MITIGATING AVIATION’S LONG TERM IMPACT ON CLIMATE CHANGE

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ABSTRACT:

The aviation sector claims to become ‘carbon neutral’ by 2020 and by 2050 even halve emissions compared to 2020. In this study we use an integrated global tourism & travel model to explore these claims and assess additional scenarios. The main conclusions of the study are that the sector’s current action such as the CO_2 standard, global market-based measures and sustainable biofuels fail to reach the carbon neutral ambition. 80-90% emission reductions can only be achieved with a ‘steady-state’ development for air transport. Economically, this is not necessarily a disadvantage for the sector.

1. INTRODUCTION

The civil aviation sector has currently a relatively small carbon footprint of about 2% of global CO_2 emissions [1]. However, the consistent growth of aviation of more than 5% per year over the period 1992-2005 [1] is expected to continue at rates between 4% and 5% in the mid-term future [2, 3] and this may cause a conflict between the agreed desire to keep climate change below 2 ° C as agreed during the UNFCCC (United Nations Framework Convention on Climate Change) COP21 (21st Conference of the Parties) meeting in Paris, December 2015 and the actual development of aviation’s emissions [4]. Efficiency improvements are considered to be insufficient to counter this trend [5]. The research presented in this paper shows aviation’s cumulative CO_2 emissions between 2015 and 2100 will use up between 25% and 50% of the total anthropogenic carbon budget agreed in Paris, 2015. Without significant reductions of air transport emissions, the Paris goals cannot be met.

Generally the economic and social effects of mitigation policies that reduce aviation’s growth potential, are considered very negative [6]. However, scenario studies like these tend to be based on models that limit their scope to air travel. The problem with this is that reductions of volume growth can only show negative economic impacts as the gains by other parts of the global tourism & travel system, like high speed rail, are ignored by the model or at best considered as an exogenous variable. In the study described in this paper, we consider the global tourism system including all transport modes and both domestic and international tourism. Tourism is here defined as suggested by the UNWTO (World tourism Organisation). UNWTO defines a ‘visitor as “a traveller taking a trip to a destination outside his/her usual environment, for less than a year, for any purpose (business, leisure or other personal purpose) other than to be employed by a resident entity in the country or place visited” and a tourist as a visitor “if his/her trip includes an overnight stay” [7].

The paper first describes the global tourism and transport model used for the study. It then proceeds by outlining a range of baseline scenarios showing growth of transport and emissions. This is followed by the development of three scenarios (‘ICAO’, ‘Green Skies’ and ‘Green Travel’) and a concluding section.

2. THE $GTTM^{DYN}$

The assessments in this paper are based on a new long term system dynamics model, the dynamic Global Tourism and Transport Model ($GTTM^{dyn}$). The scope of $GTTM^{dyn}$ is the tourism and transport system. In $GTTM^{dyn}$ the tourism & travel system consists of the accommodation and hospitality industries, service industries providing travel products and services, Meetings, Incentives and Conventions and Exhibitions (MICE) facilities and services [8]. Furthermore those parts of local tourism and leisure dedicated facilities (museums, zoos, lunar parks), restaurants, cafes, etc. that are used by tourists are also considered part of the tourism system. Regarding transport, again all transport as far as that used by tourists is part of the system. This means most of the air transport industry as some 90% of passenger air travel is tourism (including business , leisure and visiting friends and relatives) related while the tourism related share of global car and other transport is about 20% [9]. The tourism & travel system includes high speed rail as part of ‘other transport’.

The model describes the development of 60 travel segments (a combination of three transport modes and 20 distance classes). The time horizon is the period 1900 up to 2100. The 60 segments cover all trips as the transport modes are air, car and 'other' and the distance classes cover all possible one-way distances in the world from class average of 150 km return up to 31,700 km return. The core of the model is the combined trip generation and trip distribution over the 60 travel segments. The three transport modes are initially modelled using Bass models [10], a product or innovation diffusion model. Such Bass models assume that a new product initially only grows by commercial (marketing) efforts and that later also 'social' growth develops through word-to-mouth uptake of the product. The three transport modes as well as the twenty distance classes are not independent, but are coupled through 'psychological value' of each travel segment as defined in prospect theory [11]. This means that changes in volume, price and speed of air transport also affect the growth rates in car and other transport. The psychological value is based on a weighted sum of travel cost and time, is non-linear and uses a reference value that is determined by all values of all segments. A detailed description of the model is given by Peeters [12].

The model has been calibrated for 22 model variables describing the tourism system between 1900 and 2005. The Bass model was particularly important to allow for a totally new transport mode to emerge, aviation somewhere in the 1920s. Conventional econometric models generally have difficulties accommodating such new products. Also, the use of the psychological value as defined by prospect theory was necessary to create a model with a very long future time span and to accommodate very large changes [13]. Again, traditional transport economic theory fails in both cases.

Based on the trip distribution over the 60 travel segments, the shares per transport mode as well as the transport distances will be fully defined. From trips and distances all other aspects of the system are modelled including economics, accommodation use, CO_2 emissions and radiative forcing. Also the development of speed within the different transport modes has been modelled in an 'infrastructure module', based on insights from Peeters and Landré [14].

