Spacing instructions in approach: 
Benefits and limits from an air traffic controller perspective

Isabelle Grimaud*, Eric Hoffman, Laurence Rognin†, Karim Zeghal

European Organisation for the Safety of Air Navigation 
EUROCONTROL Experimental Centre, Bretigny-sur-Orge, France 
E-mail: firstname.lastname@eurocontrol.int

A new allocation of tasks between controller and flight crew is envisaged as one possible option to improve air traffic management and in particular the sequencing of arrival flows. It relies on a set of new spacing instructions where the flight crew can be tasked by the controller to maintain a given spacing with respect to a designated aircraft. In order to assess the benefits and limits of spacing instructions, two streams of air and ground experiments were conducted. The objective of the latest ground experiment was to assess usability and usefulness of time-based spacing in approach, under very high traffic. It involved six approach controllers over four weeks. The airspace consisted of two generic approach sectors derived from an existing environment. Overall feedback was positive. The proposed working method, though implying significant changes as compared to today, seemed easy to use and assimilate. Controllers perceived benefits: reduction of workload, more anticipation in sequence building and more regular spacing on final. The geographical based analysis of instructions and eye-fixations shows a positive impact on controller activity: relief from late vectoring and earlier flow integration. The analysis of inter aircraft spacing on final shows more regular spacing. The flight efficiency is slightly improved with straighter trajectories. Next steps will consist in investigating more varied situations, defining fallback procedures and addressing the issue of interaction between upstream and downstream sectors through the use of an arrival manager.

Nomenclature

- **ADS-B** = Automatic Dependant Surveillance – Broadcast
- **ASAS** = Airborne Separation Assistance System
- **E-TMA** = Extended TMA: upper and lower sectors performing pre-sequencing and sequencing of arrival flows before transfer to TMA; usually exists around dense TMA to organise the traffic in advance, and thus facilitate the integration onto final approach; arrival manager may be used
- **FAF** = Final Approach Fix
- **IAF** = Initial Approach Fix
- **TMA** = Terminal Control Area (“approach” control)

* DGAC, Aix-Marseille ACC, Aix en Provence, France.  
† Steria Transport Division, Vélizy, France.
I. Introduction

A new allocation of tasks between controller and flight crew is envisaged as one possible option to improve air traffic management and in particular the sequencing of arrival flows. It relies on a set of new spacing instructions where the flight crew can be tasked by the controller to maintain a given spacing (in time or in distance) with respect to a designated aircraft. This task allocation, denoted airborne spacing, is expected to increase controller availability. This could lead to improve safety, which in turn could enable better quality of service and, depending on airspace constraints, more capacity. In addition, it is expected that flight crew would gain in awareness and anticipation by taking an active part in the management of their situation with respect to a designated aircraft. The motivation is neither to “transfer problems” nor to “give more freedom” to flight crew, but really to identify a more effective task distribution beneficial to all parties without modifying responsibility for separation provision. Airborne spacing assumes airborne surveillance (ADS-B) along with cockpit automation (Airborne Separation Assistance System, ASAS). No significant change on ground systems is initially required.

Airborne spacing for arrival flows of aircraft was initially studied from a theoretical perspective through mathematical simulations, to understand the intrinsic dynamics of in-trail following aircraft and identify in particular possible oscillatory effects. Pilot perspective was also addressed through human-in-the-loop simulations and flight trials essentially to assess feasibility. The air traffic control system perspective was considered through model-based simulations, to assess impact on arrival rate of aircraft. Initial investigations were also performed with controllers in approach.

Since 1999, within the CoSpace project, a set of spacing instructions for the sequencing of arrival flows has been developed and refined. These instructions extend the application of in-trail following aircraft to converging aircraft, thus allowing not only to maintain spacing on a same flow but also to handle the integration of flows. To assess benefits and limits of using these instructions, after an initial air-ground experiment, two streams of air and ground experiments were conducted. Ground experiments initially focussed on upstream sectors (from top of descent to initial approach) highlighting positive impact on controller activity and on control effectiveness (increased controller availability, anticipation, better stability of flows). In 2002, a ground experiment investigated the feasibility of airborne spacing in approach (from initial to final approach). Although implying changes in working methods, airborne spacing seemed usable under medium-high traffic and seemed to have a positive impact on controller activity. A subsequent experiment was carried out in November and December 2003 to assess its benefits and limits under very high traffic. This paper will present the results of this experiment. It is organised as follows: the first section will briefly remind the spacing instructions considered. The second section will explain the design of the airspace enabling an optimal use of these instructions. The third section will describe the experiment setup and the last section will present the main results.

