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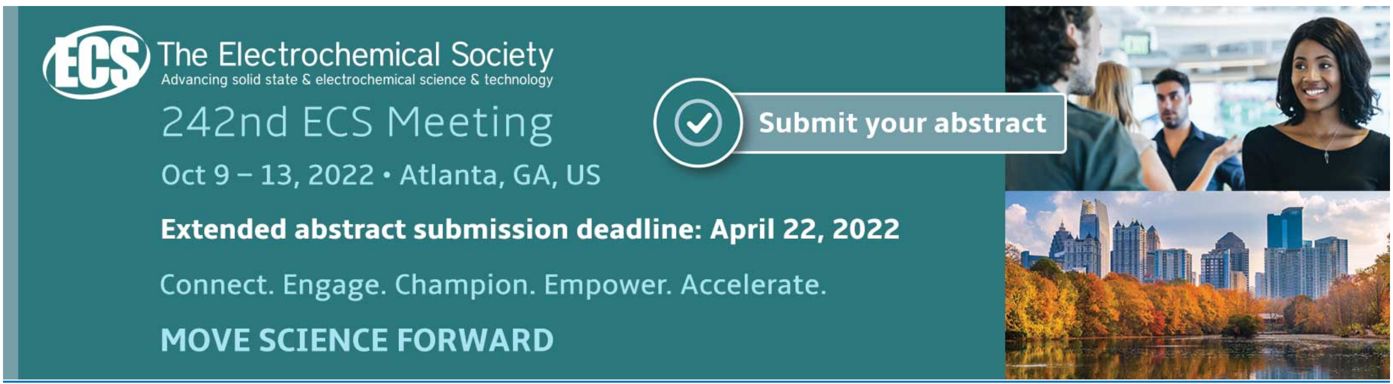

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Reduction of the environmental impact of aviation via optimisation of aircraft size/range and flight network

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Abstract. REIVON is a Clean Sky 2 Technology Evaluator project that investigates to what extent CO_2 emissions of global aviation can be reduced via optimisation of aircraft size/range and flight network. Three alternative global flight networks are created, considering (1) splitting long-haul flights into shorter legs (intermediate stop operations, ISO), (2) reducing frequency to the necessary minimum on busy routes using larger aircraft, and (3) a combination of 1 and 2. In all cases, the use of aircraft optimised for specific combinations of range and seating capacity not existing today will be considered. For the first time, REIVON will carry out a holistic analysis of the impact of an optimised flight network on global air transport system stakeholders, such as passengers, aircraft manufacturers, airlines and airports, and of potential measures to support the implementation of such an alternative network.

1. Introduction

Sustainability has become the strongest driver for innovation in aviation over the last decade, and especially with the global ambition of achieving the Paris Agreement 1.5°C goal. Remarkable efforts are being dedicated to the development of advanced aircraft concepts using sustainable fuels including electricity and hydrogen. Another important emissions reduction area consists of optimising air traffic management and airspace infrastructure for fuel efficiency. However, less effort has been spent so far on the optimisation potential of the global flight route network.

The overall objective of REIVON (Reduction of the environmental impact of aviation via optimisation of aircraft size/range and flight network), a Clean Sky 2 Technology Evaluator project, is to investigate to what extent CO_2 emissions of global aviation can be reduced via optimisation of aircraft size/range and flight network. This includes: (1) Identifying the theoretical potentials for reducing CO_2 emissions via optimisation of the network, of flight frequencies and the aircraft used for each route, in a first step without considering potential impacts on stakeholders or implementation challenges; (2) Assessing the impact on the stakeholders of a global air transport system, such as passengers, aircraft manufacturers, airlines and airports; (3) Analysing potential measures to establish a global air transport system with optimised aircraft, network and frequencies and provide an overview on the extent of the theoretical potential that can be realistically achieved.

2. Main Approaches

REIVON will look at an optimisation of the air transport system from a CO_2 emission perspective. The project will first identify the theoretical potential for reducing the CO_2 emissions via optimised aircraft, network and frequency reduction. To achieve this, three alternatives for an optimised global air transport system will be considered:

1) Splitting long-haul flights into shorter legs;
2) Reducing frequency to the necessary minimum on busy routes; and
3) A combination of 1 and 2.