3. BASELINE SCENARIOS

GTTM^{dyn} provides a range of background variables to construct a multitude of socio-economic background scenarios. These scenarios provide the following assumptions within the model: GDP/capita, total population, development of income equity and global climate mitigation policies. A total of 192 combinations may be chosen. Figure 1 gives an overview of the 12 combinations of economic and demographic growth plus two additional extreme scenarios adding equity assumptions. The high extreme combines high economic and demographic growth with unlimited global emissions growth (ignoring eventual impacts of strong climate change on the global economy and air travel) and a strong increase in equity of income distribution. Increased equity may significantly increase air travel, mainly because it increases the group for which air travel becomes an economically viable option. This high growth shows CO_2 emissions to increase by a factor of 24.1 between 2015 and 2100. The low extreme is a combination of low economic and demographic growth, strong global climate mitigation (aiming at the Paris ambition of limiting the temperature anomaly to 1.5° C) and decreased global income equity. The effect of the Paris ambition is modelled by increasing global carbon costs and assuming these costs will also apply to air travel. The cyclic behaviour of air transport's emissions is caused by the cyclic character of air transport's fleet renewal process. The lowest growth scenario still results in 2.3 times the CO_2 emissions in 2100 as compared to 2015.

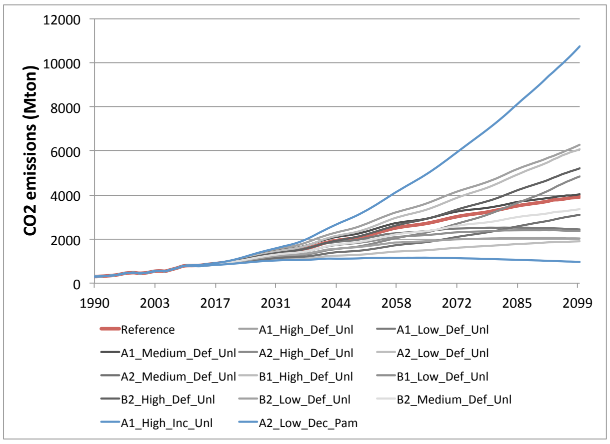

Figure 1. Overview of passenger air transport's CO_2 emissions for a range of background scenarios.

Figure 2 shows the range of air transport volume developments. Ignoring the income equity issue would significantly reduce the range of outcomes. Clearly, all combinations of socio-economic development result in growth of at least a factor of two by the end of this century over the current volume.

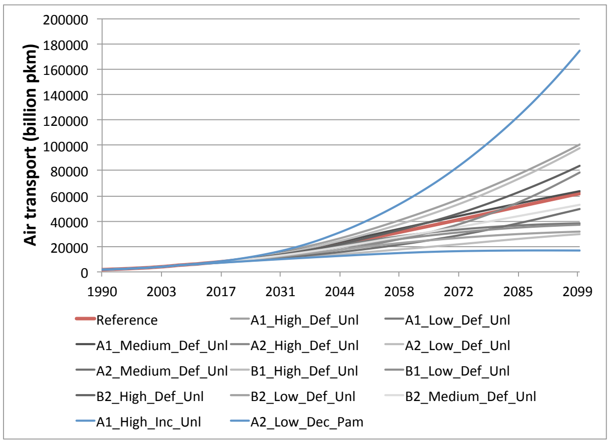

Figure 2: the development of passenger air transport volume in the baseline scenarios.

The Reference scenario, referred to in this paper as 'Reference case', has the following main growth characteristics in the year 2100:

- 7,400 million return trips (flights will be circa 4 times higher), 5.7 times higher as in 2015.
- 62 trillion pkm (passenger-km), 8.6 times higher as in 2015
- Average trip distance 8406 km return (5611 km in 2015).
- A global fleet of 125,600 aircraft over 23,540 in 2015.
- Annual ticket sales value of $2,466 billion (1990 USD) over $471 billion in 2015.
- 3908 Mton CO_2 emissions up from 833 Mton in 2015.
- Share of air transport in total tourism & travel transport is 36% of the trips, 76% of pkm and 83% of CO_2 emissions.
- Airport capacity: 149 million slots (30 million in 2015).

Even in 2100 the car with 49% of all trips forms the backbone of the tourism transport system. Air transport comprises 36% of all trips, while causing 86% of all tourism transport related emissions. This is mainly due to the much larger average trip distance for air transport based tourism.

4. SCENARIOS

4.1. Policy measures

In its simplest form, environmental impact is the product of the volume of a certain human activity times the emissions per unit of that activity. In this paper, volume is the number of pkm and the emission factor kg CO_2/pkm. Measures to reduce total emissions thus may either aim to reduce the emission factor or the volume. In this paper we will discuss technological improvements (assuming an accelerated trend to higher fuel efficiency and higher shares of turboprop and reducing the operational lifetime of aircraft i.e. the maximum scrap age), operational measures (cruise speed optimisation), alternative fuels, ticket taxes, a global carbon tax and a global airport slots limit as a proxy for any global volume-affecting measure.

