ABSTRACT

Following the Challenges of Growth 2008 study (CG08), a high-level assessment of the consequences of such levels of congestion as predicted by the CG08 at the horizon 2030 on the European airports network performance has been performed. The Network Congestion project surveyed literature on network congestion approaches in other industries and used a macro-model of the European air trasnport network to perform Congested Network Response Assessment. The results confirm the structural instability of the airports network performance in terms of predictability, recovery and geographical stability, as suggested in the CG08 report, while showing that it is possible in a reasonable time to use macro-models to study network properties at a strategic level and highlighting the need to better understand delays at airports.

KEYWORDS

airports network, network congestion, network management, performance, disturbances, delays, macro-modelling, simulation
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Communication network / Energy market / Road / Air Transport / Network Congestion
The present EUROCONTROL report was devised within the CND Strategic Studies addressing Air Transport Evolution. This thread aims to provide material to support the development, deployment and evolution of Agency policies and strategy with an ambition to facilitate informed decisions by policy makers within the Air Transport community.

Following the Challenges of Growth 2008 study (CG08), a high-level assessment of the consequences of such levels of congestion as predicted by the CG08 at the horizon 2030 on the European airports network performance has been performed using a macro-model.

The Network Congestion project included:
1. an analysis of the factors influencing congestion in air transport from the ATM network perspective,
2. a literature survey on network congestion approaches in other industries and
3. a Congested Network Response Assessment using a macro-model of the European air transport network. Highlights of the three work-packages are synthesized into the Strategic Recommendations Report that forms the Volume 1 of this publication. Volume 2 is the Technical Study Report.

The results of the macro-modelling approach with different levels of congestion showed the non-linearity of the performance degradation and confirm the structural instability of the airports network performance in terms of predictability, recovery and geographical stability suggested by the CG08 report. This study has also shown that it is possible in a reasonable time to use macro-models to study network properties at a strategic level. It has finally highlighted the need to better understand delays at airports.

By disseminating this work, EUROCONTROL aims to bring the future congestion risk consequences to the attention of the ATM, ATFM, Network and Airports specialists. The objective is to raise the awareness in the community on the risk of congestion and performance degradation and on the need to anticipate with innovative congestion management approaches.

Dave YOUNG - EUROCONTROL
The present EUROCONTROL CND Note was devised within the Air Transport Awareness workpackage of the CND/CMF/SSR Strategy workprogramme, under Strategic Studies. This workpackage aims to provide material to support the development, deployment and evolution of Agency policies and strategy with an ambition to facilitate informed decisions by policy makers within the Air Transport community.

This note reports the results of a one year study project to better understand the potential impacts of congestion in air transport in 2030 such as forecasted in the Challenges of Growth (CG08) report. This report states that “In the most-likely scenario in 2030, 19 airports will be operating at full capacity eight hours a day, every day of the year, and involving 50% of all flights each day. In the most-challenging scenario, 39 airports would be at full capacity, involving 70% of flights on departure or arrival or both”. Despite the current downturn of economy, this forecast is still considered likely.

The need was felt to understand the behaviour of such a congested network in normal and abnormal conditions such as meteo, incident on runways, security alerts. It was anticipated that even in normal conditions, a really congested network might generate sub-optimal behaviours: bunching, deadlocks, delays out of control, too long recovery times, that could spread across the network. Identifying those emerging behaviours was to contribute to determine if additional radically different network management approaches might be appropriate in the long term beyond SESAR, in areas such as scheduling at airports for example.

The project included a literature survey of network congestion approaches in other network industries such as data communication, electricity, road and air transport. The survey identified similarities and cross-fertilisation opportunities with other network management approaches, at governance as well as more operational levels.

Most of the project resources however were devoted to the Congested Network Response Assessment: a modelling and simulation study of the European air transport network behaviour and stability, using a macro-modelling approach emulating congestion rising up to the level forecasted in 2030 in CG08.

Results of the simulations with increasing levels of congestion confirm the risk of network performance degradation in terms of behaviour predictability - Average departure delay per flight at ECAC level would be more than twice the current values during the peak hours; unpredictability at a main European airport rises to five times higher than today -. Congestion increases the probability that airports enter a disrupted state and reduce their ability to recover from disruptions. The impact of external events will be amplified, and the geographical stability of the European network becomes rather weak meaning that local performance degradation spreads more easily to other part of the network.

The report welcomes the creation of a conceptual framework including an innovative modelling platform and new indicators to depict the congested state of the network, allowing exploring a wide range of scenarios where uncertainty and complexity are prevailing like in the real system. It recommends to deepen the initial performance analyses presented here, and to improve the model with comprehensive statistical air traffic data analysis. It also recommends complementing the assessment with a cost study reflecting the economic and environmental impacts of congestion.

In addition, the survey of network management approaches highlights the benefits of cross-fertilisation in particular with the data networks. It leads to recommend further exploration of flow management approaches under high levels of congestion, as well as network structure (hub and spoke efficiency, network scalability) and network management governance studies.

Authors: Nadine PILON, Marc BISIAUX - EUROCONTROL
Contributors: David MARSH, Laurent TABERNIER, Hamid KADOUR - EUROCONTROL
Marta CIDONCHA-SANCHEZ - ISDEFE
Ricardo HERRANZ, Samuel CRISTOBAL - INNAXIS
The "Challenges of Growth 2008" (CG08) report states that "in the most-likely scenario in 2030, 19 airports will be operating at full capacity eight hours a day, every day of the year, and involving 50% of all flights each day". In the most-challenging scenario, 39 airports would be at full capacity, involving 70% of flights on departure or arrival or both. Despite the current downturn of economy, this forecast is still considered likely.

The need was felt to understand the behaviour of such a congested network in normal and abnormal conditions such as meteorological events, incidents leading to unavailability of runways, security alerts at airports. Large events such as the Volcano ash crisis were not anticipated at the time of this initial study but could become case studies as well. It was anticipated that even in normal conditions, a really congested network might generate sub-optimal behaviours: bunching, deadlocks, delays out of control, too long recovery times, that could spread through deteriorating the whole network performance instead of staying local.

Identifying those emerging behaviours was to contribute to determine if additional radically different network management approaches might be appropriate in the long term beyond SESAR, in areas such as scheduling at airports for example. It might be appropriate as well at a later stage to consider whether mitigation actions –such as those explored in CG08- would be sufficient and/or still be feasible.

