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Evolving Narratives of Low-Carbon Futures in Transportation

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ABSTRACT *Scenarios of low-carbon transport demonstrate that a vast range of different outcomes is possible and contingent on policy, technology and cultural developments. But a closer look indicates that different schools of thought suggest possible pathways diverging in their fine structure. This perspective reveals how three different scientific communities — integrated assessment modelers, transport-sector modelers, and place-based modelers — emphasize distinct solution domains. While integrated assessment models focus on fuel composition, transport-sector models put slightly higher emphasis on efficiency measures; in turn place-based research specifies idiosyncratic behavioral and infrastructural mitigation options that are likely to be beneficial in realizing local co-benefits. These specific local approaches could mitigate urban transport emissions by 20–50%, higher than that revealed in aggregate global models. We discuss differences in approach, possibilities for reconciliation, and the implications of normative assumptions. Targeted three-directional interactions would foster comprehensive understanding of possible low-carbon transportation futures.*

For mitigating climate change, transportation increasingly moves into the spotlight. More than a quarter of overall energy use is allocated to the transportation sector, causing 22% of global energy end-use-related CO_2 emission (International Energy Agency [IEA], 2012). Three quarters of these emissions originate in road vehicles, and half of the latter in urban transport (IEA, 2013). The CO_2 emissions from transport increase faster than that in other sectors, as developing economies rely increasingly on the transport sector with structural change from the industrial to the service sector (Kahn Ribeiro et al., 2012; Schäfer, Heywood, Jacoby, & Waitz, 2009). At the same time, mitigation remains daunting: mobile end-use requires costly high-density energy carriers, such as electric batteries or hydrogen, or biofuels with sometimes ambiguous environmental impact (Kahn Ribeiro et al., 2012; Sims et al., 2014).

What are the main options to reduce greenhouse gas (GHG) emissions in transportation? In principle, mitigation in transport can be decomposed into reducing the carbon intensity of fuels, enhancing the energy efficiency of vehicles, shifting modes, and reducing demand (Bongardt et al., 2013; Creutzig & Kammen, 2010;

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Creutzig, McGlynn, Minx, & Edenhofer, 2011; Figueroa, Lah, Fulton, McKinnon, & Tiwari, 2014; Schipper, Marie-Lilliu, & Gorham, 2000). Modal shift and demand reduction can both be understood as behavioral changes and as the result of infrastructure modifications. A diverse set of literature analyzes mitigation options across these decomposition factors. Here, we study three sets of literature on transportation futures.

The first two are global, aggregate and synoptic: integrated assessment models (IAMs) and transport-specific models of the International Energy Agency (IEA). The other set is particularistic, place-specific and fine-grained case studies of local transport. These sets of literature were chosen because they have different scope, distinct disciplinary background, rely on different modeling approaches, and as a result also highlight different sets of solutions (Table 1). Together they cover most of the literature on transport and climate change mitigation, as discussed within the Intergovernmental Panel on Climate Change (IPCC) (Sims et al., 2014).

This paper investigates the focus and findings on relative quantitative importance of mitigation options in each set. The first two sets of literature are well established in global assessment on transport and climate change, but less so the third. Hence, the emphasis of this investigation is on (local) behavioral options and their mitigation potential. The results show that synoptic IAMs focus mostly on fuel choices, IEA studies on energy efficiency and avoid/shift, and local studies on a diverse set of behavioral options. Synoptic IAMs specify economic growth and mitigation of climate change as their objective function, relying on a generic (global) price on CO_2 emissions. Local studies are more likely to explore rather than optimize low-carbon futures; also, they often investigate a mix of demand- and supply-side policy instruments, and specify local co-objectives, such as air quality and reduced congestion. We conclude that the framework of analysis and implicit normative assumption determine the focus of mitigation options, in terms of both descriptive emphasis and quantitative evaluation.

