Policy Analysis

Specific Climate Impact of Passenger and Freight Transport

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Abstract

Emissions of short-lived species contribute significantly to the climate impact of transportation. The magnitude of the effects varies over time for each transport mode. This paper compares first the absolute climate impacts of current passenger and freight transportation. Second, the impacts are normalized with the transport work performed and modes are compared. Calculations are performed for the integrated radiative forcing and mean temperature change, for different time horizons and various measures of transport work. An unambiguous ranking of the specific climate impact can be established for freight transportation, with shipping and rail having lowest and light trucks and air transport having highest specific impact for all cases calculated. Passenger travel with rail, coach or two- and three-wheelers has on average the lowest specific climate impact also on short time horizons. Air travel has the highest specific impact on short-term warming, while on long-term warming car travel has an equal or higher impact per passenger-kilometer.

Introduction

It has been demonstrated that short-lived compounds can dominate the climate impact of various transport modes (1-3). Aviation, for instance, has a very high contribution from short-lived contrails and cirrus clouds (4-7). Consequently the climate response e.g. in terms of the resulting temperature change strongly decreases with time after the contrail or cirrus cloud formation. Other components emitted have a negative forcing, i.e. they cool the atmosphere. This is most pronounced for maritime shipping, where the net climate impact changes sign from negative to positive: For decades after the emission, the warming due to CO_2 is more than compensated by strong cooling from sulfate aerosols (both direct and indirect effects via clouds included) and by increased methane destruction due to the effects of NO_x on the oxidation processes (1, 2, 8-12). Similarly, for rail transport sulfur emissions from both electricity generation as well as diesel traction lead to a cooling that outweighs warming for up to decades.

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This paper analyses how the global climate impact of the different transport modes compares given (i) the time dependence of the sign and magnitude of their impacts and (ii) the different transport work, characteristics, and purposes of the modes. Knowing how to compare the impact of different, emissions, sources, and eventually sectors is necessary for a rational approach to mitigation across multiple sectors, gases, and aerosols. Quantitative comparisons of the impact are furthermore needed e.g. for an emissions accounting and trading scheme and for evaluating and prioritizing mitigation actions. Here, the global climate impact is calculated for passenger transport and freight transport separately. This allows for the first time normalizing transport's climate impact with the transport work. We discuss different measures for transport work and calculate the specific climate impact for each mode. This adds another dimension to analyses of climate impacts of transportation and to the discussion about efficient mitigation policies.

We calculate the response of the climate system to the emissions in terms of *net* average global surface temperature change (dT). As noted by several authors (e.g. refs 7 and 13), global mean values may hide important information about regional patterns of temperature change. However, the focus of this paper is to relate climate impacts of transportation to the transport work of the various transport modes.

In the following section the data, methods, and uncertainties are presented, section 3 compares the absolute climate impact between the modes. The transport specific climate impact is compared in section 4 for various measures for transport work. The influence of cooling and warming compounds and of future emission controls are discussed in the following section. The Supporting Information (SI) presents the results for the integrated radiative forcing (iRF) as climate metric and for passenger travel time and volume-kilometers as alternative transport measures. Furthermore, the sensitivity to lower road transport emissions is also presented there. Finally, the SI contains details on the modeling of the global transport emissions, the impact calculations, and on uncertainties.

Data, Methods, and Uncertainties

The climate impact of current emissions is calculated, i.e. a forward looking perspective is adopted as opposed to analyzing the current impact on the climate due to historic emissions. The impact of one year of global emissions is analyzed to understand the various processes; the impact from real world emissions can then be considered as a series of one year emissions, cf. ref 2. Detailed, up-to-date emissions data as well as consistent data on the global transport work for the year 2000 are taken from refs 14-16 for road, rail, air, and ship transport (cf. SI Tables 4, 5, and 7; emission data also accessible at www.ip-quantify.eu). All emissions are spatially explicit and input to sophisticated global climate chemistry models, accounting for transport, local chemistry, and meteorology. Road transport is further differentiated between five vehicle categories: mopeds, motorcycles, and three-wheelers (2wheel), cars and light duty vehicles (car), and buses and coaches (bus) in the case of *passenger transport* and light and heavy duty trucks (LDT and HDT) in the case of *freight transport*. Emissions are calculated bottom-up for the key countries in twelve major regions. Those countries account for more than 80% of total road transport fuel consumption and total road transport volume. The calculation is calibrated to the fuel consumption as reported by IEA for countries and regions (-17, 18) (cf. SI for details). All calculations refer to global totals or global average values that are actually dominated by long-distance transport. The analysis applies to the global transport system and not to individual trips, routes, vehicles, or technologies. This perspective is suitable for analyzing the total impact of a transport mode and comparing this impact with the use to society. To what extent modes can be interchanged in order to reduce the total impact is a separate issue.