Alternative fuels are one of the pillars of the sector's climate mitigation policy [15-18]. The most important advantage of biofuels is their so-called 'drop-in' ability: current bio-fuels can replace kerosene without the need for changes to engines and airframe or changes in the fuel distribution system [17]. This means no investment is needed in airport fuel infrastructure, aircraft and engines. Other alternative fuels like hydrogen, do require enormous investments in both airport infrastructure and airframe and engine design [19]. In this study we made a selection of one first generation - palm oil - and 4 second generation biofuels - micro-algae, Jatropha, Camelina and Switchgrass - [20]. Palm oil has been included as it is recently still proposed by the sector [17] even though many sustainability issues are connected to current large scale production of palm oil [21].

Item	Algae	Jatropha	Camelina	Switchgrass	Palm Oil	Fossil
Biofuel cost assumption ($1990/kg) 2015-2050	1.963-1.27	2.351-1.881	0.404-0.346	0.577-0.808	0.4837-0.8621	n/a
Net CO_2 emission factor (g/MJ (life cycle plus land-use change)	69	37	56	59	54	89
Yield (kg/ha/yr)	16435	779	2727	4869	3486	n/a

Table 1: Overview of biofuel feedstock assumptions (sources on [22-32]). The data are surrounded with large uncertainties [22]. We have tried to use some middle of the road estimates.

These were chosen because of their relatively widely different properties in terms of overall emission reduction performance, land use, cost technical availability, current use and other sustainability issues. We have omitted waste based feedstock for biofuels for a range of reasons and uncertainties.

Regarding the use of waste (e.g. cooking oil residues) there are serious volume limitations to cover more than a couple of per cent of fuel demand [e.g. for Australia 23], problems that are likely to increase when other sectors reduce their emissions by waste reduction. Using frying oils is another option sometimes mentioned, but just looking at some numbers this would, for the Netherlands, only supply about two days of flying from its main airport per year based on the 23000 ton potential frying oil [1] and circa 3.5 Mton kerosene bunkers at Schiphol [33].

Using agricultural residue is generally considered to be a 'free' sustainable feedstock but there are concerns this sustainability will be limited because of a range of problems as listed by [34] "even a partial removal (30–40%) of crop residue from land can exacerbate soil erosion hazard, deplete the SOC pool, accentuate emissions of CO_2 and other GHGs from soil to the atmosphere, and exacerbate the risks of global climate change".

However, also the use of the five crop based feedstock will be limited by both physical availability of suitable land and sustainable land use requirements [35]. Therefore GTTM^{dyn} requires a choice between physical or sustainable maximum volumes for biofuels as defined by the World Bank Group [29]: a maximum land use of 13,300 Mha as a 'physical' limit and 446 Mha as a 'sustainable' limit. It seems unlikely aviation can acquire all liquid biofuels produced in the world. The more the global emissions will have to be reduced (i.e. the higher the global mitigation ambition) the larger will be the demand for biofuels from other sectors. There is no concrete evidence of the strength of this effect and whether it might even be countered by for instance the introduction of non-biofuel based energy sources in other sectors. We have assumed the following for the share the aviation sector may ultimately acquire on the market:

- Unmitigated: 40%
- Moderate: 30%
- Paris agreed: 20%
- Paris Ambition: 10%

Further feedstock assumptions are shown in Table 1. A range is given when the property varies over the period between 2015 (first value) and 2100 (last value).

Figure 3 shows two sets of biofuel measures and the effect on the emissions pathway of passenger air transport. Following the sector's ambition to use only sustainable alternative fuels and assuming pure marked based replacement without further government incentives ('Sustainable fuels market'), may save some 4.2% CO_2 in the year 2100. If subsidies on biofuels are assumed to make them competitive to fossil based kerosene ('Sustainable fuels subsidised'), the overall emission reduction would be 7.5% in 2100 compared to the Reference case in 2100. Note that such subsidies would amount to some $660 billion per year (1990 USD's) and one may discuss whether such support of a sector serving mainly the wealthy minority in the world would be justified. Though there may be room for higher volumes of sustainably-grown feedstock, it seems clear that sustainability requirements will limit the effect of biofuels to a maximum of some 10% of net emissions reductions over the reference case.

Technology forms one of the main 'pillars' for the aviation industry [36]. For air transport, the drive for improved fuel efficiency is large and not only fuel cost driven: a more fuel efficient aircraft will also have improved pay-load-range and take-off and landing capabilities [37, 38]. We have taken the (slightly pessimistic) curve as proposed by Peeters and Middel [39] based on data given by Lee, Lukachko [40] for the Reference case leading to some 30% reduction by 2100 over 2005. Furthermore we assume a maximum possible reduction of 50% by 2100 over 2005. Based on this, the additional reduction turns out to be on average 0.2686%/yr. This would lead to a maximum evolutionary efficiency caused CO_2 emission reduction of 16.7% in 2100 over the emissions of the reference case. These measures exclude revolutionary technologies such as blended-wing-body aircraft layout, propfans and fully electric aircraft, because there is at present no serious work underway to develop such aircraft for the whole range of aircraft categories (combinations of seat capacity and range) [41]. Development of a 'conventional' clean sheet aircraft now takes over a decade from concept to entry into service. This time lag is expected to become greater over time. As aircraft can remain operational for up to 50 years and production of an aircraft type typically extends over one to two decades, it is clear that revolutionary technologies will not lead to large reductions of emissions even in this long term study [37, 41]. So we consider such measures to come available on the market at best at the end of this century but at volumes too small to be really effective.