Alternative 1 is known as intermediate stop operations (ISO). The possibility of using aircraft with a shortened design range for the operation of long-haul flights and refuelling them in between was discussed for the first time by Green [1]. He demonstrated that the fuel efficiency for the transport of a given payload decreases with increasing design range, as aircraft with longer range require larger fuel tank capacities resulting in an increased structural weight. For an increase in Operating Empty Weight (OEW) additional fuel is required for the same range, which must be accommodated in the fuel tank. This so-called snowball effect leads to a disproportionate reduction in efficiency with increasing range. Numerous studies have been devoted to the topic of ISO, such as [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12], using different approaches to quantify the potential of the concept. The analysis scope ranges from generic individual missions to fleet or global level analyses, while both optimally located intermediate airports and real geographical airport distributions and route structures were assumed. In addition to the achievable fuel savings, implications on flight times, operating costs, life cycle costs, environmental impact and safety were also analysed. REIVON will extend the above-mentioned studies by conducting a global ATS level assessment, not focusing on one or two aircraft types only. Moreover, in contrast to previous research, REIVON will also consider the aircraft seat capacity to be a variable within the optimisation.

REIVON alternative 2 considers replacing a large number of flights on busy routes, which are serviced by smaller aircraft, with larger aircraft at reduced flight frequencies (LARF). Recently, Nollau and Thießen [13] have examined to what extent the number of flight movements in Europe can be reduced while accommodating all passenger demand. However, the study only considered the use of existing aircraft types. As a consequence, many widebody aircraft types, originally designed for long ranges, were utilised, which led to sub-optimal results for economic and fuel efficiency. In contrast, REIVON will treat aircraft design range as an optimisation variable.

Lastly, REIVON will for the first time also look into the potential of a combination of ISO and LARF. For all three alternatives, REIVON will include a joint optimisation of network and aircraft to include both aircraft design and operational improvements as mitigation options and also do a comprehensive evaluation of the impact of the new procedures on aviation stakeholders, namely airlines, airports, air navigation service providers (ANSPs), passengers, manufacturers and airport neighbours.

3. General concept

Figure 1 shows the general concept used in REIVON that consists of modelling a baseline air traffic network and fleet, as per the Clean Sky 2 Technology Evaluator First Assessment Report [14], and the related CO_2 emissions, and then developing an optimised network according to the three REIVON approaches, together with the inclusion of new aircraft types that are better adapted to the typical combinations of route distances and passenger capacity into the new network.

The main steps are briefly described as follows:

Step 0: Collection of input data: Performance data of aircraft in the existing fleet are taken from PIANO (Project Interactive Analysis and Optimisation) [15], while the performance data of the new optimised aircraft designs (considered within the alternative scenarios) are obtained using the NASA Flight Optimisation Program (FLOPS) [16]. To model the baseline flight network, OAG data for the years 2000 and 2014 are used together with the DLR's internal forecast data for future air traffic (multiple years) until 2050 [14].

Step 1: From the baseline network and aircraft performance data, fuel consumption and, hence, CO_2 emissions for global traffic in the baseline years of 2000 and 2014, as well as future years up to 2050 will be calculated.

Step 2: Three alternative flight network scenarios will be generated and these correspond to the main approaches described in Section 1, i.e. replacing (a) direct long-haul flights by ISO operations, (b) frequent flights on busy routes with the LARF concept, and (c) a combination of both. Global fuel burn and CO_2 emissions will be calculated similar to the baseline cases in Step 1.

Step 3: The impact on aviation stakeholders will be determined; and for this purpose, suitable metrics are defined for all relevant impacts. Using these metrics, the impact on airports as well as on other stakeholders will be assessed.

Step 4: Finally, potential measures that could support the implementation of optimised networks together with aircraft types adapted to them will be proposed. Their effectiveness will be analysed at a qualitative level.