II. Spacing instructions for sequencing

The proposed task allocation relies on an analogy with existing practices – the visual separation clearance. The controller remains in charge of analysing the situation and defining solutions and, when appropriate, he/she can task the flight crew to execute an instruction with respect to a designated aircraft. Four instructions are proposed for sequencing of arrival flows and can be applied all along the arrival sectors (from top of descent to final approach). The controller tasks essentially consist in sequencing aircraft with same strategies and same solutions as today, but with these spacing instructions. Practically, these instructions enable the maintaining of spacing from aircraft on same or converging trajectories, when the desired spacing has to be created or is obtained (Table 1). The task of the flight crew is defined as follows: (1) when the desired spacing has to be created, after an initial heading issued by the controller, the flight crew has to initiate the resume action when the desired spacing is obtained; (2) when the desired spacing is obtained, the flight crew has to maintain it by adjusting speed.

As for any standard instruction, the use of spacing instructions is at the controller’s initiative, and he/she can decide to end it at any time. The flight crew however can only abort it in case of a problem onboard such as a technical failure.

Table 1. Spacing instructions for sequencing arrival flows.

<table>
<thead>
<tr>
<th>Spacing instructions</th>
<th>Same trajectories</th>
<th>Converging trajectories</th>
</tr>
</thead>
<tbody>
<tr>
<td>To maintain spacing</td>
<td>Remain</td>
<td>Merge</td>
</tr>
<tr>
<td>To create then maintain spacing</td>
<td>Heading then remain</td>
<td>Heading then merge</td>
</tr>
</tbody>
</table>

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The use of spacing instructions is composed of three phases:
1) Target identification, in which the controller designates the target aircraft to the flight crew.
2) Issuing of the spacing instruction.
3) Termination of the spacing instruction.

For illustration purposes, let us consider the situation of two arrival aircraft converging to a point, then following the same route to the airport. Today, the controller must ensure that the spacing is maintained, and therefore has to continuously monitor the situation and if necessary issue heading and/or speed instructions. With airborne spacing, the controller is relieved of the maintaining of the spacing, which is performed by the flight deck through speed adjustments. However, the same conditions as today for sequencing need to be respected, e.g. aircraft speeds compatible. An example of dialogue is given in Table 2.

In E-TMA, the aircraft would generally arrive not under spacing. The controller tasks consist in sequencing aircraft as today but with spacing instructions (mainly “merge” and “heading then merge”), and transfer aircraft under spacing to TMA. In TMA, the controller tasks essentially consist in maintaining spacing for aircraft of a same flow (keeping aircraft under “remain”) and handling final integration (with “merge” or “heading then merge”). However, since aircraft from a same flow would arrive under spacing, the controller has to decide for every pair of aircraft, whether to keep spacing or cancel it to integrate aircraft from the other flow(s). For E-TMA and TMA, two constraints have been identified: the required anticipation to setup airborne spacing (i.e. target selection), and the restrictions to manoeuvre aircraft under airborne spacing (e.g. heading not compatible with “merge”). In addition, in TMA the integration of flows may require to delay aircraft of one flow while keeping them under spacing. This imposes specific constraints, essentially in terms of airspace design.

### III. Airspace design

Ground experiments initially focussed on E-TMA allowed building a method of use and identifying the constraints attached. In 2002, the objective was to apply the spacing instructions in TMA. An analysis of the specificity of TMA compared to E-TMA along with prototyping sessions led to adapt the method of use and identify how to design the airspace.