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[1] See http://www.ecosupporter.nl/welke-afvalstromen/frituurvet-inzamelen.

Two measures may improve the average fleet fuel efficiency by changing the composition of the fleet: increasing the share of more fuel efficient turboprops [42] and early scrapping of old inefficient aircraft [43]. The effects are shown in Figure 3 and are 2.8% for turboprops and 2.2% for a scrap age limited to 30 years. The latter also shows a rather unstable effect due to 'shocks' occurring in the fleet development dynamics by this artificial operational life cut-off.

Capacity limits due to environmental constraints are a known and proven measure for several environmental problems such as noise and air quality [44]. Only recently has the possibility of restricting airport expansion because of climate change concerns started appearing in the international literature [45]. On the other hand, grass-root NGO's (non-governmental organisations) have started to link airport capacity limitations with climate change mitigation policies through such actions as "Stay grounded. Aviation growth cancelled due to climate change" [46]. The effect of a slot capacity limit is of course directly proportional to the strength of the measure. The example given in Figure 3 shows the maximum that GTTM^{dyn} can handle. This would reduce CO_2 emissions by 90%, but of course have disruptive consequences for the air transport sector, changing its current growth potential to a state of 'de-growth'. The effect on the tourism sector itself would be one of change but not necessarily disruptive as the total number of tourists is not necessarily affected by it, only the distribution of places of origin and destination change such that distances are significantly reduced and a strong modal shift away from air transport to both car and (high-speed) rail. Individual destination choice will also significantly change away from the small but emissions intensive number of long and medium haul segments to more low carbon short haul trips.

Another, softer, way to change the development of air transport volume is through taxes on air travel and subsidies for low emission alternatives. Taxes on air travel are generally not popular with the industry [e.g. 47]. But in the scientific literature there is much support for taxing CO_2 emissions as an economically efficient way to reduce emissions [13, 48-50], although there are also worries about effectiveness [51, 52]. We tested two measures at the maximum modelled in GTTM^{dyn}: A global carbon tax of 1000 \$/ton[2] CO_2 and an air transport dedicated ticket tax of maximum of 200% of ticket price. The effect of the rather extreme carbon tax - the literature discusses such taxes in the range of up to \$100/ton CO_2 [48] even though theoretical studies also consider taxes up to \$1000/ton CO_2 [53] - is 36% emission reduction with respect to the reference scenario. A 200% ticket tax results in 44% emission reduction.

A final measure we considered is optimising air transport's cruise speed for low emissions. It is known that the most economic cruise speed, providing the lowest direct operating cost per pkm – is higher than the most fuel efficient speed, generally defined as the long range speed [54]. Reducing aircraft speed below the long range speed will cause fuel efficiency to deteriorate, contrary for instance to the situation for land or water based transport where lower speeds provide a much larger window of opportunity for emission reductions. Reduction of aircraft speed will also cause some modal shift to other forms of transport as travel time is considered a cost. As the fuel consumption difference between economic optimum and long range is small and the speed reduction itself is also relatively small, the overall the effect is just 4.2% in 2100.

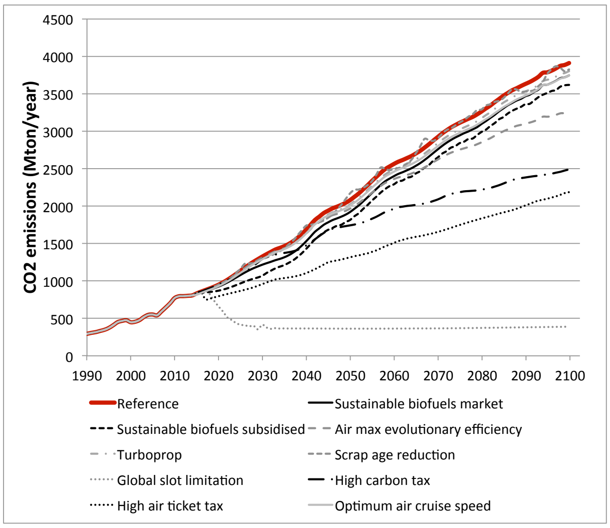

Figure 3: Overview of the effects of individual measures on air passenger transport's CO_2 emissions.

Apart from constraining slot capacity, none of the other measures considered is able to reduce air travel's emissions below its 2020 emissions. And only two were found to be able to reduce emissions by more than 30%: a global \$1000/ton CO_2 carbon tax and a 200% ticket tax. This shows that even very high individual financial measures are unable to reduce aviation's emissions. Therefore, a first conclusion is that only combinations of the measures at the most effective level will be able to reduce emissions below the level in 2020. In the next section we discuss

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[2] A global tax also on low carbon transport modes. Still such a tax would much benefit these low carbon modes over air transport and thus is effective.

several scenarios as there is clearly no 'silver bullet' solution. Only combined measures may achieve the emission reductions needed to achieve the Paris agreement level of ambition.