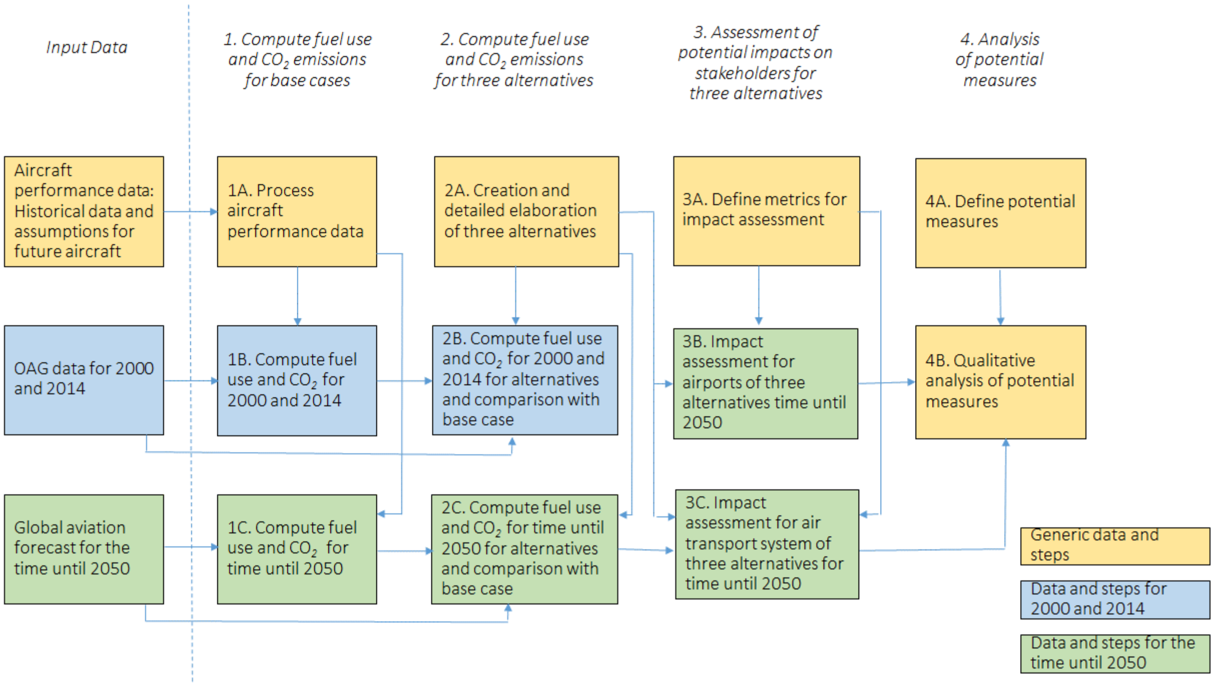

Figure 1: General concept of REIVON including interactions between the analytical steps and input data.

4. Data collection, optimisation process and emissions modelling

Figure 2 depicts the relationship between data collected, the optimisation process and emissions modelling, as outlined in Steps 0 to 2 of Section 3. These steps are crucial as they establish the baseline flight operations, fleet and network that will be optimised to produce the three alternative scenarios. These steps will determine the theoretical potential for reducing global fuel and CO_2 emissions, in addition to providing relevant data (airport movements, fleet composition, pollutant emissions, travel times and similar parameters) for the local environmental and stakeholder impact assessments. The optimisation process and emissions modelling will be described in further detail in Sections 4.1 and 4.2 respectively.