Methods

A web-based literature research with the keywords 'climate change mitigation' and 'transport/transportation' was conducted. Papers that fall in either of three classes were selected: (a) Global climate stabilization scenarios with resolution on transportation and equilibrium between sectors (13 studies); (b) Transport-sector-specific studies, without equilibrium with other sectors (13); (c) place-specific studies (25). All studies accepted for the review had to include scenarios. Studies were excluded when they were reviews, books, or had a policy focus. For each study, the keywords displayed in Figure 1(a) and 1(b) were searched and counted. A log-transform was applied on each individual count to dampen paper events with extreme counts. The statistics are discussed in the context of the assumption and solution space of these papers.

The disciplinary background of the three perspectives was quantitatively examined by determining the educative background by the CVs of authors (Table 1). Five different disciplinary clusters were considered: economics, physics, geographical studies (including urban sciences, architecture, and sociology), engineering and non-physics nature sciences, including notable public health, and environmental sciences. Double counts were allowed if degrees were in more than one field. For complete statistics see the appendix.

Table 1. Characterization of epistemic communities investigating low-carbon futures in transportation based on statistics from the paper surveyed

	Scope	Dominant discipline	Solution focus	Approach	Strength	Weakness
IAMs	Global, all sectors	Economists (50% of authors)	Technologies and fuel shift	Deductive with techn. parameter input	Integration/equilibrium between sectors	Only generic representation of efficiency and behavioral options
Transport sector models	Global, transport sector	Engineers (40%) and Environmental Scientists (33%)	Efficiency and infrastructures	Inductive transport-specific input	Understanding techn. options in transport	No equilibrium with other sectors
Place-based models	Local	Public Health (38%) and Geographers (30%)	Behavior and infrastructures	Inductive place-specific input	Idiosyncratic identification of multiple objectives & policies	Lack of upscaling beyond place

Note: See Text for explanation and Methods for the statistics on the dominant discipline.

Global Synoptic Transportation Futures

Global synoptic energy/economy/environment models investigating low-carbon futures include (a) macro-economic, top-down, general equilibrium models that compute equilibrium effects between economic sectors, as, for example, resulting from technological change, climate policies, or fuel price shocks; (b) bottom-up partial equilibrium models with often higher technological specification but that keep most macro-economic dynamics exogenous; and (c) hybrid models that combine the individual advantages of bottom-up and top-down models, that is, economic comprehensiveness and technological explicitness (Schäfer, 2012). Most IAMs belong to hybrid models (the MIT economic projection and policy analysis model belongs more to the macro-economic model class) and have centered their attention on exploring (optimal) climate mitigation scenarios, especially in the IPCC context (Fischedick et al., 2011). Their explicit goal is to analyze global comprehensive climate change mitigation across all emission sources and sectors (Figure 1(a)). They aim to achieve certain mitigation targets, for example, measured in restricting GHG emissions, at lowest costs possible (Figure 1(a)). In IAMs, transport is investigated as subsector, and transport technological options are analyzed as part of an economy-wide carbon policy (Kim, Edmonds, Lurz, Smith, & Wise, 2006). Compared to the power sector, the transport sector has been less well investigated in IAMs (fewer studies and scarce representation of the end-use characteristics of transport) (Fischedick et al., 2011). In these models, the decarbonization of the transport sector is understood to be comparatively challenging, because (a) the envisioned low-carbon transport technologies are argued to be more costly than options in the power sector; (b) it requires technological change for billions of end-users compared to technological change of a few economic agents in the power sector; and (c) it requires the substitution of the energy carrier oil, which is highly valuable due to its high energy density. In other words, the challenge goes beyond the primary energy source and includes the storage medium (Barker, Pan, Köhler, Warren, & Winne, 2006; Luderer, Bosetti, et al., 2012). The structural change of economies from industrial societies toward service economies also predicts a more than proportional increase in the size of the transport sector (Schäfer et al., 2009). As a result of an inelastic demand with respect to the oil price, strong behavioral effects, and assumed high costs in technology deployment, a global carbon price is assumed to be less effective in decarbonizing transport compared to other sectors. Oil remains the main source of primary energy that powers transportation, which renders the transport sector the main emitter of CO_2 emissions at the end of the twenty-first century in some models (Azar, Lindgren, & Andersson, 2003; Clarke, 2007; Luderer, Pietzcker, Kriegler, Haller, & Bauer, 2012).