The global mean temperature change (dT) is used as metric for climate change in the main body. The same calculations using the integrated radiative forcing (iRF) as climate metric are presented in the SI. Continuous values for transport's temperature impact have been presented in ref 2. Here we choose three distinct time horizons to illustrate the temperature change 5 years, 20 years, and 50 years after the emission. The short time horizon is adequate to capture the impact from clouds and aerosols; the trade-off between warming from ozone produced initially and subsequent cooling as more methane is oxidized is captured at the intermediate time scale. Finally, the impact from the long-lived gases, essentially CO_2, is captured on the scale of several decades. Our choice is furthermore justified as climate mitigation is defined as avoiding dangerous anthropogenic interference with the climate system in terms of *level* as well as *rate* of change. Therefore, a shorter time horizon is relevant to assess the impact in terms of rate of change, while the longer-time horizons rather relate to the absolute level of change. Which time horizon is however chosen is a political decision, and resulting values depend (sensitively) on it.

Global average dT-values per component were calculated for each transport mode (2). These numbers are rescaled according to the ratio between our updated emissions and the emission data used in the previous studies. This emissions' update affects notably road and rail transport. The (nonlinear) effects on ozone formation and the resulting methane lifetime change have been duly accounted for according to ref 19 (p 269) (details in the SI).

Given are $dT_{mode}(c)$ factors per unit emission Em of compound *c* for each mode (2). The fraction α of emissions due to passenger and freight transport is derived above for each compound and mode. This allows to calculate the global average climate impact factors (CI, can be dT or iRF) for a *passenger* (P) and *freight* transport (F) mode according to eq 1, for the example of the surface temperature change dT(P)

$$\mathrm{dT}_{\mathrm{mode}}(P) = \sum_{c} \mathrm{dT}_{\mathrm{mode}}(c)^{*}\alpha_{P}(c)_{\mathrm{mode}}{}^{*}\mathrm{Em}_{\mathrm{mode}}(c) \qquad (1)$$

The '*transport specific climate impact*' is defined here as the respective dT or iRF value divided by the transport work. This *transport specific climate impact,* sCI*,* is hence for each mode a function of the time horizon or the target year y chosen, of the climate metric employed and of the measure for transport work (cf. eq 2)

$$\mathrm{sCI}_{\mathrm{mode}} = \frac{\mathrm{CI(metric},\ y)}{\mathrm{tr.work}}_{\mathrm{mode}} \qquad (2)$$

Transport work is usually expressed as the product of the number of *passengers traveling times their average travel distance* in the case of passenger transport and of the *tons of cargo transported times their average transport distance* in the case of freight transport, called passenger-kilometers (Pkm) and ton-kilometers (tkm), respectively. Travel time and volume transported are also discussed as alternative denominators (see the SI).