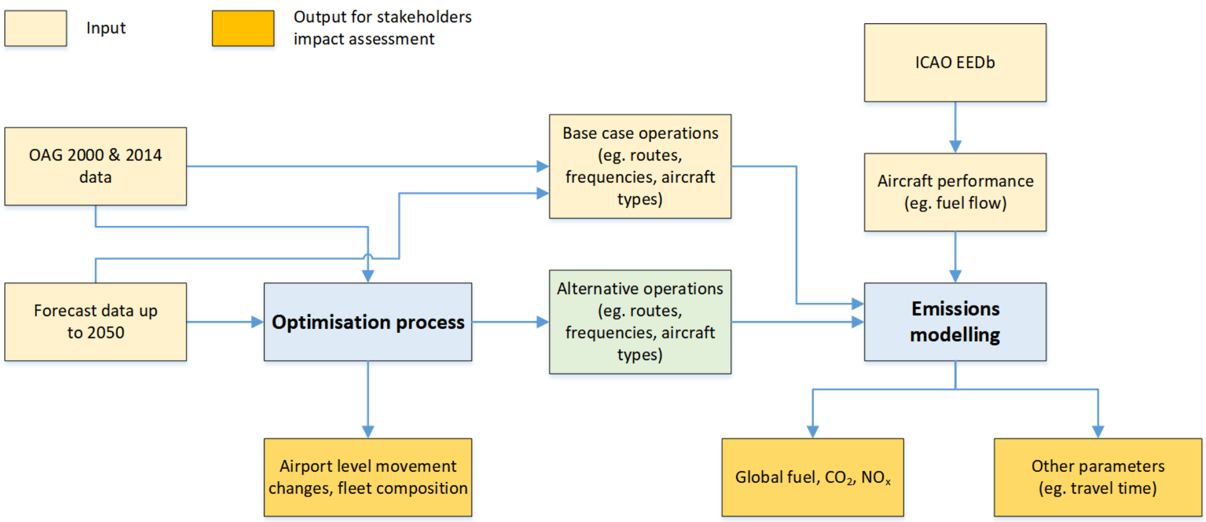

Figure 2: The relationship between the optimisation process and emissions modelling (Steps 0 to 2)

4.1. Optimisation process

The identification of alternative air transport systems of variable aircraft fleet and route networks with minimum CO_2 emissions while fulfilling boundary conditions is a complex combinatorial optimisation problem. Complexity reduction is required at an early stage to simplify the problem and reduce the computational effort without increasing uncertainty with respect to the optimum solution. Therefore, a number of preparatory steps need to be carried out, before the combinatorial problem is solved.

In order to be able to efficiently determine the CO_2 emissions of a given mission internal to the optimisation process, a response surface model will be generated. This model will consist of a set of formulas that allow for a fast calculation of fuel consumption and flight time as a function of aircraft design range, passenger capacity (i.e. number of seats) as well as the actual mission or stage length.

Saving potential for ISO is limited to mid- to long-haul routes, and for LARF to the busiest routes. We selected 2500 nm (ISO) and 1 million available seats per year (LARF) as first-guess lower limits to filter the entire flight plan and separate it into different datasets for the optimisation alternatives to reduce computational effort. Also, an airport database for the selection of the intermediate stop airport has to be compiled taking some suitability criteria, like available infrastructure and equipment into account.

4.1.1. Design response surface model

The aircraft design response surface model is generated using NASA FLOPS, a multidisciplinary system for preliminary design that can be used to vary certain design variables or optimise a configuration with respect to design variables [16]. The tool also provides the mission performance, i.e. mission profile, fuel consumption and flight time for design and off-design missions. Using published data for a set of reference aircraft types, the FLOPS tool will be validated and deployed to calculate the redesigned aircraft by varying the design range and seating capacity. The mission performance with the redesigned aircraft will be calculated for a set of off-design missions. The fuel consumption will be calculated for each aircraft derived from the combination of design range and seating capacity. A set of formulas correlating the relation between fuel consumption, design range, number of seats and off-design mission will be established, e.g. by using regression analysis. This will then be used in the optimisation chain. Similarly, a response surface for flight time can be generated as a function of aircraft design.

4.1.2. Optimisation Problem

A mathematical optimisation architecture will be set up to minimise the fuel consumption for the three alternatives. The pre-filtered datasets for each alternative will be used as the input flight plan. For the ISO alternative, a pre-processing step has to be conducted to create a shortlist of suitable intermediate-stop airports, which will be done using a "nearest neighbour"-algorithm from the midpoint of every long-haul route. A refinement of this geometrical approach will be investigated further. In principle, the optimisation architecture for all three alternatives stays the same. The different kinds of pre-processing steps of data and setting the constraints in a particular way will enable the optimisation to investigate different alternatives.

The main functionalities and constraints for the optimisation are as follows:

Target Function: The minimisation of fuel consumption will be accomplished via minimising the fuel consumption per flight, consisting of a route and an aircraft, multiplied with the frequency.

Constraints:

- *Demand:* The demand will be modelled via available seats per route. This shall be larger or equal to the actual forecasted demand.
- *Minimum frequency:* In case of ISO, the flight frequency shall not be decreased. Therefore, the frequency per route (on ISO routes, not on LARF routes) shall be the same or larger compared to the actual frequency.
- *Airport movements:* For the ISO alternative, it should be possible to limit the number of airport movements to avoid an unrealistic increase of flight movements at airports that are geographically well suited for intermediate stops.
- *Maximum number of aircraft types:* This constraint will allow the limitation of the number of different aircraft types to find a balance between maximal CO_2 reduction by using the optimal aircraft for each route and a limited number of aircraft types manageable by manufacturers and airlines.