By definition of spacing instructions, aircraft must be either on same trajectory (“remain” instructions) or on converging trajectories (“merge” instructions). Therefore, standard trajectories with merging point(s) must be defined in TMA. To avoid complex situations and keep the use simple, there should be a unique standard trajectory for each flow, and all trajectories should be converging to a unique merging point (located upstream of the FAF). To provide the required anticipation, it seemed necessary to group the arrival control positions into one (i.e. initial/pickup and intermediate/feeder positions grouped), and to man this unique position with an executive and a planning controller. The planning controller is thus in charge of early analysis of the sequences (in addition to classical cross-check). It was acknowledged however that these characteristics imply changes in working methods: use of standard trajectories as opposed to radar vectoring; integration on a point as opposed to integration on an axis; a unique approach control position as opposed to two distinct positions; and two controllers per position as opposed to one.

From the 2002 experiment, despite positive feedback on usability, some limitations were raised. Firstly, controllers mentioned that, although they like the “merge”, they were not comfortable with the “heading then merge” which

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(*) The target aircraft is designated by a unique identifier, here the Secondary Surveillance Radar code.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Pilot</th>
</tr>
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<tbody>
<tr>
<td>Designates the target aircraft: “XYZ, select target 1234”</td>
<td>Identifies target aircraft: “XYZ, target 1234 identified, 8 o’clock, 30 miles”</td>
</tr>
<tr>
<td>Gives initial heading, waypoint and desired spacing: “XYZ, heading 270 then behind target merge WPT 90 seconds behind”</td>
<td>Flies heading 270</td>
</tr>
<tr>
<td>When appropriate, cancels spacing: “XYZ, cancel spacing, speed 180 knots”</td>
<td>Cancels spacing and follows speed</td>
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</tbody>
</table>

† Approach control position receiving traffic from E-TMA (e.g. via IAF), organising traffic (e.g. stack management, initial vectors to delay traffic or to create gaps between flows) and maintaining spacing before transfer to intermediate/feeder position.

‡ Approach control position receiving traffic from initial/pickup position, handling integration onto final approach and runway axis interception before transfer to tower.
required too much effort. This was not anticipated as the “heading then merge” was expected to relieve the controller from time-critical monitoring and resume action, which are still needed for the “merge”. Secondly, some airborne spacing initiated by E-TMA might have to be cancelled to integrate aircraft from the other flow. This would increase workload and thus they sometimes found easier and quicker to get back to conventional control than to re-issue spacing instructions to several aircraft. Thirdly, to delay aircraft for integration, controllers had to issue vectors. This sometimes led to incorrect spacing situations, typically aircraft under “remain” not following the same route. These three limitations were attributed to traffic not organised enough for spacing purposes, essentially due to numerous aircraft on different heading in an airspace weakly structured. To tackle these limitation, it was envisaged to adapt the standard trajectories to the level of traffic, e.g. long trajectories for high traffic and short ones for low traffic.

To go a step further in the scope of the 2003 experiment, the requirements for the airspace design have been refined:
1) To allow for flow integration with spacing instructions, it shall be possible to “expedite” or delay aircraft while staying on trajectories. This can be achieved by adding “holding legs” to the standard trajectories along with the possibility of giving direct to merging point at any time.
2) To be able to give direct at any time, the whole range of possible paths should be available without ideally any restrictions. This may impose segregated arrival and departing flows, and no crossing traffic.
3) To allow for delay absorption, there should be “enough” length difference between longest and shortest trajectories, e.g. at least 5Nm corresponding approximately to 90s (a slot).
4) The controller should be able to maintain aircraft on heading beyond normal turning point when the capacity of delay absorption has been exceeded.
5) To easily visualise the situation, e.g. respective ordering and spacing between aircraft, holding legs could be straight parallel segments.
6) To avoid losing space, every holding leg shall be separated from the other by a distance lower than the usual spacing value, e.g. 3Nm for a 90s spacing.
7) To avoid highly diverging situations (e.g. for aircraft from opposite legs) that could result in losing space, the end of each holding leg should ideally not exceed the abeam of the merging point.
8) To avoid any issue in terms of separation, holding legs shall be vertically separated.

With two entry points, these requirements lead to the following design of trajectories (Figure 1). Three or more entry points (IAF) would lead to parallel holding legs leading to a unique merging point, with the entry points laterally or vertically separated. These additional entry points would allow handling slow aircraft (propellers) with distinct trajectories.