4.2. ICAO scenario

First we developed an 'ICAO' scenario. This shows the impacts of the aviation sector's ambitions for carbon neutral growth [18, 36]. The three main 'pillars' of ICAO's strategy are the development and implementation of a CO_2 standard for new and in-production aircraft types [55], introduction of global market based measures (GMBM) [56] and the introduction of biofuels [56]. The effectiveness of the more revolutionary technologies mentioned in the IATA 'Roadmap' [18] have been criticised previously, for instance by [57]. Since the chance that these revolutionary technologies will materialize within the 21st century, we will stick here to the measures ICAO proposes. These are the CO_2 standard, GMBM and, as a more voluntary option, biofuels.

The ICAO CO_2 standard, decided in February 2016, requires all new aircraft of in-production types certified before 2020 and produced after 2023 and all new aircraft of types certified in or after 2020 to comply with a metric value that is composed of the average of three specific air ranges (SAR in kg fuel per aircraft km) at three specified aircraft weights divided by a floor area based correction factor. The standard is not 'technology forcing' [58], meaning it cannot incentivise revolutionary technology as proposed by the industry [18]. The level of compliance – the stringency level – varies for different categories of aircraft and maximum take-off weight [36, 59, 60]. The effect of the CO_2 standard has been claimed to be a cumulative saving of 650 Mton between 2020 and 2040 [61]. However, 350 Mton of this reduction is assumed to emerge due to manufacturers modifying their products to comply between 2023 and 2028, while the standard in fact includes an exemption up to 2028 for new in-production types. Cumulative emissions for 2020-2040 as calculated for passenger transport with $GTTM^{dyn}$ are at least 45.9 Gtons CO_2, so the optimistic 650 Mton would represent some 1.30% of total CO2 emissions. This amounts to an additional saving of 0.1325 %/yr over the Reference case.

The proposed GMBM will only affect additional emissions after 2021 or even later over 2020 levels, thus excluding each year all emissions up to 2020 levels. Furthermore there will be very significant exemptions for flights to and/or from developing countries. So the GMBM will affect less then 50% of flights as the excluded domestic flights are already about 30% [62]) and initially only a small fraction of all emissions. The GMBM has two effects: the reduction of emissions elsewhere through buying credits on the global carbon market and some decrease of volume growth due to the cost of these offsets that will translate into higher ticket prices. For several reasons we ignore the reductions of emissions obtained elsewhere through offsets because in the mid-term this will become impossible. As Figure 4 clearly shows, global air transport emissions will exceed the maximum emissions allowed under the Paris 2015 UNFCCC Agreement or Ambition. In such a situation offsetting becomes meaningless as no credits will be available. The second reason is the issue of 'additionality' of offsets. Bartz [63] observes that even though proving additionality is core to the development of effective VERs (Verified Emission Reductions), those that in reality do make a difference in global emissions, there is still much controversy about how to prove this additionality. According to [64], alternative energy projects are particularly vulnerable to double counting and other additionality issues. Generally it is assumed that 'gold standard' verified VERs (GS VER) are the most reliable ones available. Indeed offset project reports including verification reports, are easily accessible from a website maintained by Markit, a commercial organisation. From the reports and evaluations of a certain Turkish GS VER project[3] the case for additionality is mainly based on the effects of current Turkish energy policies. Turkish policy gives preferential treatment to fossil energy based electricity production in terms of cost for state-owned infrastructure use and taxes. This causes an insurmountable commercial deficit for wind energy projects. But how can a 'solution' with VERs solve such a problem and make Turkish wind projects really reduce global emissions? The problem is that if aviation would reduce its own emissions, they would not buy the VERs and thus the Turkish wind projects would never evolve. So in either case global emissions stay at the current unsustainable level and are not reduced. Furthermore, buying VERs will not incentivise the Turkish authorities to change their policy nor incentivise the aviation sector to further reduce their emissions. The principle of 'additionality is also problematic under a Paris agreement because the required rate of reduction of global emissions is very high. To achieve this every possible option to reduce emissions needs to be captured leaving little to no room for the existence of 'additional' emission reductions.

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[3] See https://mer.markit.com/br-reg/public/project.jsp?project_id=103000000002544.

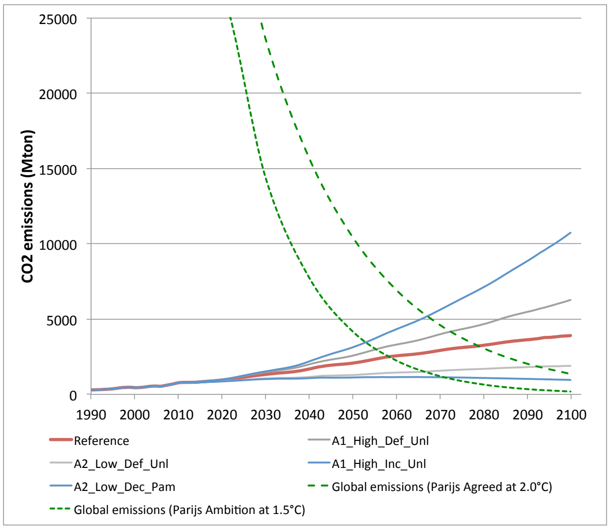

Figure 4: The air travel CO_2 emission baselines compared to global emissions pathways as agreed or proposed in at the Paris UNFCCC meeting, December 2015.