Uncertainties result from both the climate impact calculations and the estimated transport work per mode. The modeling uncertainties along the impact pathway from emissions over changes in atmospheric concentration to resulting radiative forcing and a temperature change, i.e. the numerator, have been calculated in refs 1 and 2 and are adopted here (cf. SI Table 9). Uncertainties are lowest in the case of long-lived gases and very high in case of short-lived species with high radiative forcing (e.g., cirrus, contrails, and indirect effects of SO_2). Therefore, the overall uncertainty is the smaller the lower the share of short-lived species is for the total climate impact of a mode. For the same reason the relative uncertainty decreases with time, i.e. when the impact of short-lived species decays. The current transport work, i.e. the denominator in eq 2, is uncertain in terms of distance traveled and the passenger and freight turnover. For both exist statistics, and, importantly, the activity is constrained by the total fuel consumed for each mode. We calculate the standard deviation between 15% and 30% for each mode in terms of passenger-kilometer or ton-kilometer (cf. SI Table 11 for details). The combined uncertainty of the transport specific climate impact is therefore dominated by the uncertainty in the absolute climate impact, for each mode except for road transport (cf. SI Table 12 for details). The combined uncertainty is ±44% in the case of road transport and 1 order of magnitude higher in the case of aviation and shipping. The uncertainty for rail transport is in between these values. Similar uncertainties apply to our impact estimate per passenger-hour and volume-kilometer, as they are based on the same sources. Notwithstanding these significant uncertainties, the qualitative statements below remain robust.

Comparing the Absolute Climate Impact by Transport Mode

The *passenger* transport volume was about 30 trillion passenger-kilometers globally in the year 2000. Car travel accounted for 51% of the total volume, buses and coaches for 20%, air travel for 16%, rail for 7%, and motorized 2- and 3-wheelers for about 6%. The travel is powered to 98% by fossil fuels; regenerative fuels, mostly ethanol, nuclear and hydro power, contribute the remainder (14, 17, 18, 20). The emissions from the travel in this year alone will lead to an average increase of the surface temperature of 1.5 mK 50 years later. The relative contribution of the modes (Table 1) is almost equal to their share in fuel consumption on this long time horizon as the temperature response is primarily due to the forcing from the CO_2. The shorter the time horizon the larger becomes the role of short-lived compounds. Only 5 years after the emission, the global travel of the year 2000 with car, planes, bus, 2- and 3-wheelers, and rail have respectively contributed 1.75 mK, 2.1 mK, 0.35 mK, 0.2 mK, and −0.1 mK to a total surface temperature change of 3.9 mK. Thus, the short-term temperature increase from one year of global air travel is higher than that from one year of road passenger travel, although passenger aviation is more than a factor of 3 and 4.5 lower in terms of transport volume and fuel consumption, respectively. The short-term aviation impact gets strongly enhanced by induced cirrus clouds, ozone, and contrails. Their combined warming in terms of GTP_5 is more than eight times bigger than the warming from aviation emitted CO_2 alone. The impact from car travel is increased by the warming due to ozone and black aerosols (BC) that more than outweigh cooling effects from sulfate aerosols and methane destroyed as a consequence of NO_x emissions. These same effects also enhance the shorter-term warming from bus and coach travel. As both are essentially diesel powered, the contribution from both black carbon and sulfate aerosols are proportionally higher. With a high share of two-stroke engines notably in Asia, the global fleet of motorized two- and three-wheelers emitted relatively high amounts of CO and unburnt HC. Therefore their short-term climate impact is strongly enhanced by a high warming contribution from ozone. For rail travel however, the warming due to carbon emissions, ozone, and aerosols is more than offset by cooling from sulfate aerosols on short-time horizons. High SO_2 emissions notably from the electricity produced in coal fired power plants lead to a strong cooling from sulfate aerosols.

Table 1. Transport Volume and Fuel Consumption by Transport Modes in the Year 2000 Globally and Resulting Average Surface Temperature Change (dT) 5, 20, and 50 Years Afterwards

			temperature change at year *y*		
	transport volume, 10^{12} pkm/tkm	fuel consumption, Tgoe	dT_5, mK	dT_{20}, mK	dT_{50}, mK
passenger transport	*30.1*	*1145*	*3.94*	*1.72*	*1.50*
car	15.4	783	1.75	1.30	1.03
bus	6.2	108	0.35	0.11	0.13
2wheel	1.9	40	0.20	0.13	0.06
ship	na	21	−0.41	−0.08	0.01
aviation	4.7	166	2.12	0.22	0.23
rail	2.0	26	−0.07	0.04	0.04
freight transport	*56.4*	*772*	*−1.66*	*−0.04*	*0.88*
LDT	0.63	145	0.38	0.25	0.20
HDT	6.4	361	0.81	0.22	0.44
ship	42.6	176	−3.46	−0.63	0.12
aviation	0.14	48	0.62	0.06	0.07
rail	6.6	42	−0.01	0.06	0.06
total transport	**na**	**1917**	**2.28**	**1.68**	**2.38**