The Network Congestion 2030 project, launched in 2009, was designed as a two phased approach:

**Phase 1**

An investigation of the issue of congestion in 2030 by performing a series of dimensioning studies including:

- A review of the early SESAR concept & validation activities, (including EPISODE 3) in particular regarding network stability and resilience in order to identify the influence factors of instability in the context of congestion.
- A Congested Network Response Assessment, assessing the probability of disruptions of the network in the 2030 time-frame, based on:
  - an estimation of orders of magnitudes of network disturbance, either caused by internal of external factors (chronic-congestion with excessive local demand/capacity imbalance, events such as meteorological conditions, runways unavailability, …)
  - a network model as representative as possible to the SESAR environment; submitted to increased constraints to quantify the magnitude of the network response, as a tool to assess typical network responses to such conditions. This model describes, beyond ATC modelling, the airports network dependencies involved as aircraft move across the network from airport to airport through the day and from day to day.
- A multi-disciplinary survey of successful approaches in handling demand spikes in network systems close to saturation (road, IT, electricity … ) and of methods addressing instable networks.

**Phase 2 - Optional**

Assessment of the potential impacts of congestion, such as:

- Cost of congestion (not only direct, but also indirect and induced)
- Environmental impact (noise, CO2, air quality)
- Consequences of ATM induced CO2 emissions on ETS arrangements

The Phase 2 has been suspended due to changes within EUROCONTROL. The current report summarises the findings identified during the Phase 1 of the project and suggests further lines of research.

The Congested Network Response Assessment was performed by a modelling team of ISDEFE and INNAXIS experts that proposed a macro-modelling approach of the European air transport network supported by a simulation platform. Such a macroscopic approach with stochastic events was felt most appropriate for addressing network-wide complex phenomena with uncertainty under multiple scenarios in a reasonable time.

The work was enriched through discussions linked to the Challenges of Growth 2008 study, between different Units of EUROCONTROL including STATFOR, the PRU, Airspace Research and CMF - Strategy.

This report includes a high-level summary of the Congested Network Response Assessment final report based on its Executive Summary. The integral version of this report is available … ref [28]
The first step of the Network Congestion project was to explore the early SESAR concept and validation activities regarding network stability and resilience, in order to identify the influence factors of instability in the context of congestion. SESAR is the Single European Sky ATM system being developed as the modernisation project of the European ATM system. In parallel with the Definition Phase, a number of activities in Europe have been redirected towards achieving SESAR goals. This has been the case of the European project EPISODE 3 (EP3), which provided a number of results, methodologies and guidelines related to ECAC-wide concept and system validation, and have been a direct input to the early SESAR validation activities.

The knowledge on factors influencing the performance of the SESAR concept had already been widely captured as part of the EP 3 Project Performance Framework, in the form of an influence model representing the SESAR system’s interrelationships. The approach through Influence Modelling is a very powerful technique to support complex problem analysis. It provides a clear graphical representation of problems to better understand and capture the knowledge and develop a common expert vision, and can also be supported by a detailed mathematical model. An influence model can be defined as a probabilistic network for reasoning about decision making under uncertainty. It is both a graphical and a mathematical representation of a decision problem.

The Network Congestion 2030 project reused the EP3 Influence Model representation to analyse factors influencing congestion in the Air Transport Network. The objective was to build on the common expert vision of the influences captured in EP3 and to extend it to represent Congestion issues in a unified manner. The reflection led to the diagram in Figure 1, representing the factors influencing congestion and its consequences, without underlying mathematical model.

This representation uses the EP3 (SESAR) Key Performance Areas (Safety, Efficiency, Capacity, Environment...). It provides new Key Performance Indicators e.g. Geographical disruption, Network ECAC stability, Recovery time..., that could complement the SESAR Performance Framework.

Figure 1 - “Air Transport Network Congestion” Influence Diagram (Execution phase)
This influence diagram is generic and supports the representation of congestion for all the actors of air transport (Flights, Airports, Passengers and Handling operations). The dotted line delineates the perimeter of the Air Transport Network model used for the following Congested Network Response Assessment (cf next chapter "Congested Network Response Assessment").

The diagram can be explained as follows. The performance of the Air Transport Network system is influenced by both External and Internal disturbances. External disturbances are events such as meteo/weather, security threat, etc.… Internal disturbances are events such as system, aircraft or communication failures, etc.… These two categories of factors, that don’t have the same probability of occurrence, could affect the capacity for flights, as well as passengers and handling at airports.

Congestion for flights occurs when the Demand/Capacity ratio exceeds a saturation threshold, and the main consequences are flight delays.

There are two ways to change this ratio:
- The main one, used by the operators (airlines, airports, etc…), is to influence the demand with tactical measures based on delayed and/or cancelled flights.
- The second one, used by the Air Navigation Providers (ANSP, Airports), is to influence the capacity with tactical measures based on a modification of the air transport capacity.

From this Demand/Capacity ratio it is possible to deduce the airport congestion level, the geographical disruptions, the ECAC-wide network stability as well as the consequences on fuel consumption, time efficiency that impact on the Airport and ANSP, Airspace Cost, the recovery time, the reactionary delays and the volumes and cost of emissions.

Some of those Key Performance Indicators (typically Safety, Cost, Reactionary delay and Emissions) could also reversely play a role in the decision for the tactical measures to be applied in case of congestion (see arrows 2 on the diagram).

Finally, consequences of an initial congestion can create other congestion somewhere else. As an example, congestion caused by the weather, reducing the capacity in a phase of flight (airport, TMA, en route) can generate delays and flight cancellation at the arrival airport. This may evolve and later create passengers' congestion, with people missing their connections, while the initial flight congestion is already recovering.
The objective of the Congested Network Response Assessment was to perform a high level analysis of the behaviour and stability of the highly congested 2030 Air Transport Network, both under nominal and abnormal conditions. It aimed at understanding and assessing the risk of performance degradation due to airport congestion levels such as those expected in the Challenges of Growth 2008 study at the 2030 horizon. It also aimed at identifying potential emerging behaviours generated by the congestion of the European air transport network at such horizon.