IV. Experimental design

A. Objectives
The objective of the present experiment was to assess, under very high traffic, usability and usefulness of time-based spacing in TMA. The experimental condition was the use of spacing instructions: without spacing instructions (No) and with time spacing instructions (Time).

B. Experimental set-up
The airspace consisted of two generic approach sectors derived from an existing environment (Paris TMA). Each sector (APO and APR) had two entry points and was feeding a single landing runway (Figure 2). APR has two base legs, and APO one base leg and one downwind leg. Standard trajectories following the design requirements were available with a capacity of delay absorption of approximately 1 slot for the base legs and 2 slots for the downwind leg. Although no departure traffic was simulated, an altitude constraint was applied to strategically segregate arrivals on the APO downwind leg from departures to the South (FL060 maximum at KAYEN).
The traffic entered each approach sector already sequenced (8Nm at 250kt without spacing, 90s with spacing). This was achieved by scripts to ensure identical deterministic experimental conditions among runs. In condition with spacing, aircraft arrived in TMA under spacing. The traffic level was 34 arrivals per hour with sequences of up to 7 aircraft.

Each sector was controlled by a unique approach position manned with an executive and a planning controller. The role of each executive controller (with support from the planning controller) was to integrate the two flows onto final approach, and to transfer them to tower. Required spacing values at transfer were: 90 seconds between aircraft (or 120 seconds if medium behind heavy) in spacing condition, equivalent to 4.5Nm (or 6NM) at 180kt in conventional condition.

The working environment was similar to today, making use of progress paper strips. No arrival manager (sequencing tool) was available.

Graphical markings dedicated to spacing instructions were available, consisting of markers set around the position symbols of the aircraft under airborne spacing and of its target, and of a link between them (Figure 3). These markings served as a reminder and also allowed to visualise aircraft coming from E-TMA under airborne spacing.

Six approach controllers from London Gatwick, Paris Orly and Roma participated. The experiment was structured around two main sessions: two weeks of training and two weeks of measured exercises. One week break between the two sessions enabled controllers to further assimilate the concept. Each controller played once as executive controller on both sectors and in both conditions.

Figure 2. Simulated airspace.

Figure 3. Example of a radar screen.
C. Data collection and analysis

The validation framework and metrics previously defined for E-TMA was applied. Four dimensions were considered (human factors, activity, effectiveness and safety) with associated metrics (Table 3). Two types of data (objective and subjective) were collected. Objective data consisted of aircraft data, controller instructions (pilot inputs), radio communications, controllers’ eye movement recordings, spacing at final approach point and potential losses of separation. Subjective data consisted of ISA (Instantaneous Self Assessment) scores and NASA Task Load Index questionnaire for workload assessment, blank maps for situation awareness assessment, questionnaires and debriefings. Quantitative and qualitative data analyses were performed. A quantitative analysis consisted in processing simulation data (including eye movements) to provide statistical figures. A qualitative analysis aimed at understanding controllers strategy and activity, through the replay of recorded aircraft plots and controllers’ instructions.

<table>
<thead>
<tr>
<th>DIMENSIONS</th>
<th>METRICS</th>
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<tbody>
<tr>
<td>Human Factors</td>
<td>Workload, skills and training needs, motivation, usability, teamwork.</td>
</tr>
<tr>
<td>Activity</td>
<td>Traffic flow management, traffic situation monitoring, flight service provision, coordination and transfer handling, unexpected events handling and hand over situations.</td>
</tr>
<tr>
<td>Effectiveness</td>
<td>Quality of flow management, of monitoring, of service provided, of coordination, of transfer, of unexpected events handling and of handover.</td>
</tr>
<tr>
<td>Safety</td>
<td>Error management, predictive error model (detection / recovery possibility), control errors (loss of separation, unstable transfer, omissions, …), airborne spacing errors (applicability conditions, misuse).</td>
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V. Results

A. Human factors

1. Motivation

Overall feedback was positive. Beyond acknowledging usability, controllers perceived benefits in terms of reduction of workload, increased anticipation in sequence building and more regular spacing on final. The spacing instructions seemed to enable to handle more aircraft and to reduce the time on the frequency. The instructions were also thought to make stacks easier to handle. However, controllers questioned their ability to detect unexpected events and recover from degraded situations. Last of all, the applicability of airborne spacing to other TMA was questioned.