The *freight* transport work was about 56 trillion ton-kilometers globally in the year 2000. Maritime shipping accounted for three-quarters of it, rail, heavy, and light trucks for 12%, 11%, and 1%, respectively. Air freight accounted for 0.2% of the total transport volume (14, 20). One year of emissions from this transport will lead to an average increase of the surface temperature of 0.9 mK 50 years later. Heavy and light trucks, ships, planes, and trains will contribute about 0.4 mK, 0.2 mK, 0.1 mK, 0.07 mK, and 0.06 mK, respectively (Table 1). Thus road freight transport contributes five times more to the warming from freight transport than its share in global transport volume, air cargo even 40 times more, while ships contribute five times less than their share in transport volume. In fact, shipping's high SO_2 emissions lead to a high burden of sulfate aerosols in the maritime environment. These aerosols scatter back light; this cooling is for a few decades stronger than the warming from the CO_2 emitted. In addition, as ships emit in relatively pristine areas their NO_x emissions lead to a much higher ozone formation when compared to an equivalent emission from road transport on the continents (1, 21). The warming from this extra ozone is however more than balanced by the ensuing destruction of methane. The net temperature effect from shipping is negative on time scales of up to three decades (cf. SI Table 2). As pointed out by ref 12 the SO_2 emissions and their cooling effects do not necessarily lead to a benign effect on climate even if the cooling reduces the global mean temperature.

Table 2. Ranking of the Specific Climate Impacts of Passenger and Freight Transport Modes Relative to Car Travel and Truck Transport Respectively (=100)[a]

Freight Transport

	dT_5		dT_{20}		dT_{50}		iRF_{20}		iRF_{100}		iRF_{500}	
	per ton-km	per vol-km	per ton-km	per vol-km	per ton-km	per vol-km	per ton-km	per vol-km	per ton-km	per vol-km	per ton-km	per vol-km
aviation	3570	1430	1375	550	720	290	4210	1685	1475	590	875	350
LDT	485	195	1175	470	460	185	855	340	555	220	450	180
HDT	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
rail	−1	−5	25	99	12	49	9	38	12	49	12	47
ship	−64	−260	−44	−175	4	17	−72	−290	−11	−44	3	11

Passenger Transport

	dT_5		dT_{20}		dT_{50}		iRF_{20}		iRF_{100}		iRF_{500}	
	per pkm	per p-hr	per pkm	per p-hr	per pkm	per p-hr	per pkm	per p-hr	per pkm	per p-hr	per pkm	per p-hr
aviation	400	4660	56	650	74	860	250	2910	130	1500	90	1080
car	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
2wheel	90	45	79	39	47	23	97	49	64	32	48	24
bus	50	33	20	13	33	22	30	20	31	21	33	22
rail	−30	−30	24	24	29	29	0	0	20	20	27	27

a Mean global temperature change (dT) and integrated radiative forcing (iRF) over different time horizons and for various measures for transport work.

The temperature impact from heavy and light trucks is enhanced on short time scales. NO_x, CO, and VOC emissions lead to ozone formation; their warming is however more than offset by cooling from reduced levels of methane and sulfate aerosols in the first years after the emission. However black carbon emissions lead to a strong, but short-lived warming, such that the temperature increase 5 years after the emission is about 0.8 mK and 0.4 mK, respectively. The short-term impact from air cargo is strongly enhanced due the high short-lived contributions from clouds, as already discussed for passenger air travel. Thus, 5 years after the emissions, air cargo transport has resulted in a global average warming of 0.6 mK. On the contrary, the shorter -term impact from rail transport is reduced. In the same way as for passenger travel, the SO_2 emissions from power plants result in cooling aerosols.