A variation of constraint setups will allow the optimisation of different scenarios for each alternative to be conducted. The results of the optimisation will be post-processed and stored in a new and optimised flight plan. This will then be used for more detailed emissions and noise analyses.

4.2. Emissions modelling (global)

Fuel flow for the existing aircraft types will be derived from the PIANO database, while for the new aircraft types, a combination of PIANO and NASA FLOPS data will be used. The global aircraft emissions model, Future civil Aviation Scenario software Tool (FAST) [17] will use the operations data for the baseline cases and the alternative scenarios, along with the respective fuel flows and relevant emission indices from the ICAO Engine Emissions Databank [18] to compute global fuel use, CO_2 and NO_x emissions. During the emissions modelling process, other parameters that will be useful in Steps 3 and 4 such as travel time, operations and fleet changes will also be identified.

5. Impact on stakeholders

Both main REIVON approaches for flight network optimisation (ISO and LARF) have a considerable impact on a broad scope of aviation stakeholders, which is the main reason that they have not been widely implemented in the past. Contrary to previous studies, REIVON is studying these impacts in a systematic and holistic way. Figure 3 shows a schematic overview of the main stakeholders and the related impacts. These can be divided into two broad categories:

- Impacts at local (airport) level, i.e. affecting airport operators as well as airport neighbours;
- Impacts at network (air transport system) level, i.e. affecting mostly airlines and passengers as well as aircraft manufacturers and ANSPs.

5.1. Airport impacts

Impacts affecting the airport operator are essentially capacity and profitability.

The two REIVON network optimisation approaches have opposite effects on airport capacity: The ISO concept adds movements to the intermediate stop airports, and it must be ensured that their capacity is not exceeded; however, this is a concern only if airport capacity cannot be improved by simple means within the timeframe that would be needed to implement the REIVON network optimisation.

LARF operations reduce the number of movements, mainly at large hubs, which is a relief that would allow the introduction of future new flight connections at congested airports. However, the increased use of larger aircraft may require accommodations at airport gates and terminal buildings.

A detailed analysis of the relevant constraints and impacts at representative airports for the baseline and alternative scenarios is therefore being done. The environmental impacts on the airport neighbourhood are simulated with well-proven tools, namely LASPORT for local pollutant emissions (NO_x) and AEDT for noise. LASPORT is a standard tool for emissions and dispersion calculations approved for use by ICAO/CAEP. Emission inventories for each selected airport, year and scenario considered will be provided, using available emissions indices for existing aircraft and indices typical for the relevant engine category for re-designed aircraft.

Both airport capacity and noise impact studies are critically dependent on flight schedules: Capacity limitations are reached mainly at peak periods occurring several times per day. Noise sensitivity is much higher during the evening and night periods than during daytime. Changes in flight schedules can therefore modify the noise impact at departure, arrival and ISO airports, noting that many ISO movements are likely to occur in the night time.

5.2. Air transport system impacts

Both ISO and LARF operations have significant impact on airlines, passengers and aircraft manufacturers. The most obvious impacts are:

Passenger travel time: ISO flights always lead to longer travel times due to additional landing, turnaround and take-off. While LARF flights do not increase air travel duration, passengers have fewer choices for their preferred departure time, which will often result in personal time losses.

Ticket prices: This is a complex aspect as there are several opposing factors, especially for ISO flights (fuel savings vs higher staff costs). A detailed analysis is necessary.

Airline demand: Suboptimal travel schedules and durations could divert passengers from airlines offering ISO and LARF flight schemes towards airlines not operating to these schemes, and also potentially to high-speed ground transport in case of short-haul connections.

Fleet composition and flexibility: Full benefits of ISO and LARF flight concepts require optimisation of aircraft models for specific payload/range combinations. The best emissions reduction would be achieved if a large variety of models are available, which would allow the selection of optimal aircraft for each flight. On the other hand, this would increase complexity and costs for aircraft development and production for manufacturers. In addition, airlines, especially small ones, would not be able to procure a specific aircraft model for each route category, but may prefer versatile aircraft that can operate efficiently on many different routes and thus react flexibly for an evolving airline network.