So we only modelled the cost increase of GMBM by assuming a ‘ticket tax’. Based on cost and emission data and estimates of the volume of offsets and their cost per ton CO_2 as estimated by ICAO/CAEP [65][4] we modelled the additional cost as a ‘ticket tax’ to simulate GMBM cost. These vary from 0% increase of cost in 2021 up to 4.4% in 2100.

Biofuel policies are less well defined by the sector although there is much speculation about ‘roadmaps’ [16-18]. Global sector emission reduction ambitions from the use of biofuels range from 20% to 50% [66]. One problem is that it is unclear who will pay for the subsidies needed to achieve such high levels of biofuel use. Some consider subsidies inevitable [23]. On the other hand, we found Camelina might be available at costs competitive to fossil kerosene. Another strong policy statement from the sector is the idea that biofuels should be sustainably produced [17]. The term SAF (“Sustainable Alternative Fuel”) is consistently used. Therefore we assume in the ICAO strategy the application of subsidies together with a sustainable land-use limit. Because the sustainability condition limits land-use and as algae have the highest yield per hectare, we assume subsidies for algae only. So overall we – optimistically – assume an ICAO CO_2 standard be contributing 0.133% additional technological improvement over the long term, a 1% ticket tax for air transport and subsidies for algae. Figure 5 gives an overview of the main results per individual measure and the total. We also assume that the proposed ICAO measures will be maintained to 2100. The CO_2 standard manages to reduce emissions by 4.3% in 2100, GMBM just 0.9% and SAF 4.2%. Combined the effect is 9.6% at a revenue loss of 4.8% in 2100 as compared to the Reference case in 2100.

The basic ICAO scenario does provide emission reductions at some revenue loss but it certainly does not result in the ‘carbon neutral growth’ from 2020, claimed by industry and ICAO.

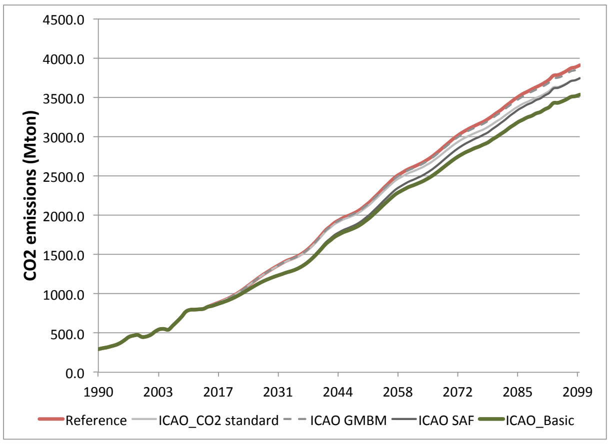

Figure 5: Overview of the ‘ICAO Ambition’ strategy results.

4.3. Green Sky scenario

We now present a scenario ‘Green Sky’, that explores the limits of mitigation assuming maximum evolutionary development of fuel saving technologies, subsidised biofuels and long range cruise speeds, all ‘sector conform’ i.e. avoiding measures compromising air transport’s growth prospects both in transport volume and net revenues.

First we have added the Paris Agreement global emissions pathway as the background scenario to the ICAO Basic scenario because in GTTM^{dyn} this will raise the carbon cost, including for aviation. At the same time some additional fuel efficiency will occur because of the additional cost of carbon. This is calculated using an abatement cost curve as described in [12]. Figure 6 shows the accumulated effect of adding additional measures. First we apply the ICAO scenario as described in section 4.2 reducing emissions by 9.6% in 2100 as compared to the Reference case. Adding the Paris agreement emission path assumption means global carbon cost will increase and air transport’s emissions reduce further to 15.5%. The next step is to add maximum evolutionary technology increasing the emissions reduction to 26.7%. Then

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[4] This is a confidential paper in possession with the author.

we assume subsidies on Algae based biofuels. This choice is made because under sustainable land-use conditions, land-use is limiting the maximum volume and algae has the highest yield per hectare. However, algae are very expensive and a fast market penetration can only be achieved through a 90% subsidy over the whole period 2015-2100 costing governments many trillions of USD per year. Total emission reduction will now be 32.4% with respect to the Reference case emissions in 2100. The last step is to assume airlines will fly as much as possible at long range speed and flight level (altitude) further reducing emissions to a total saving of 35.8% for the full Green Skies scenario. This is still a growth of emissions of a factor of 2.6 with respect to 2020 emissions and not in line with the 'carbon neutral' growth ambition of the sector.