As a result of the strong cooling from maritime shipping, the net temperature impact from freight transportation has been negative, i.e. cooling for the first years. Thus, freight transportation offsets the warming from passenger transportation on shorter time horizons.

Comparing the Specific Climate Impact by Transport Mode

The transport work performed varies considerably between the modes, and this is one important reason for different magnitudes of their absolute climate impact. Popular are comparisons of the fuel consumption or of the related CO_2 emissions per transport work, e.g. refs 22 and 23. However they measure the share in emissions only, i.e. are ignorant about the *impacts* or *response* of the climate system to the different emissions on various time scales, and they ignore all but one relevant gas and implicitly adopt a long-term perspective on climate change since short-lived effects are omitted. Here we calculate the ratio of the full climate impact (CI) for the comprehensive range of species as determined above and of the transport work from the year 2000 for each mode (cf. eq 2).

Per passenger-kilometer the transport specific climate impact is lowest for rail and bus travel and highest for car and air travel (Figure 1a). At long time horizons, i.e. when the impact of CO_2 prevails, the transport specific climate impact of car travel is larger than air travel on global average (yet not significant at 1 SD). Both are then about three times higher than the impact from bus and rail travel. Cars are relatively inefficient and have low average occupancy, while buses have on average a high load such that their resulting specific climate impact becomes comparably low as rail's.

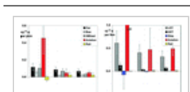

Figure 1. Temperature change per transport work by mode for various years after the emissions: per passenger kilometer for passenger travel (left) and per ton-kilometer for freight transport (right). Global average values for the year 2000. Bars represent 1 SD.

On short time scales however, the transport specific climate impact from aviation is strongly enhanced, while rail's impact is reduced (cf. SI Tables 1 and 2 for details per mode and compound). Air travel's specific climate impact becomes four times higher than the impact from car travel per passenger-kilometer at 5 years time horizon. On the opposite, rail travel has a negative, i.e. cooling impact in the first years following the emission. Surprisingly, the specific climate impact from motorized two- and three-wheelers is as high as from cars within the first years after emission. This is the consequence of high to very high VOC and CO emissions leading to a high ozone formation and, in the absence of significant NO_x emissions, a reduced methane destruction. In other words, average travel in the year 2000 with a moped, typically in an Asian country, caused as much (shorter-term) warming as traveling by car, typically in an industrialized country for the same passenger kilometer. However, on time horizons of decades the difference in specific fuel consumption and the related CO_2 emissions dominates giving rise to about twice as much warming from cars than from motorized two- and three-wheelers. Furthermore, the global travel volume by cars is eight times higher than the volume with motorized two- and three-wheelers. The ratio between the least and the highest warming per passenger-kilometer is a factor of four on the long time horizon; on the time horizon of years the ratio grows to a factor 10 and more.

For freight transportation the differences between modes is even more pronounced. *Per ton-kilometer* the transport specific climate impact is by far lowest for rail and shipping and highest for light trucks and air transport (Figure 1b). For dT_{50} the warming from rail or ship transport is 8 and 25 times lower compared to average truck transportation in the year 2000, while transportation in delivery vans or planes resulted in 4 to 7 times higher warming per ton-kilometer. In other words, rail and ship are very efficient, on global average, for mass transport, while air cargo and delivery vans are not. The shorter the time horizon the higher the specific climate impact of aviation. The very strong additional warming from induced cirrus clouds, ozone, and contrails enhances the specific impact in the same way as for air passenger transport. For dT_5 the specific climate impact of air cargo becomes 35 times more warming than average truck transport. For shipping and to a lesser extent also for rail, sulfate aerosols lead to a net cooling in the first decades after the trip. Thus, the ranking in terms of transport specific climate impact is not changed when considering shorter time horizons; but relative differences are amplified to now 3 orders of magnitude.

Distance traveled is not the only aspect of passenger travel; *travel time* is equally important. Likewise, volume requirements determine in many cases the vehicle size and the number of trips and hence the total vehicle-kilometers required for freight transport. Therefore we also calculated the climate impact per passenger-hour and per volume-kilometer as alternative measures for transport work. Rankings remain the same, but differences to aviation are magnified for passenger transport, while the spread between modes becomes lower for freight transport. Full results are presented in the SI.