To establish a baseline for understanding congestion, a conceptual framework has been built:

- The model used represents the current (2006) European Air Transport Network as seen from an ATM perspective: airports, airspace and flights. It has the capability to “linkage” flights and aircraft, therefore allowing the representation of underlying dependencies between flights, not explicit in the traffic data traditionally used.

- The simulations of the air transport network were performed from a macroscopic point of view, the main and fundamental aspects of the air transport system being incorporated by means of statistical modelling. The uncertainty associated to all the sub-processes and elements of the real system were captured in the model by introducing probabilistic parameters, as “stochastic effects” that induce deviations from a deterministic performance. Traffic was dynamically adapted to the network constraints, meaning that processes simulated were kept realistic, by managing aircraft according to capacity restrictions, and not allowing that the maximum capacities of the network elements were exceeded.

- Specific indicators have been developed to better address the issue of congestion and its consequences (see chapter Scoping - Influences of Air Transport Network Congestion p7).

- The 2030 airport level of congestion has been recreated on the current air transport network. Statistical evaluation and Monte Carlo simulations have been used to estimate the probability distribution of a number of local and global indicators. Through a number of credibility checks such as comparison with actual data on current congestion level, trends analysis, the approach has proved to be suitable to understand and assess the effects of congestion.

- The simulations were based on a set of four scenarios: a baseline scenario with current (2006) level of congestion, and three scenarios with increased level of congestion, 10%, 20% and 30%, the last one corresponding to the 2030 level of congestion as considered in the CG08 study. These four scenarios have been studied under nominal and abnormal conditions:
  - In nominal conditions the air traffic network is subject to the intrinsic variability of the internal processes and elements.
  - Abnormal conditions appear due to events that are not part of the air transport network. Several of these events can take place in real world. The present study is focussed on two categories: a storm in Europe Central, and a terrorist threat at one airport producing a more thorough security check of the passengers.

The innovative model used in the study allowed a flexible and realistic approach to the production of results. The model, as the real system, incorporates uncertainties associated to air transport processes and elements as an intrinsic part of the system. Nominal performance of processes and elements is taken into account for the scenario definition, but, during the execution of simulations, certain variability regarding this nominal performance is allowed, as in real-world. The product is a model that, given a specific scenario, produces different responses in each simulation run. With a high number of simulation runs, the set of responses produced allows the analysis of network behaviour from an innovative point of view. The approach has allowed the identification of some behavioural trends that start focussing the picture of the blurry congested network. The simulation results obtained confirmed, with measured evidences, the accelerated structural instability of the congested network suggested in the EUROCONTROL Challenges of Growth 2008 report.
The results presented and commented here do not only characterise the future congested network performance and behaviour, but also deepen in how predictable this performance is. The following sub-sections depict the impact of congestion on network behaviour predictability.

- A scattered set of results (high standard deviation) indicates that, under the specific conditions imposed by the scenario, quite different responses of the network are possible, and that even the most likely response is not highly probable. The network behaviour is highly unpredictable;

- A concentrated set of results (low standard deviation) indicates that all possible responses of the network are close to the average response, which is a good prediction of the most likely response. The network behaviour is quite predictable.

A clear distinction must be made between network behaviour predictability – in the sense on how "forecastable" is the response of the network to certain conditions – and network predictability – which is a Key Performance Area dealing with performance indicators such as arrival delay. Highlights of the main results are given in the following sections. Please refer to the full report [28] for integral view of the analyses.

**Performance Degradation**

Congestion levels such as the ones forecasted by Challenges of Growth for the 2030 horizon would lead to a serious degradation of network performance: average departure delays per flight at ECAC level will double the current values during the peak hours. Even in the absence of any external disturbance, 13 of the top 25 European airports would have a probability above 75% of having an average departure delay of more than 15 minutes for at least 4 hours a day. Compared to results obtained for 2006 traffic (the baseline), with only two airports with a probability above 50% of having this delay above one hour a day, the performance degradation of the network is severe.

Furthermore, the performance degradation does not increase linearly with the increase of congestion: degradation is faster as congestion increases. As an example, the figure below shows how a 30% increase in the average level of congestion leads to a network-wide Average Departure Delay that is more than 2.4 times the current value, and 1.5 times greater than what would correspond to the linear degradation.
Behaviour Predictability

Increasing network congestion would lead to a more unpredictable network response. The combination of the inherent internal uncertainties of the system with high levels of congestion creates an environment where the network response to specific conditions is difficult to predict. This effect is depicted in the figure below for reactionary delay at network level.

This effect is even more noticeable when examining the results at airport or airline level: as an example, the unpredictability of the average departure delay at one of the main 25 European airports with CG08 2030 level of congestion is five times higher than with current congestion level.

Amplified Impact of External Events

Performance degradation caused by external events under severe congestion levels is stronger than the combination of degradation due to ‘congestion’ and ‘external events/storm’ as individual factors. Airport congestion has a catalytic action on the consequences of an external event. This effect –that can be intuitively expected- has been measured and confirmed in the study through simulations.

With a level of congestion equivalent to one third of the 2030 level as envisaged by CG08, the catalytic effect of congestion in the impact of the storm is translated into 6% more overload occurrences. When reaching the 2030 level of congestion, this increase raises from 6% to 27%. In comparison, the sum of the number of overloads due to ‘congestion’ and ‘storm’ as individual factors is 1.550, reaching 1.960 when the storm takes place under high congestion.
The results are depicted in the figure below, which represents

- in blue the sum of the number of overloads at network level caused by a storm and an increasing level of congestion as individual factors, and
- in green the measured combined effect of the storm under the same levels of congestion.

![Figure 4 - Amplified Impact of Storm under Congestion](image)

The ability to recover from disrupted states is reduced, both at network and local level, which translates into in much longer recovery times. The effects of external disturbances propagate faster through the network, and their impact is aggravated, both in terms of number of airports affected and of severity of performance degradation. As an example, in the simulation of a storm in Europe Central, in the 2006 scenario, 164 out of 213 simulated airports experienced a variation in their performance; when reaching the 2030 level of congestion, up to a total of 207 airports were impacted by the propagation of the effects of the storm: almost the whole network.

**Weak Geographical Stability**

High airport levels of congestion in the network deteriorate regional stability, due to a very limited capacity buffer to re-accommodate delayed flights. This means that in a more congested network ATFM and airlines will have to deal with significantly higher levels of uncertainty to manage local performance.