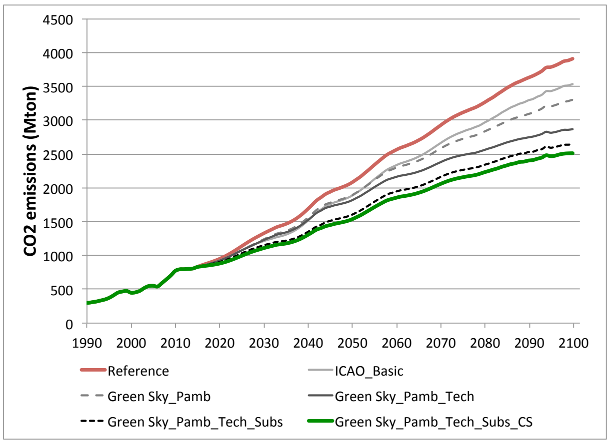

Figure 6: Overview of the accumulated effects of the Green Sky scenario.

Considering the revenues for the air transport sector adding carbon costs incurred to meet the Paris agreed global emission pathway results in an revenue loss of 10.3% in 2100 and the full Green sky scenario a loss of 19.5%, both compared to the Reference case. Revenues reduce also because only part of the carbon tax will be absorbed by increased ticket prices, the remainder has to be found through efficiency and possibly lower margins.

4.4. Green travel scenario

Would a Paris compatible scenario for air transport be possible and at what cost? To explore this question, a third scenario 'Green travel' is developed. This shows what mitigation efforts will be required to see the whole tourism industry better conform to the Paris agreement. It is important to include all elements of the tourism sector as this opens windows of opportunity for modal shift (less flights but more rail or car trips), and part of the mitigation being taken up by other transport modes and accommodations. It also tells us what the specific effects on aviation will be if such a tourism mitigation scenario is assumed.

We created a scenario based on strong measures, but avoiding extremes where the last additional saving would come at very large costs. For instance, the global carbon tax we have assumed is much lower as the \$1000/ton CO_2 maximum the model can handle but has almost exact the same effect within the context of all measures together. The complexity of the whole system, partly reflected in $GTTM^{dyn}$, most likely allows for further optimisation of cost versus emission reductions.

The goal is to keep emissions at a pace consistent with those for global emissions agreed upon in Paris. For the background scenario the following assumptions were made:

- Paris Agreed global emissions (2.0° C)
- Reference economic and population growth
- Decarbonisation of electricity production at 10% of 2015 value by 2035

Furthermore the following measures are assumed:

- Biofuels on the market with 90% subsidy for algae, Jatropha and Palm Oil at sustainable land-use limit[5].
- Fast change to 100% electric cars and maximum energy efficiency.
- Other transport (rail, coach, ferry) and accommodation emission factors reduced by 2.5% per year.
- Turboprop fleet aimed at 40% share (number of aircraft not capacity) by mid century.
- Continued high speed rail annual investment of 100 billion USD (1990) in 2015 increasing slightly to 110 billion in 2100.
- Global airport slot capacity reduced to 10 million flights.
- Global carbon tax starting at \$90/ton CO_2 (1990 USD) increasing to \$450/ton CO_2 in 2100.
- Global air ticket tax of 2% in 2015 increasing to 6% in 2100 (very high taxes have no effect on the global slot restriction).
- 7% cruise speed reduction (long range optimum).
- 30% increase of other transport speeds due to timetable optimisation (so additional to the effect of increased shares of high speed rail).

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[5] In this scenario it appears adding some Palm Oil and Jatropha provides some additional emission reductions due to the relatively poor net emission factor of Algae. Note the sustainability issues with palm Oil [21].

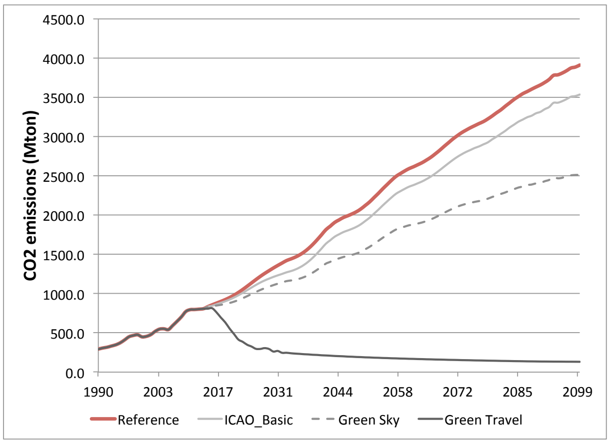

Figure 7: Overview of the CO_2 emission paths for air travel for the four main scenarios.

Figure 7 gives an overview of the four main scenarios showing the environmental superiority of the Green Travel scenario. Overall emissions reduce by 95.5% with respect to the Reference case and 80% compared to the emissions in 2020. The main cause for this is the effect of the global airport slot restriction, which effectively eliminates air transport's growth and reduces volumes to 2005-2010 levels, in other words, air travel will reach a 'steady state'. For the whole tourism & travel sector, emissions will be reduced by the same order of magnitude. Total number of tourist trips (for all transport modes together) stays equal to the Reference case, but the average distance travelled per trip will reduce by about 40%, mainly due to the much lower share of air transport. The average distance of air transport itself still increases by 20% compared to the 2020 value, thus the global air transport network is basically not compromised and air accessibility does not need to be compromised in this strong mitigation scenario. Figure 8 shows how transport modes shift in Green travel. In Green Travel air trips will move equally to both car and other transport modes, but the air transport volume (pkm) shifts mainly to (high speed) rail. Overall tourism & travel revenues stay the same as in the reference case.