Climate Impact under Future Emission Controls

The results presented above depend on the composition and amount of gases and aerosols emitted per mode. There will be important changes due to better control of exhaust emissions in the future. Their impact on the most important compounds is analyzed for each mode individually:

For *shipping* the warming CO_2 and ozone is by far offset by cooling from sulfate aerosols and reduced methane in the short- and medium term. These contributions depend among others on the amount of SO_2 and NO_x emitted by ships. Recent regulation of the International Maritime Organisation is expected to decrease SO_2 emissions per kWh by 80% and NO_x emissions per kWh by up to 20%, each in the long term (24), i.e. after fleet renewal. In consequence, much less sulfate aerosols would be formed, less light scattered back, and hence cooling from ship emissions would be strongly reduced. Reducing NO_x emissions would also reduce cooling via methane. But this effect is of much lower importance. Thus, the climate impact of shipping would grow strongly on all time horizons (Figure 2, left). This means that, first, ship emissions would contribute within a few decades (and not within centuries) to global warming, e.g. as illustrated by dT_{50} (Figure 2). Second, and on the global scale more important, cooling due to ship emissions would not outweigh any more the warming from the other freight transport modes on short to medium time horizons. On the contrary, global freight transport would become visible as an activity adding to global warming from early on. While a desulfurization of the shipping fuels would reduce adverse impacts on health and the environment, global warming would be increased. See also refs 9, 12, and 25 for calculations of current and future climate impacts of shipping. Notwithstanding these important changes in the longer term, shipping would still have the lowest transport specific climate impact, i.e. per ton- or volume-kilometer.

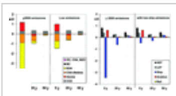

Figure 2. Comparison of temperature change for various years after the emissions due to ship emissions with standard y2000 emissions and with reduced SO_2 (−80%) and NO_x (−20%) emissions. Temperature change per compound for shipping (left); temperature change of freight modes (right).

The high specific climate impact of *motorized two- and three-wheelers* per passenger-kilometer, as calculated for the year 2000, is a consequence of high emissions of hydrocarbons and carbon monoxide leading to a strongly enhanced ozone formation. In the meantime, more stringent exhaust emission regulations have been implemented in the biggest markets, China and India, and technology has largely shifted from highly emitting 2-stroke engines to cleaner 4-stroke engines (26, 27). To simulate the impact of this technology change we assume an 80% decrease of hydrocarbons and CO emissions per km compared to the average level in the year 2000. Then much less ozone is formed per trip and short-term warming from two-wheelers becomes much lower (Figure 3, left). In consequence, the specific climate impact of two-wheelers is less than half the impact from car travel *per passenger-kilometer* already at short time horizons (Figure 3, right). This difference essentially reflects the different fuel efficiencies. Thus such a control of air pollutant emissions is beneficial for mitigating both air pollution and shorter-term climate change.

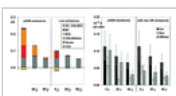

Figure 3. Comparison of temperature change for various years after the emissions due to motorized two- and three-wheelers with standard emissions for the year 2000 and with reduced emissions (CO, VOC, OC: −80%). Temperature change per compound (left); specific climate impact of road passenger modes per passenger-km (right).

The short-term climate impact of *aviation* is dominated by warming from cirrus clouds, contrails, and ozone. The aviation industry has committed itself to further reducing its environmental impact in general and its climate impact in particular (28). Efforts are focused on increasing fuel efficiency and reducing NO_x emissions. For this sensitivity calculation it is assumed that these measures would reduce CO_2 emissions and NO_x emissions by 20% each *per passenger-kilometer* on fleet average. Consequently the short-term warming from ozone would be slightly reduced. However, as long as aviation induced cloud effects remain as high, marginal change in e.g. NO_x emissions results in only a very small reduction of the overall warming on the short time horizons (Figure 4). Aviation's specific climate impact per passenger-kilometer on the shorter time scales would still be two to three times higher than car travel's impact. Nonetheless, any reduction in CO_2 emissions per passenger-kilometer reduces the climate impact on the long time horizons. If road vehicles were not to reduce their climate impact in the future as well, then future air travel could have a somewhat lower impact *per passenger-kilometer* than average car travel, but still two times higher than travel by bus or rail (Figure 4). This once more underlines the importance to address aviation induced cloud effects as the single biggest warming agent from aviation. One way to approach this problem would be to develop forecasts of regions that are supersaturated with respect to ice. It has been shown that persistent contrails form under these conditions (29). The flight control could then redirect the aircrafts to avoid flying in these regions, however possibly at the expense of higher fuel consumption. Hence, there would be a trade-off between the short- and the long-term warming impact.