The weak geographical stability due to congestion is reflected in the propagation of external events between regions. Regions that are not significantly impacted when an external event occurs outside of their boundaries are impacted when the level of congestion increases.

As an example, a capacity shortfall in Europe Central region with current level of congestion, produces in the Mediterranean region an 3.9% increase of average departure delay over the day, with a maximum increase of 16.6% when the propagation wave reaches the region. The same event under the level of congestion envisaged by CG08 for 2030 produces in the Mediterranean region an increase of 5.5% in the average departure delay over the day, with a maximum relative increase of 32.8% and the propagation wave reaching the region earlier in the day.
Conclusions on the Response Assessment

The main objective of the Congested Network Response Assessment to increase the understanding of the structural behaviour of the network facing congestion has been achieved. The study has confirmed the accelerated structural instability of the congested network suggested in the EUROCONTROL Challenges of Growth 2008 report. The simulation results show the emergence of network properties such as performance degradation, deteriorated behaviour predictability, amplified impact of external events, and weak geographical stability.

Through the development of a conceptual framework and the application of an innovative modelling and simulation approach, the study has demonstrated that it is possible to simulate the network from a macroscopic point of view in a reasonable time.

The techniques and metrics developed have provided a better understanding of congestion, in particular of the effects of congestion on the performance of the air transport network and on the predictability of such performance.

In complement, the modelling effort and the results of the simulations have also raised a number of questions, which open interesting research avenues for the future:

- While the proposed modelling approach has proven to be a powerful tool for performance assessment, aspects of the modelling are highly dependent on the availability of high-quality, quantitative data to support statistical modelling. The continuous efforts from STATFOR to maintain and improve high-quality, comprehensive statistical air traffic data reveals itself of utmost importance for improving the model with more realistic and accurate data.

- A wider scope of the cases studied in order to model and simulate longer periods of execution and a variety of external events, and to use several traffic samples would allow in-depth investigation of the trends captured so far and the extension of the conclusions, e.g. by analysing aspects such as delay evolution at the city-pair level or relation between domino effect and the airline business model (hub-and-spoke versus point-to-point, etc.)

- An exhaustive analysis of the sensitivity of the results to the different parameters of the model, not possible due to the limited size of the project, would be necessary to refine the model and confirm the findings. As an example, the behaviour of the network in other scenarios with similar levels of congestion, but with different flight scheduling strategies, could vary significantly.

Figure 5 - The Conceptual Framework with main behaviour properties
Another point is the analysis of the impact of the uncertainty associated to the air traffic management processes and elements on the network behaviour and performance. In the present study, interesting results have pointed out to the sensibility of the network to changes in the parameters associated to this uncertainty. To deal with a more congested network, in addition to the mitigation of congestion by investing in more capacity, the reduction of uncertainty and its appropriate incorporation into the decision making processes –including in ATM–, should be of utmost importance to guarantee a satisfactory quality of service, and therefore should be modelled in further studies.

A next natural step is to develop methods and tools to optimise the way to deal with congestion. A more congested network may necessitate adopting new ATFM strategies, or changing the optimal strategy for airlines regarding how much buffer they keep in their schedules, or even adapting the way delays are tactically managed. The work carried out in the Congested Network Response Assessment may contribute to build richer models where the behaviour of the different users is simulated in order to capture the complexity of the system when looking for both an optimal congestion management strategy and a minimisation of performance degradation due to congestion.
This section provides elements from a multi-disciplinary literature survey of network management approaches which was conducted in parallel with the Congested Network Response Assessment work package (cf section 3) in order to identify domains where successful approaches have been applied in handling peaks of traffic in networks close to congestion. It was considered of interest to perform this review in order to envisage how air traffic network congestion could benefit from new methods from other domains of network management.

This review was to provide an understanding of the typology of issues and resolution approaches in various domains, and their potential transposition in air traffic management. Although it was considered initially to include rail transport and production management aspects, this part was finally not covered.

Sources considered in this review include a search of recent papers in the fields of data networks, road, electricity, as well as in air transport where new approaches of congestion management have already been applied or tested. For each of the domains reviewed, the paper identifies how congestion is defined, what are the current management techniques, what the recent orientations of research are and what would be the applicability to air traffic.
Congestion Management in Communication Networks

Communication networks are internet, telephone, mobile phone and more generally telecoms. They transmit data in the form of messages. The transmission process splits messages in packets that are sent across the network according to communication protocols, and reconstituted at the arrival point.

**Definition of Congestion**

Congestion occurs in data networks when transfer requests exceed the actual overall capacity of the network nodes. This may translate into degraded quality of service for the user. It may also result in packet loss, delay or blockage of new connections.

**Network Management Techniques**

Communication Networks Management techniques sometimes include retransmission to compensate for packet loss. However, in case of congestion this strategy tends to keep the system in a state of congestion. Different methods to address congestion more directly have been introduced:

- Congestion control
- Congestion avoidance
- Implementation of priority schemes
- Specific allocation of resources to certain flows

Congestion control is acting at the level of traffic entry into the system, by controlling the rate at which packets are sent. It was primarily modelled by applying economic theory in a convex optimisation approach attempting to define individual flow rates of the network elements so as to obtain an optimal network-wide performance. Many implementations of this initial approach to congestion management have been derived in the form of distributed network optimisation algorithms. The range of approaches varies depending on:

- the way the network interacts with the algorithm (network awareness),
- the fairness criteria applied in the optimisation,
- the performance objective considered,
- the deployment considered for implementation.

Congestion Avoidance is a mechanism acting at the level of (i) routers to reorder or drop packets under overload, and (ii) flow control mechanisms at end points to respond to congestion appropriately. The main router mechanisms to prevent congestion are "Fair Queuing" and "Random Early Detection".

"Fair Queuing" is a scheduling algorithm to allow multiple packets flows to fairly share the capacity of the link so that a high-data-rate flow cannot use more than its fair share of the link capacity.