IAM models combine an economically minded framework with details on technologies, fuels, and efficiency, often adapted from the engineering literature. The evolution of important variables such as economic growth and technological progress are determined by the interplay of exogenous assumptions and model dynamics. A crucial tenet is the application of optimal cross-sectoral mitigation with market-based equilibrium concepts (Figure 1(b)). For example, results from one modeling exercise imply that the transport sector would decarbonize slower in the presence of carbon capture and storage, as price pressure is comparatively smaller; in turn, large-scale availability of concentrated solar power would push market penetration of electric cars (Grahn et al., 2009).

As solutions, IAMs find that both efficiency gains and fuel shifts can contribute about 25% emission reduction compared to baseline in 2050 (Figure 1(c)), while also reporting wide uncertainties based on different techno-economic characterizations, nesting structures, and substituting elasticities (Clarke et al., 2014; Sims et al., 2014). While efficiency is usually modeled as a generic dimension, representing energy efficiency improvement at constant prices[1] and the market reaction to price signals, fuel shift is displayed in higher detail in IAMs. Most of the long-term options for mitigation are realized by fuel shift and generic efficiency improvements (Figure 1(c)). Modal shift and behavioral option have until recently not been investigated (see below for exceptions). The IPPC's special report on renewable energy reports illustrative scenarios with IAMs pointing to 10–27% biofuels and 7–12% electricity in 2050. The modeling exercises in the IPCC's 5th Assessment Report (AR5) see biofuels as the most important low-carbon fuel in 2050, but hydrogen and electricity dominating overall fuel shares in 2100 (fig. 8.12 in Ch. 8; Sims et al., 2014). A detailed model comparison with focus on the transport sector reports unqualified agreement in its resolution on fuel shift, especially in the second part of the twenty-first century, along with generic efficiency improvements, but disagreement on the kind of fuels: some models prefer biofuels, while others focus on electric cars or fuel cell vehicles (Pietzcker et al., 2014).[2]

There are, however, increasing exceptions to the focus on fuel shift. For example, a global model — that is focused on aggregate variables such as travel time budget and travel money budget — indicates that these and other behavioral factors might contribute to up to 50% reduction in activity compared to baseline between 2005 and 2100 (Girod, van Vuuren, & de Vries, 2013). But behavioral and infrastructural options remain outside the usual scope of IAMs because they cannot easily be operationalized in monetary costs but are closely entangled with quality of life, norms, and cultural values.

