development and implementation of a motorway-to-motorway version of ALINEA to be applied to the merge of A6 into the Boulevard

Périphérique (Figure 2). These new ramp-metering implementations, together with the three metered ramps of the Boulevard Périphérique reported earlier in this paper, provide an opportunity for an extended evaluation of ramp metering in a motorway network and comparison with coordinated options.

In the Netherlands a standard on-ramp controller unit has been developed. This controller is based on the basic specification for intersection control and includes the ALINEA and RWS strategies. Ten on-ramps throughout the country are so equipped. Further investigations are under way to compare local control strategies, such as fuzzy control. Also under way is the comparative assessment of four coordinated control strategies on A10-West, which includes a centrally commanded ALINEA and METALINE as mentioned earlier in this paper. It should be noted that ramp metering increasingly is seen as a means to control unwanted deviations of traffic to urban parts of the network.

In Glasgow, Scotland, implementation of ALINEA at one ramp of the eastbound M8 corridor is under way within the DRIVE III Project TABASCO in combination with variable message signs and real-time parallel arterial signal control (19).

ALINEA has been included and is provided as an option to the users of several generic simulation tools such as METANET, METACOR, FLEXYST, DYNASmart, SISTM.

## CONCLUSIONS

ALINEA may be considered a highly efficient local ramp-metering strategy according to the reported field results. The main distinguishing features of ALINEA are the following:

- **Simplicity.** ALINEA consists of a single Equation 3 (an integral regulator) without any switching, threshold values, and so forth.
- **Transferability.** ALINEA was applied successfully to three ramps of Boulevard Périphérique and four ramps of A10 West (and to many other ramps in simulation), always with the same parameter  $K$ . Moreover, ALINEA is readily applicable on both a traffic-cycle and a one-car-per-green basis.
- **Low implementation cost.** ALINEA requires only one mainstream measurement, downstream of the ramp. In the reported implementations the measurement site was located between 40 m

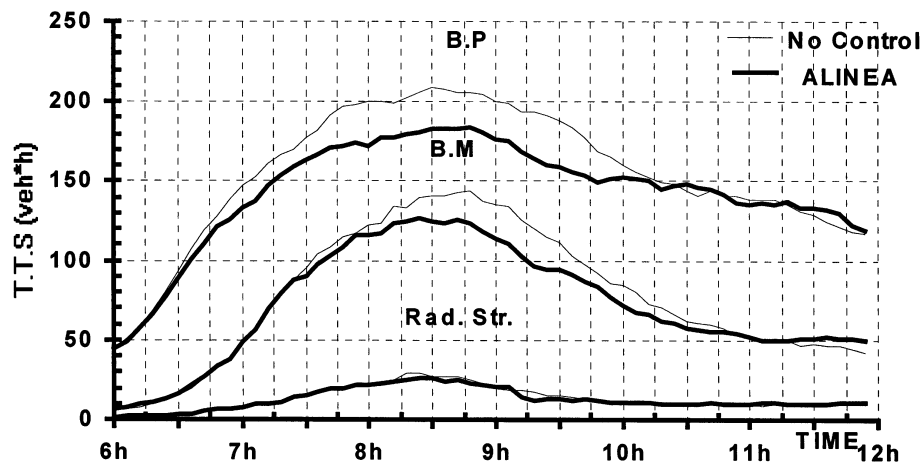


FIGURE 7 Average TTS histograms including incidents.



and 500 m downstream of the ramp without any apparent difficulties arising from different distances.

- Efficiency. ALINEA was found in all implementations to improve on the no-control case and to be superior to all other control strategies with which it was compared, under all assessment criteria. ALINEA was found not to be inferior to coordinated ramp metering (METALINE) in the absence of incidents. Application of ALINEA was found to improve traffic conditions not only in the motorway but also in the adjacent street network (corridor context).

- Flexibility. The set value  $\delta$  included in ALINEA may be changed at any time, either automatically by a superior coordinator or manually, to adapt to changed requirements.

In conclusion, ALINEA is a simple, flexible, robust, and efficient local ramp-metering strategy, which can be applied virtually without any theoretical preinvestigation and without calibration to a broad range of motorway ramps where congestion problems exist.

## ACKNOWLEDGMENT

The reported implementations have been supported in part by the European DRIVE and DRIVE II Projects CHRISTIANE (V1035) and EUROCOR (V2017). Planned implementations will be supported in part by the DRIVE III Projects DACCORD (TR1017) and TABASCO (TR1054).

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Publication of this paper sponsored by Committee on Freeway Operations.