"Random Early Detection" (RED) monitors the average queue size and drops packets based on statistical probabilities. It is an early approach to a broad range of algorithms of Active Queue Management. Sally Floyd and Van Jacobson (1993) introduced the RED algorithm for Transmission Control Protocol (TCP) gateways and demonstrated their performance in simulations. In their demonstration, When an Explicit Congestion Notification is implemented, the packets are marked to notify emergence of congestion. When the buffer is nearly empty, all incoming packets are accepted. As the queue grows, the probability for dropping an incoming packet grows too. When the buffer is full, the probability has reached 1 and all incoming packets are dropped.
Other methods to avoid the negative effects of network congestion include:

• implementing priority schemes, so that some packets are transmitted with higher priority than others. Priority schemes do not solve network congestion by themselves, but they help to alleviate the effects of congestion for some services

• the explicit allocation of network resources to specific flows. One example of this is the use of Contention-Free Transmission Opportunities, which provides high-speed (up to 1 Gbit/s) Local area networking over existing home wires (power lines, phone lines and coaxial cables).

Different taxonomies of network congestion management approaches in data networks can be envisaged based on properties of these approaches. One possible taxonomy is based on the level of network awareness, that is to say the level of potential knowledge of network dynamics during communication. Mamatas, Harks, and Tsaoussidis (2007) have provided such a classification of the associated management methods and explored the remaining issues, in particular in wireless networks, when packets loss is not necessarily symptomatic of congestion.

Recent Orientation Of Research

Recent studies display a wide range of variants of algorithms dealing with network congestion, such as fuzzy logic approaches, which proved to be less sensitive to operating conditions.

Fuzzy Logic Control has been used since the 90’s, investigating solutions to congestion control issues in networking, especially in Asynchronous Transfer Mode (ATM) networks. Fuzzy logic was introduced more recently in Active Queue Management approaches for TCP. C. Chrysostomou & A. Pitsillides. (2008) demonstrate, via extensive simulative evaluation, that Fuzzy control methodology offers inherent robustness with effective control of the system under widely differing operating conditions, without the need to (re)tune any parameters.

Wireless networks present new challenges where information loss is not necessarily due to congestion.

Applicability to Air Traffic

Numerous studies of air transport systems are derived from communication networks analogies, either when modelling the air transport network using queuing networks analogies, or when applying global optimisation approaches to flight planning problems.

When dealing with the problem of flow management and its associated slot allocation algorithms (ground delay calculation), attempts have been made to improve the performance of the system by introducing heuristics equivalent to global optimisation approaches. Such heuristics were proven to provide significant delay improvements as compared to simpler heuristics based on a first come first served principle. However it was shown that despite delay savings, the gains would be very dependent on the way alternative rules set in such algorithms would be accepted and on the potential impact that their application might have on capacity declaration. At the same time that these studies were made, the European flow management system was more evolving toward the application of larger sets of flow and capacity management approaches; introducing changes in the working arrangements was felt to possibly hamper the potential benefits of improved optimisation. [20]

Although direct analogies between handling data networks and air transport networks cannot be directly made, capacity management approaches in air traffic management could perhaps benefit from analogies with congestion avoidance mechanisms in data transfers where the network elements informs themselves of the emergence of congestion, in opposition to a centralised approach. Would it make sense to have independent air traffic management entities mutually informing themselves of their state of saturation to provide adaptability?

Another area of possible analogy is the capacity management in air traffic control systems; while congestion avoidance algorithms attempt to determine optimal queue length, similar approaches have already been explored for air traffic, where configuration of resources are managed according to demand. [?]
Further studies in the management of air traffic control capacities would likely bring benefits, both to reach more optimal and flexible approaches, as well as to better adapt capacity margins to fit the predictability of traffic. In this domain, preliminary studies [24] of the performance of flow regulations have indicated that uncertainty costs 5% of capacity when no flow regulations are applied (ground delay), while the introduction of flow regulations provides better predictability and therefore better use of capacity.

At the frontier between data and transportation networks, a study from R.S. de Camargo & al. (2009) is addressing congestion effects in hub-and-spoke networks. It proposes a non-linear mixed integer programming problem resolution based on a classical formulation. The results addressing the congestion effects lead to the conclusion that, under huge congestion, "the hub-and-spoke network has its effectiveness reduced to provide savings on the transportation costs. This counter-intuitive observation is derived from observing from the results obtained by this study that although, in general, the congestion effects can be addressed by installing additional hubs in the network, when above a given threshold, the congestion reduces this flexibility. If a node is already under heavy congestion, creating a hub instead would create even larger Congestion Costs. This node would not be able to handle third party traffic. … As the whole idea of hub-and-spoke networks is to exploit economies of scale by bundling flow on the installed hubs, these hubs have to be able to deal with other flows besides their own, in order to achieve the expected savings. Otherwise, these savings can be completely destroyed by the congestion effects."

More lessons can be learned by considering the governance of network industries and their market approaches. Gökçe Benderli (2005) investigated what could Air Traffic Management learn from other network industries. The study adopted a market focus and analysed possible scenarios for improving ATM efficiency, based on analogies derived from mobile communication, passenger air transport and the Internet. Through comparison of the various potential ATM services with approaches taken in other industries, three approaches for a future ATM, in the spirit of the Single European Sky, were elaborated in the form of three scenarios:

- the introduction of third party organisations between airspace users and ANSPs, dealing with the negotiation of good quality service with airspace providers, satisfying the needs of their airline customers, and acting as “SES Access Points” SESAP; in such an approach, several SESAP would have to be introduced in order to create competition;
- the introduction of new capacity management approaches based on airport and ATFM slot pricing mechanisms taking into account airlines willingness to pay to get access to preferred conditions;
- the creation of “backbones”, by analogy of the Internet, for the control of the upper airspace; in this concept, hubs would be interconnected through these upper airspace highways regrouped in international backbones.

Such scenarios were only proposed as innovative thoughts in response to the SES issues, and were not further validated for their sustainability. This study is to be linked with the analogy study with the energy market (Dumez, Jeunemaitre, 2009) quoted later in this report.
Congestion Management in the Electricity Market

In electricity networks, energy is physically transferred from the transmission systems to its destination users that can be individual households, industrial buildings or factories.

Definition of Congestion

In the electricity network context congestion occurs where demand for power transmission exceeds capabilities of the transmission network (potential violation of security limits).

Network Management Techniques

The resolution of congestion in the electricity domain receives a specific focus on cross-border congestion of the international grid, while congestion aspects in each country are dealt with in the more homogeneous internal context using specific methods. The management of the interconnections is currently ensured by Transmission System Operators (TSOs), although these operators were historically not designed to facilitate international power trade.