Transportation-Sector Models

Transport demand models, in contrast to the energy/economy/environment models limit themselves on the transport sector, and besides climate change mitigation also address transport-specific issues like congestion (Figure 1(a)). Hence, for example, the fuel shift in the electricity sector is taken as a boundary consideration; optimal mitigation strategies across sectors remain uninvestigated. In turn, infrastructure and modal shift options are well represented, highlighting the contribution of climate change mitigation on the demand side. At the core, however, are traditional considerations of efficiency improvements in vehicles, fuel economy and the technology behind it. The IEA takes a highly visible position in this community, gathering expert knowledge and translating it into their models. Traditionally, the IEA's emphasis has been on energy use and the supply side, for example, on oil markets, highlighted in its annual World Energy Outlook. In its 2009 report *Transport, energy and CO_2: Moving towards sustainability*, the IEA (2009) made a decisive step in contributing toward mitigation solutions in the transport sector. The report identifies "how the introduction and widespread adoption of new vehicle technologies and fuels, along with some shifting in passenger and freight transport to more efficient modes, can result in a 40% reduction in CO_2 emissions below 2005 levels", for 2050. The language reveals a prioritization of technological options, such as fuel economy, followed by the identification of modal shift options. In the scenario that combines all mitigation options, about 70% reduction versus baseline is achieved in 2050, with about 45% of the mitigation attributed to fuel shift, 35% to efficiency improvements and 20% to modal shift. The investigation of fuel shifts puts an emphasis on end-use vehicles technologies. In its 2012 Energy Technology Perspective, the IEA is comparatively more pessimistic, suggests only 57% reduction compared to a 2050 baseline in its combined scenario,[3] mostly because of a reduced contribution from fuel shift, reflecting that low-carbon fuels are taken up more slowly than previously expected. In this report, the demand-side component is now explicitly split up into modal shift and activity reduction (Kahn Ribeiro et al., 2012; Sims et al., 2014), for example, by better infrastructure planning (IEA, 2012). Their combined contribution remained similar to that of the 2009 report (ca. 1 $GtCO_2e$). The IEA investigates the latter two options in more detail in its study A tale of renewed cities, emphasizing the urban location of this class of mitigation options, albeit without providing additional quantification. Importantly, the contribution of modal shift and activity reduction is calculated after fuel shift and efficiency. This results in a relative small absolute contribution of about 1 $GtCO_2e$ mitigated as efficiency gains and fuel shifts have already rendered modes more similar in their specific energy use per distance traveled and specific GHG emissions, and points to the general challenge of unambiguously attributing emission reductions along a chain of options (Fulton, Lah, & Cuenot, 2013). Modal shift and activity reduction would contribute more to mitigation if they precede fuel shift and efficiency gains.

Overall, this body of literature is in broad consistency with IAMs (Figure 1(c)), but puts special emphasis on describing technological end-use options and especially efficiency gains such as fuel economy improvements. It focuses on the next decades up to 2050 but rarely beyond that time frame. Models are less economically motivated, ignoring inter-sectoral equilibrium effects, but extrapolate detailed understanding of experts on technological developments and demand-side options.

Place-Specific Models

Place-specific models limit themselves to one or a small number of locations, often cities. They comprise a variety of methodological approaches, that is, based on econometrics, or on agent-based modeling and investigate infrastructure effects, demand-side responses of policies, and urban development. The location-specific analysis is highly relevant as urban transport emissions constitute 40% of all transport emissions (IEA, 2011, 2013). Activity reduction opportunities in urban, mostly but not exclusively private, transport have been best studied. Public health and environmentally minded models tend to be more optimistic about the potential, and focus more on induced welfare benefits, while more economically minded studies tend to be more conservative on the potential, and emphasize undesired economic welfare losses. Urban modeling studies mostly consider multiple objectives besides climate change mitigation, including congestion, physical activity benefits, air quality and accessibility (Figure 1(a)). The global aggregate demand effect of behavioral and infrastructure change has not yet been estimated. Box 1 elucidates the potential effect that urban demand-side measures could have until 2050.

Box 1. Estimating the potential of reduced activity and modal shift options

This box scopes the existing literature in to derive a tentative estimate of how much reduced activity and modal shift options can contribute to climate change mitigation. Clearly, a more comprehensive meta-analysis would need to further substantiate or modify this estimate.

Urban planning. Urban planning that reduces the distance between residential location, jobs, and activities also reduces transport GHG emissions. Compactification is seen as a main strategy for reducing emissions.[4] A econometric study on the USA suggests that a compactification/ in fill scenario between 2005 and 2054 would reduce urban transport-induced GHG emissions by up to 63% compared to the business-as-usual scenario, a rather speculative value (Marshall, 2008). A more detailed meta-study concluded that compact versus sprawled development reduces GHG emissions only by 20–40% (the precise magnitude depending on density, diversity, design, destination accessibility, and distance to transit, and the baseline scenario). Hence, compact development in the USA, compared to business-as-usual development, could enable 7–10% reduction in distance traveled and associated GHG emissions between 2007 and 2050 (Ewing, 2007). Similarly, a reasonable increase in population density in California would decrease fuel consumption by only 5.5% (Brownstone & Golob, 2009). Three English case studies, investigated by a detailed land-use/transport model, revealed about 5% reduction in distance traveled in a compactification scenario (in years 2001–2031) compared to trend (Echenique, Hargreaves, Mitchell, & Namdeo, 2012).