The AERO-MS tool will be used to model the different REIVON scenarios, in particular, the number of operations and impacts on various stakeholders including air transport passengers (impacts on travel time and ticket prices), airlines (impact on passenger km transported and operating revenues) and aircraft manufacturers (impact on fleet size and new production requirements).

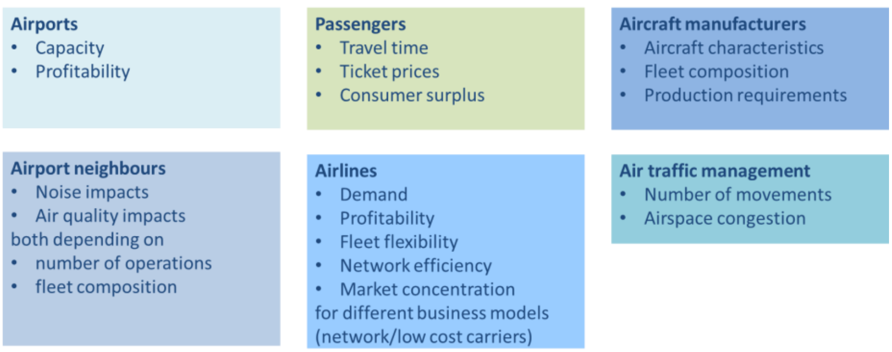

Figure 3: Aviation stakeholders affected by the REIVON approaches and related impacts

5.3. Multi-disciplinary assessment
The quantitative multi-disciplinary assessment of the REIVON scenarios will be done, taking into account all the aspects described previously, and discussed with representatives of the affected stakeholder groups, both via dedicated workshops and the REIVON Advisory Board.

6. Potential measures to support implementation
As seen in Section 5, there are various impacts of both ISO and LARF on stakeholders that would prevent a straight-forward implementation of these potential mitigation efforts. REIVON will provide a quantification of the overall emissions benefits of the approaches, which is an important contribution to an objective discussion of the pros and cons of such schemes. A clear demonstration of the environmental benefits is a prerequisite for implementation, but other measures are likely necessary to support it. Some first ideas for such measures include:

- Regulatory measures, which might include environmental aircraft certification standards, incentives for airlines to use aircraft at optimal range, and a reduction of airport and ATC charges for intermediate stops;
- Operational measures, such as favouring the optimised use of airports and aircraft sizes by the network manager, and preferential treatment of intermediate stop operations by ATC;
- Infrastructural measures to support airport capacity extension to improve ISO and to accommodate larger aircraft;
- Other measures, such as incentivising airline cooperation to offer flexibility despite reduced flights; this could also include aircraft pooling or creation of white label operators for use by multiple airlines;
- Compensation to interim stop airport neighbours for additional noise annoyance.

7. Summary and Outlook
Currently, the global air transport network and the choice of aircraft type for each flight route are not optimised for overall reduction of CO_2 emissions. The objective of the Clean Sky 2 project REIVON is to achieve this optimisation through the introduction of intermediate stop operations (ISO) on long-haul routes and the use of larger aircraft while reducing flight frequencies (LARF) on busy routes with numerous flights per day. As shown by earlier studies, the use of aircraft with optimised payload/range combination is an essential prerequisite for these concepts to be fully effective in terms of emissions reduction. REIVON puts a focus on the selection of suitable aircraft concepts, such as a high-capacity, short-to-medium range “people mover” for LARF operations.

Both the ISO and the LARF concept have a significant impact on aviation stakeholders, namely airports and their neighbours, passengers, airlines as well as aircraft manufacturers. The detailed modelling being done in REIVON will produce quantitative datasets allowing the evaluation of relevant environmental, economic and operational impacts on stakeholders. Once these results are available and if a significant CO_2 emissions reduction benefit of the network restructuring has been demonstrated, supporting measures will be proposed to enhance its implementation.

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9. Disclaimer
The content of this paper reflects only the authors' views and the JU is not responsible for any use that may be made of the information it contains.

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