Congestion management methods can be categorized as:
- sensitivity factors based methods;
- auction based congestion management;
- pricing based methods;
- re-dispatch and willingness to pay methods;

Regulation No 1228/2003 of The European Parliament and of the Council of 26 June 2003 on conditions for access to the network for cross-border exchanges in electricity stipulates that Network congestion problems shall be addressed with non-discriminatory market based solutions which give efficient economic signals to the market participants and transmission system operators involved. Network congestion problems shall preferentially be solved with non transaction based methods, i.e. methods that do not involve a selection between the contracts of individual market participants. It also provides guidelines on implementation of congestion management methods based on explicit auction.

The study from Frontier Economics and CONSENTEC, commissioned by EC DG/TREN, and issued in 2004 analysed the cross-border congestion management methods. Integration of national electricity markets is constrained by transmission capacity at borders. This results in congestion for which various methods were initially proposed by stakeholders. Transmission capacity is shared by applicants in the transmission. Congestion forecast one day before operation identifies sets of power generation and consumption which can be considered safely. Alternatively, congestion relief can be planned.

Basic capacity allocation methods, prior to the 2004 regulation, included:
- first come, first served: allocation of capacity to the order of transmission request
- pro rata: all requests partially accepted - each applicant receives a fixed share of the capacity amount proportional to the initial request
- explicit auction: declaration of acceptable amount to pay for capacity - allocation in order of offers until maximum capacity is used - price at the lowest bid generally
- implicit auction: transmission capacity is managed implicitly by the spot market where the transmission capacity is implicitly defined within the purchase or sale bid
- counter-trading can be initiated by the transmission operator in counter direction of the congestion to relief - currently not applied to cross-border issues.

Proposals for future development of capacity allocation made by organisations imply multilateral coordination across several borders.
A further report from CONSENTEC issued in 2007 (on request by EC) analysed how to develop an outline of a common co-ordinated congestion management method fulfilling Regulation 1228/2003. This study retained only implicit auctions, explicit auction and counter trading as meeting the criteria of being non-discriminatory and market based. The examination of the various trading options led to reject the counter-trading approach as not giving sufficient economic efficiency (insufficient investment signals). A combination of hybrid implicit/explicit auction was recommended, together with a transition period from an explicit to an hybrid mechanism.

The analysis of auctions designs concluded to the recommendation of year ahead and month ahead auctions with simultaneous offering of interconnectors.

**Recent Orientation Of Research**

Beside the competitive approach being used to manage the electricity market, research is actively performed in methodologies that can help Transmission System Operators (TSOs) in managing networks with limited security margins. Possible approaches considered include network reconfiguration through switching and change over of lines in electric substations. The most suitable optimisation approach considered in this field combines "branch and bound" algorithms with approaches derived from artificial intelligence such as genetic algorithms. [8]

**Applicability To Air Traffic**

In the field of Air Traffic Management, a possible analogy could be sought between the interconnection of national electricity networks and the interconnection of functional airspace blocks (FABs). Similarly to interconnectors such as TSOs in energy networks which have limited capacity – transfer of flights between local route networks need to be performed in consistency with the constraints of the neighbouring airspaces. This is currently ensured through central flow management. Setting specific mechanisms analogous to auctions at this level, while it remains to be shown applicable, would require the explicit identification of products or services to be exchanged between independently managed systems.

Unless a different governance would allow the introduction of such measures it will remain that the connectivity of the European network across FABs will have to be ensured, as highlighted by Jeunemaitre and Dumez (2009). In this study of the dynamics of air traffic management, they highlight the potential cross fertilization of the ATM domain with the electricity market on the issue of unbundling the infrastructure management from operations. Contrary to the electricity market, ATM has not been as much opened to competition. Moreover, the current EU legislation does not yet provide the mechanisms that would allow a full economic approach to congestion and infrastructure development. It seems rather unlikely that a full competitive environment can be put in place in ATM considering the heavy weight of collaborative mechanisms already in place, unless a change in the current path followed through the SES initiative occurs in future steps. The study concludes that such an inflexion could still be possible through the effective creation of an infrastructure manager, together with that of a regulator with a strong restructuring perspective.

A statement from the study is that, where at first sight, the place for economic mechanisms seemed difficult to establish, in particular auctions, different governance might give the possibility of introducing other mechanisms such as booking, congestion charging, yield management.
Congestion Management in Road Transport

Road transport refers to the transportation of persons and goods through ground transportation networks, in urban areas or inter-urban modes, using vehicles from light cars to trucks.

Definition of Congestion

Extreme traffic congestion occur on road networks when demand approaches road capacities – it results in slow speeds, full blockage of traffic - other causes include incidents , leading to reduction of capacity, speeds and changes in the nature of flows.

Network Management Techniques

Attempts to model road traffic have included in particular fluid dynamics. Such theoretical models have shown to be poorly correlated with observations of traffic - empirical models are used for traffic situation forecast need to be calibrated - recent models based on gas-dynamical detonation waves are claimed to accurately represent the phenomenon.

Economic theories have suggested approaches to solve road congestion as management of scarce resources (road pricing) - this can be combined with various approaches to improve road infrastructure such as urban design, reduction of demand through reducing available infrastructure capacities. Intelligent transportation systems are more recent approaches to bring information technology to transport infrastructure to better manage congestion issues. This can extend to research in coooperative systems involving communication between vehicles and infrastructure.

Recent Orientation of Research

Hensher & al. (2007) provide an overview of the global trends in road traffic demand management and associated debates. While the economic argument for congestion charging was long recognised, the implementation of charging scheme appeared only recently due to increased political interest.

In late 2005 the European Parliament introduced a regulation focused on harmonisation of truck tolls levied on its roads. The EU decided that a Eurovignette will apply as of 2012 to vehicles of 3.5 tonnes or more. This harmonisation followed the early German initiative to collect lorry road user charges through satellite based electronic fee collection mechanisms. The regulation is based on the user pays principle and aims to take account of the environmental and social impacts of heavy road freight, shifting some freight from roads onto rail or waterways. Toll revenues should be used for the maintenance of the road infrastructure concerned or to cross-finance the transport sector as a whole.