The rate of use of the spacing instructions is an indicator of both usability and motivation. This was assessed by the percentage of aircraft under spacing when passing the merging points. The resulting rates were very high in both sectors: 86% in APO and 85% in APR. The “heading then merge” instruction was predominantly used (83% of the spacing instructions).

2. Workload

The analysis of NASA-TLX, ISA subjective data suggest that airborne spacing induces a reduction of the mental and temporal demand for the executive controller but not for the planning controller. In terms of objective data, there is a drastic reduction of the number of manoeuvring instructions (heading, speed, level, spacing), larger in APO (53%) than in APR (36%). Even when adding the number of target selection messages, there is still a reduction, again larger in APO (48%) than in APR (28%).
B. Impact on activity

1. Manage traffic flows

To understand the impact of airborne spacing on controller strategies, the first step consisted in analysing the type of manoeuvring instructions used. Four types of instructions were considered: heading (including direct), speed, level and spacing (when applicable). The respective reductions of manoeuvring instructions were 67% for speed and 73% for heading. For all types of instructions the reduction was higher in APO than in APR. In APO (Figure 4), speed were reduced by 71% and heading by 81%. In APR, speed were reduced by 64% and heading by 59%. The sector configuration might explain the difference. In APO, in conventional situation, the final interception required successive heading instructions, whereas in APR one heading instruction was enough to intercept the axis. Under airborne spacing, aircraft merged to a point located before the axis. Once at this point, aircraft were back on the standard trajectory and did not require further vectoring from the controllers.

The second step consisted in analysing the distribution of manoeuvring instructions as a function of distance to a reference point (Figure 5). In APO, a bulk of instructions can be observed 10Nm before the FAF without airborne spacing, and 30-35Nm before the FAF with airborne spacing. In addition, with airborne spacing, from 35Nm down to the FAF, almost no manoeuvring instructions were given. In APR, the impact is less important but still visible: the bulk of instructions is shifted 5Nm upstream, and from 20Nm before the FAF, almost no manoeuvring instructions were given. These results suggest two points: (1) with airborne spacing controllers could integrate the flows earlier; (2) airborne spacing relieves the controller from late vectoring. These results confirm controllers feeling in terms of increased anticipation (and also APR being more difficult than APO due to the absence of a long downwind leg). Beyond, whereas controller dependant strategies of flows integration were observed (on the geographical distributions) in conventional condition, a same strategy was observed with airborne spacing. This suggests that airborne spacing tend to standardise the sequencing activity.

Figure 4. Manoeuvring instructions repartition, APO.

Figure 5. Mean geographical distributions of instructions.
2. Monitor traffic situation

To assess the impact of airborne spacing on monitoring, the geographical based analysis used for instructions was applied to eye fixations (Figure 6). In APO fixations were concentrated in the final area (between 5 and 20Nm from the FAF) in conventional condition, and further away (between 25 and 40Nm from the FAF) in the condition with spacing. In APR, as for instructions, the impact is less important but still visible: fixations were concentrated between 5 and 20Nm before the FAF in conventional condition, but further away (between 15 and 30Nm from FAF) in the condition with spacing.

When mapping the fixations on the sector (Figure 7), it can be seen that fixations were concentrated near the interception in conventional condition, and on holding legs in condition with spacing (where spacing instructions were given to prepare the flow integration). These results clearly show that airborne spacing modified the controller locus of attention. It is noteworthy that the impact on the distribution of fixations is in line with the impact on the distribution of instructions and confirms the increased anticipation.

C. Impact on effectiveness

1. Quality of flow management

The quality of flow integration was assessed by the number of aircraft passing over the FAF and by the inter aircraft spacing at FAF. In APR, the same number of aircraft passed over the FAF during the analysed period. In APO, in half of the exercises, more aircraft flew over the FAF with airborne spacing than in conventional condition. The analysis of the runs with a replay tool showed that aircraft did enter the sector at the same time in both conditions, but without spacing, aircraft had to fly longer trajectories, which resulted in delays in passing the FAF. The distribution of inter aircraft spacing shows a strong impact of airborne spacing (Figure 8). The spacing deviation is below ±5s for 75% of the aircraft with airborne spacing, and for 31% in conventional condition.