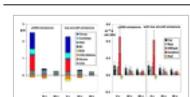

Figure 4. Comparison of temperature change for various years after the emissions due to aviation with standard emissions for the year 2000 and with reduced CO_2 and NO_x emissions (−20%). Temperature change per compound (left); specific climate impact of passenger modes per passenger-kilometer (right).

Recent studies of how BC emissions from aircraft alter the physical and optical properties of clouds indicate that these emissions may result in either positive or negative RF effects (warming/cooling) (30, 31). The estimated values, sign, and even existence are very uncertain as they depend on the mode of nucleation in the background atmosphere and the specific nucleation properties of aircraft soot emissions (6). More studies of these effects are needed. If the negative forcing is confirmed, the warming from aircraft would be lower than previously thought. However Haywood et al. (32) recently indicated that the warming from aviation induced cirrus may have been underestimated.

Road vehicles are expected to reduce exhaust emissions, increase fuel efficiency, and reduce the carbon contents of the fuel (33, 34). The impact of a reduction by 75% of NO_x, BC, VOC, and CO and a 20% decrease of CO_2 emissions, each per kilometer, are calculated in Figure 2 of the SI. In conclusion, reductions of air pollutant emissions from road vehicles affect the ratio of the short-term specific climate impact notably between two-wheelers and cars, but the ratio between road in general and the other modes remains rather stable. The long-term climate impact is determined by the CO_2-intensity of the transport; here air and car travel are at a similar level per passenger-kilometer, but aviation has a ten to twenty times higher impact per hour traveled.

Discussion

The specific climate impact of a mode is a function of emissions, climate metric, time horizon, and transport work (cf. eq 2). Summarizing, modes are ranked according to their specific impact (Table 2); cf. SI for results on the integrated radiative forcing (iRF), passenger-hour (p-hr), and volume-kilometers (vol-km).

An unambiguous ranking can be established for the *freight transportation* of the year 2000: The specific climate impact of air transport is 3 to 42 times higher, for a light truck it is 2 to 8 times higher than average truck transport. Rail transport of heavy goods has a 4 to 10 times lower specific climate impact than trucking, while it varies from negligible to half to a similar impact for volume products. Ship transport has by far the lowest climate impact: It exerts 5 to 10 to 30 times less warming per transport work than trucking and is even cooling on shorter time scales. This ranking holds for both climate metrics and both measures for transport work; most importantly it is robust for the time horizons considered.

For the *passenger travel* of the year 2000 the modes with clearly lower specific climate impact than car travel can be readily identified: Rail travel has at least a factor 4 lower specific impact and is cooling on shorter times, bus and coach travel has 2 to 5 times lower specific impact, while travel with two- or three-wheelers has up to a factor 2 lower specific climate impact than car travel. Air travel results in a lower *temperature change per passenger-kilometer* than car travel on the long run; the integrated radiative forcing of air travel is on short- to medium time horizons much higher than for car travel. Per passenger-hour traveled however, aviations climate impact is a factor 6 to 47 higher than the impact from car travel.

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Supporting Information

Results for the integrated radiative forcing (iRF) as climate metric and for passenger travel time and volume-kilometers as alternative transport measures. Furthermore, the sensitivity to lower road transport emissions is presented there. Finally, the SI contain details on the modeling of the global transport emissions, including regional fuel efficiencies of the modes, on the impact calculations and on uncertainties. This material is available free of charge via the Internet at http://pubs.acs.org.

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