Other approaches to introduce congestion charging for road traffic have been attempted or implemented in various cities worldwide:

- London trials 2005
- Stockholm 2006 (agreed by vote after trial period)
- UK project to introduce national road pricing (2005) then cancelled in view of prior introduction of a system for trucks (pilot in 2008) complemented with local demand management schemes
- New York Manhattan Island study (2005), not implemented.
Research on roads congestion charging identify three areas which require attention to achieve successful application of pricing measures aiming at redistribution of traffic:

- **essential need to get public buy-in in by clearly highlighting why traffic demand management through pricing should be attempted instead of maintaining charging based on equal access to the network**
- **design of appropriate means for implementing congestion charging, balancing efficiency and transparency**
- **the need to perform impact assessments on mobility, accessibility, financial burdens.**

In road congestion pricing, toll prices may be fixed by estimating the cost of externalities caused by congestion on an homogeneous basis. The study by S. Markose & al. (2007) uses a simulated auction, where computer agents represent decision rules for behaviours to assess the valuation of the travel by the potential users. A ‘cap and trade’ approach is used, inspired by the principle of assigning property rights to the negative impacts of economic activity as a means of controlling them. The marginal bids simulated in this study were shown to reflect the true values of these externalities.

**Applicability To Air Traffic**

Congestion pricing either directly or through auctioning has already found its applicability to attempt solving airport congestion. These approaches are reviewed more extensively in the next section.

Collection of route charges in a centralised way is a mechanism already applied to air transport to finance the infrastructure while it does not include yet the compensation of environment externalities, although the new air traffic charges mechanisms contain provisions for the introduction of variable components.
Congestion Management in Air Transport

Definition of Congestion
Congestion occurs when demand for infrastructure exceeds capacity, resulting in particular in travel delays.

Network Management Techniques
Air Transport Congestion may be addressed at several levels:

- Operational solutions to limit congestion through operational improvements and by providing ways of increasing infrastructure capacity, or providing a better use of existing capacity, either at airport or in en-route airspace.
- Demand management through pricing strategies (congestion charging and airport slot auctions), which are reviewed below.

In recent years (2008), due to heavy congestion at major airports in the USA, the FAA intervened by cutting peak traffic of major carriers. Landing fees were allowed to vary with time of day to allow airport to apply congestion pricing. The FAA offered in parallel to carriers the possibility to redistribute a portion of their slots through auction; the proposal was strongly opposed by the airlines considering the impact on their costs. Withdrawal of the approach was formally requested by the Air Traffic Association, and the request was approved by the FAA subsequently in 2009.

In Europe, heavily congested airports are submitted to coordinated slot allocation under the EC regulation 95/93. This regulation was revisited in 2004 to clarify certain points of the initial regulation. The possibility to exchange slots in a limited set of cases and without monetary compensation was kept unchanged from the original rule. Later in 2008, the EC issued a communication stating their views on a number of issues which had been raised regarding the efficiency of application of the slot allocation regulation. Among these issues, doubts had been raised regarding the compatibility with the Regulation of exchanges of slots at a number of congested European airports against monetary value and other considerations. The EC considered that the self-emergence of secondary slot trading at certain airports allowed the creation of new services, and therefore would not sue these practices, while revision of the rule to cover these aspects was pending. Further in 2009, due to the economic crisis, the EU issued a regulation amending the slot regulation 95/93, to prevent air carriers to lose their slots entitlements despite the low levels of traffic. Currently the EC has maintained the revision of the slot regulation in its 2010 Work Programme (Initiatives for 2010 and beyond) and it will form an integral part of the future airport regulatory package. This Airport Package will take stock of the progress in the implementation of the capacity action plan and address the need to review the Slot Regulation and the Ground Handling Directive.

Recent Orientation of Research
Schank (2005) examined why peak runway pricing had never been effectively implemented, while attention was rising on slot auctions. Peak pricing is based on charging operators the marginal cost of landing on a given runway at a specific time. This approach saw little implementations and it proved not to be particularly effective despite being supported by theory. The study examined three case airports: Boston Logan, New York and London where peak pricing had been applied. Such approaches, when there are no alternative airport in the vicinity, may lead certain groups of users to think that pricing is particularly targeted at them and would therefore initiate fights in court. Attempts to introduce a distance based component in the landing fees were also argued as apparently based on the ability to pay rather than linked to congestion. The case study reviews the history of the numerous variants of pricing schemes applied on the selected platforms and concludes that there might be institutional barriers preventing effective implementation while suggesting that substitutes for air travel should be available to address airport congestion.
Mott MacDonald (2006), in a study commissioned by the EC, considered the potential impact of extending secondary slot trading more widely in EC. This study reviews previous experience in introduction of slot trading by the US FAA, in particular the application the four US high density airports of La Guardia, JFK, O'Hare and Washington National. This study was also looking at application of secondary trading as in other fields such as gas, electricity, spectrum etc. Assumptions were made that trading would be applied without conditions as practiced in the UK. Assessment of the impact in 2025 was made on eight airports with an assumed demand growth of 3.1% per annum. While the local environment impact might be minimal, the global warming impact might be considerable linked to the expansion of long-haul services. The study also reviewed the effect of slot trading on the primary slot allocation, based on the EU slot regulation. It considered the amendment of the ‘use it or lose it’ provision, the auctioning of newly created slots and slots withdrawal. The study showed that secondary slot trading would allow an increase of 7% in passengers handled; it would allow a better access to congested hubs to new entrants while some airlines would experience difficulties in maintaining their slots. This study forms part of the body of information considered by the EC in revisiting the slot regulation.

More recent research explores the impact of slot auctions and pricing policies in view of informing the policy debate around the application of these approaches. Bruekner, 2009, presents a comparative analysis of "Price vs quantity-based approaches to airport congestion management" in USA. It focuses its analysis on the congestion aspect by assuming in the models that carriers face perfectly elastic demands for air travel. "A key lesson of the analysis is that a slot-distribution regime, where slots are distributed to the carriers and then traded through a clearing house, is equivalent to an efficient regime of differentiated congestion tolls. Since such a toll regime is bound to be controversial given its inverse relation between tolls and carrier size, the analysis generates a clear presumption in favor of the equivalent slot distribution regime". The study further identifies that "to foster more active trading, the current bilateral system could be replaced by a central clearing house, and airlines could be given clearer property rights, replacing the current tenuous arrangement in which slots are ultimately the property of the FAA".