![Figure 6. Geographical distribution of eye fixations.](image1)

![Figure 7. Locus of attention, APO.](image2)

![Figure 8. Inter-aircraft time spacing at FAF. For a required spacing of 120s, the spacing value is normalised at 90s.](image3)
2. **Quality of flight service provided**

Two aspects related to the quality of flight service are presented here: flight efficiency and pilot perspective. In terms of flight efficiency, with airborne spacing, aircraft trajectories are straighter (Figure 9) and time and distance flown per aircraft are reduced (respectively 10% and 5%).

![Aircraft trajectories without (left) and with airborne spacing (right).](image)

In terms of pilot perspective, the analysis of the number of manoeuvring instructions per aircraft shows that with airborne spacing, more aircraft received fewer instructions. In APO (Figure 10), with airborne spacing the median value is 4 instructions per aircraft, whereas it is more than 9 in conventional condition. The same results are observed when looking separately at speed or heading instructions. In addition, we considered the time spent under heading select mode (HDG) compared to lateral navigation mode (NAV). By default aircraft enter the TMA under NAV. The heading select mode results from either a “continue heading” or a heading change. Aircraft spent more time under NAV (80%) in the condition with spacing than in the conventional condition. Furthermore, the HDG mode in condition with spacing mainly corresponded to “continue heading”, as opposed to heading changes in condition without spacing. Beyond respective use of HDG and NAV, and based on the geographical distribution of instructions, it is interesting to note that the HDG mode was used on the holding legs (between 40 and 20Nm from FAF) in spacing condition, and in the last part (less than 20Nm from FAF) in condition without spacing.

![Percentage of time spent on NAV and HDG modes.](image)

**D. Impact on safety**

1. **Subjective feedback**

   When using the spacing instructions, controllers seemed to have more time to deal with aircraft, which could be safer with very high level of traffic. However, controllers felt that their monitoring is reduced once spacing instructions have been issued and raised safety concern. Surprisingly, the analysis of periods between successive eye fixations on a same aircraft shows that aircraft were more frequently fixated in the Time condition than in the No condition. This would contradict controllers feeling.

2. **Control errors**

   To detect cases of loss of separation, we looked for aircraft with longitudinal separation lower than 3 Nm. This corresponds to 16 aircraft out of the 1072 controlled (less than 1.5%). All cases occurred in conventional condition. No case was detected in condition with spacing. Most of the cases (75%) occurred on APO sector. The analysis of the losses of separation in APO showed that all cases corresponded to problems integrating aircraft from the downwind leg in the base leg flow. Out of the 1072 aircraft controlled, only 12 transfers were omitted (1%). In APR, cases were observed in both conditions, whereas only in the condition without spacing in APO.

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3. Airborne spacing errors

The use of spacing instruction required controllers to respect initial applicability conditions and then to maintain them during the procedure. Typical incorrect applicability conditions are: too small spacing, target not direct, incompatible speeds, incompatible instructions. For only 8% of the “heading then merge”, the initial spacing was appropriate. For less than 0.7% of the “heading then merge”, the target was not direct to the waypoint. For only 8% of the “heading then merge”, aircraft had similar speed. Less than 1.5% of the aircraft under spacing received incompatible instructions (e.g. a speed while under “remain”, a heading while under “merge”).

VI. Conclusion

The objective of present experiment was to assess usability and usefulness of time-based spacing in approach, under very high traffic. Overall feedback was positive. The proposed working method, though implying significant changes as compared to today, seemed easy to use and assimilate. Controllers perceived benefits: reduction of workload, more anticipation in sequence building and more regular spacing on final. The geographical based analysis of instructions and eye-fixations shows a positive impact on controller activity: relief from late vectoring and earlier flow integration. The analysis of inter aircraft spacing on final shows more regular spacing. The flight efficiency is slightly improved with straighter trajectories. From the initial safety analysis of errors and misuses, no serious cases could be identified. Next steps will consist in investigating more varied situations, defining fallback procedures and addressing the issue of interaction between upstream and downstream sectors through the use of an arrival manager.

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References