The air transport sector will see large changes:

- Volume (number of trips) goes down to 70% of the Reference 2020 value.
- Transport (pkm) reduces to 80% of 2020 levels.
- The global fleet will stabilise at about 11,000 aircraft.
- Overall revenues will increase by 30% over 2020.

Though air transport growth reduces from a factor 5.6 (trips) to almost nothing, within the global tourism & travel system, this loss of growth is compensated for instance by an additional growth of 340% of transport volume (pkm) for other transport modes (mainly rail).

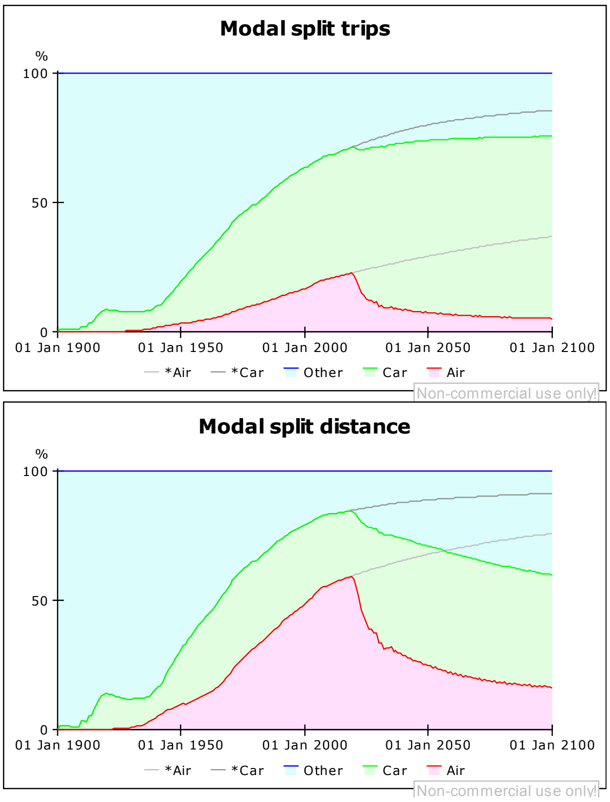

Figure 8: Development of modal split in Green travel scenario for number of trips (upper graph) and distance travelled. Note: the graphs include the full twentieth century history.

5. CONCLUSIONS

In this study we used a global tourism and transport model (GTTM^{dyn}) to explore policies to reduce tourism & travel related air transport CO_2 emissions. We first explored air transport development in a large range of socio-economic background scenarios and concluded that all show robust growth both economically as well as in terms of CO_2 emissions. The outcome varies extensively from a growth of 130% over 2015 in 2100 up to a 2310%. Air transport volume (pkm) and CO_2 emissions will grow by a factor 8.6 respectively 4.7 in the Reference case, showing efficiency gains are to be expected.

Then we explored dedicated measures and concluded that no single policy exists with the potential to significantly reduce emissions. Neither technology nor biofuels will reduce emissions compared to 2020 and only marginally compared to the Reference case. Also very high taxes are unable to stop emission growth. Only a global airport slot capacity limit resulted in emission reductions compared to current (2015) emissions.

Slot capacity limits are only one way to achieve 'hard' volume reduction. Alternatives with equivalent effects may be a global air transport dedicated closed capped emission trading system or a fleet capacity limit. The latter is a practice used in fisheries. Air transport capacity limitations will cause supply shortages and thus increase ticket prices and improve economic margins.

As single measures cannot generate the kind of emission reductions needed in the context of the UNFCCC Paris agreement, we combined policy measures in three scenarios. The ICAO scenario combined the pillars of the aviation sector's mitigation ambitions and found this scenario may potentially reduce emissions by up to 9% (in year 2100) compared to the reference case. Although we did include the price effect of global market based measures, we ignored the emission reduction of the voluntary offsets involved because of a range of issues with such offsets.

To explore the limits of an 'air transport sector' compliant scenario, we developed 'Green Skies'. This scenario assumes strong evolutionary technological developments, subsidised sustainable biofuels and long range cruise speeds. This scenario was more effective with a CO_2 emission reduction of 36% compared to the 2100 reference case. But still with growth of emissions by 160% compared to 2020, thus failing to provide 'carbon neutral' growth.

Therefore we also explored an ultimate mitigation scenario, Green Travel, that included measures in other sectors and aimed at bringing the whole tourism & travel sector emission pathway in line with the 2015 Paris agreement. This scenario achieved almost 80% CO_2 emission reduction in 2100 compared to 2015. This was achieved through a 'steady-state' economic development of aviation. Still the global tourism & travel sector overall will see the same increase of its revenues as in the Reference case. So an important lesson from an integrated assessment of the whole travel industry, as opposed to an air travel only study, is that the economic effects of the very large changes required to successfully mitigate tourism's CO_2 emissions can be kept moderate even though the effects very much differ between the main tourism subsectors.

A final conclusion is that the envisaged ICAO measures – CO_2 standard, GMBM and alternative fuels – will fail to achieve relevant emission reductions and will see aviation exceeding the entire global CO_2 emission budget as agreed in Paris, sometime between 2060 and 2090.

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