In a very different domain, light has been brought into air transport network analyses from studies of scale-free network (such as data networks). These approaches consider the ability of the network to adapt its capacity in opposition to scarcity management. A network is called scale-free if its degree distribution (i.e. the probability that a node selected uniformly at random has a certain degree) follows a particular mathematical function called a power law. The degree of a node is defined as the number of arcs that are connected to other nodes in the network.

Bonnefoy and Hansman (2007) investigate the mechanisms by which the US air transportation system scaled to meet demand in the past and will do so in the future. These studies refer to theories of scale-free and scalable networks. They show that the U.S. air transportation network was not scalable at the airport level due to capacity constraints. The results of the analysis of multi-airport systems, through the aggregation of these multiple individual airports into single nodes showed that the air transportation network was scalable at the regional level.

"In order to understand how the network evolves, an analysis of the scaling dynamics that influence the structure of the network was conducted. Initially the air transportation network scales according to airport level mechanisms – through the addition of capacity and the improvement of efficiency - but as infrastructure constraints are reached; higher level scaling mechanisms such as the emergence of secondary airports and the construction of new high capacity airports are triggered. These findings suggest that, given current and future limitations on the ability to add capacity at certain airports, regional level scaling mechanisms will be key to accommodating future needs for air transportation".

Bonnefoy (2008) PhD thesis subsequently gives a worldwide perspective to his analysis. An in-depth multiple-case study analysis of 59 multi-airport systems worldwide is performed based only on worldwide airports that had more than 500,000 passengers in 2005 were used for further analyses. This filtering process resulted in a set of 451 airports worldwide. Multi-airport systems in the United States and Europe evolved in the recent past through the emergence of secondary airports rather than the construction of new airports. The in-depth analysis of the factors leading to the emergence of secondary airports showed that the role of low-cost carriers was substantial in the dynamics involved. The analysis suggests that existing unused airport infrastructure should be preserved to provide future scalability to cope with future congestion.
... on Network Congestion assessment approaches

The Congested Network Response Assessment has explored a number of behaviours and effects associated to the increase of congestion in the air transport network, assuming 2030 en-route congestion not to be a constraining factor, owing to implementation of the on-going developments.

The study has allowed the creation of a conceptual framework including an innovative modelling platform and new indicators to depict the congested state of the network, but was however limited in scope due to its short time span and limitations which had therefore to be introduced such as a limited set of data, simplifications in the traffic growth algorithms used to replicate indirectly the 2030 congestion levels. The capture of reactionary delay was also limited to an extension of current scheduling practices.

The simulations performed allowed however to extract conclusions on the potential impact of congestion.

- In a business-as-usual situation, for the most probable scenario forecasted by the Challenges of Growth for the 2030 horizon, the resulting congestion levels would lead to a serious degradation of network performance. Average departure delay per flight at ECAC level would be more than twice the current values during the peak hours. Congestion increases the probability that airports enter a disrupted state and reduce their ability to recover from disruptions.

- The predictability of global and local behaviour is degraded due to the increase of congestion. Congestion not only degrades the average value of most performance indicators, but renders them less predictable.

- The presence of elevated airport levels of congestion in the network deteriorates regional stability due to a very limited buffer capacity to re-accommodate delayed flights.

- In a more congested network, the ability both at network and local level to recover from disrupted states is reduced.

- Performance degradation caused by external events under severe congestion levels is stronger than the combination of congestion and external events as individual factors.

- The effects of external disturbances propagate faster through the network, and their impact is aggravated, both in terms of number of airports affected and of severity of performance degradation.

- Congestion affects the geographical stability of the regions studied.

The scope of the cases studied so far should be expanded in further work, to modelling and simulating longer periods of execution and a variety of external events, and using several traffic samples. This should allow the in-depth investigation of the trends captured so far and the extension of the conclusions, e.g. by analysing aspects such as delay evolution at the city-pair level or relation between domino effect and the airline business model (hub-and-spoke versus point-to-point, etc.).

These analyses can only be confirmed on the basis of high-quality, quantitative data to support statistical modelling. Comprehensive statistical air traffic data reveals itself of utmost importance for improving the model with more realistic and accurate data. In particular, analyses of existing delays at airport in terms of stochastic laws would bring additional elements in macroscopic modelling of the airports network.

Such extensions of the current analyses could not be undertaken without a strong cooperation with the SESAR and the NETWORK pillars of the Agency.

In conclusion, the macroscopic stochastic modelling approach taken to analyse the properties of the congested network has shown its strength as a framework for exploring a wide range of scenarios where uncertainty and complexity are prevailing like in the real system. Similar results could not be obtained with the same amount of scenarios considered using deterministic simulators. Consideration should be given to the systematic use of such tools in further strategic studies in air transport.

The project initially foresaw a second phase where the impacts of congestion would be assessed in terms of cost and environmental effects. Considering that strong non linear effects have been identified through these initial simulations of high levels of congestion, the exploration of the induced consequences in the economic and environmental areas should be further considered.
... on Network Management approaches

The literature survey of congestion management approaches in different transport domains confirmed that cross-fertilisation had already been effective in many ways. There is an obvious interest in continuing to maintain the awareness across network domains. There is still a high potential of cross-fertilisation from the telecommunication networks as well as from other transport mode - in particular some optimisation studies would be required concerning the overall structuring of the European air transport network, in order to identify more globally optimal solutions. The Congested Network Response Assessment part of this project, in its review of the various congestion management approaches, also identified the potential need to explore flow management approaches in a highly constrained environment. It suggests a series of further exploratory topics in the field of air transport:

- Flow management approaches under high levels of congestion such as global optimisation approaches, still extending analogies with data network management approaches, optimisation of capacity management;
- Exploring the limits of Hub & Spoke efficiency;
- Governance alternatives for network management;
- Studies in airport network scalability.

In conclusion, beyond the suitability of macroscopic modelling for future risk assessment at the European air transport level and the need for further statistic data analysis to refine such modelling, the study recommends to continue exploring wide range network management approaches and learning from their potential similarities and differences with the European air transport network.
Communication networks


Energy market


Road


Air Transport


[22] Philippe A. Bonnefoy and R. John Hansman, Jr.. 2007. Scalability and Evolutionary Dynamics of Air Transportation Networks in the United States. International Center for Air Transportation, Department of Aeronautics & Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA


[25] Wikipedia, the free encyclopedia. Keywords : Network Congestion, Random Early Detection, Congestion Control, …


Network Congestion