Modal shift by pricing and infrastructure provision. Both pricing of private motorized transport and provision of alternative mode choice encourage modal shift. Parking prices can reduce distance traveled by 2–12% (Salon, Boarnet, Handy, Spears, & Tal, 2012), and congestion charging can reduce distance traveled within the charging zone by 10–20% (Eliasson, 2008; TFL, 2007). In two cases studies of London and New Delhi — focusing on improving public health — a modal shift from car and motorcycle toward active travel (walking and cycling) would reduce GHG emissions by 38% and 47%, respectively, in 2030 (Woodcock et al., 2009). An evaluation of Beijing urban transport demonstrated that an economically optimal combination of congestion charging and investments into bus rapid transit would reduce distance traveled by up to 30% (Creutzig & He, 2009).

Soft incentives and information. Soft incentives can change the behavior of traffic participants. Changes in car distance traveled for telecommuters are large (50–75%) but absolute city-wide average effects are unclear; employer-based trip reduction achieve car distance travel reduction of about 4–6% among participants, with region-wide effects of about 1%; voluntary travel behavior change programs achieve city-wide car distance travel reduction of up to 5–7% (Salon et al., 2012). Similarly, a UK study identified a potential of altogether 11% in reduced traffic by soft measures such as marketing, information and tailored new services (Cairns et al., 2008). In addition to directed information measures, social network and spillover effects can lead to nonlinear uptakes of low-carbon modes such as cycling (Goetzke & Rave, 2011).

Combination of measures. In four European cities, a combination of pricing, non-motorized and public transport investment, and compactification, could enable up to 50% reduction in urban transport GHG emissions from 2010 until 2040 (Creutzig, Mühlhoff, & Römer, 2012). The contribution of land-use planning is the highest where population grows the most. A case study of Bengaluru, India, sees a potential of 36% reduction in GHG emissions reduction versus a trend scenario within 20 years, by combining subway line building with land-use planning and pricing instruments (Lefèvre, 2009). A mix of urban planning and public transport subsidies (excluding pricing of car transport) results in 36% reduced vehicle km compared to baseline in a model of 2030 (Viguié & Hallegatte, 2012).

With similar demographics and GDP/capita, Barcelona consumes 11 times less CO_2/capita in urban transport than Atlanta (Lefèvre, 2010; Newman & Kenworthy, 1999). This documents the wide range of possible choices in developing cities, especially in China and India.

Overall, urban planning could reduce GHG emissions from urban transport by 5–10%, with significantly higher values expected in rapidly growing cities, by 10–30% by pricing measures and infrastructure provision for non-motorized and public transport, and by around 5–7% by information. A combination of these measures might achieve between 20% and 50% reduction in GHG emissions by activity reduction or shifted transport until 2050 relative to baseline growth, though the additivity, synergies and trade-offs between these measures deserve further research.

Box 1 focuses on private urban transport for which a wide range of literature is available. Freight transport has been less investigated and is likely to be more challenging, as modal shift is often not an option (Sims et al., 2014). The demand on freight transport depends crucially on demand in goods, underlying consumption patterns, and specific pattern of world market integration. For example, a shift in tariff preferences from proximate and land-adjacent regions to global integration would lead to twice as much transport emissions than trade-related product output emissions (Cristea, Hummels, Puzzello, & Avetisyan, 2013). The literature on activity changes in aviation and maritime transport is also limited. A number of studies suggest that demand reduction versus baseline in aviation is essential to reduce the overall emissions from the transport sector (Bows, Anderson, & Mander, 2009; Chèze, Chevallier, & Gastineau, 2013) with a net change of aviation demand growth rate of up 8–12% in tourism (Peeters & Dubois, 2010). Other studies suggest that moderate demand measures could be part of a portfolio approach to stabilize GHG emissions from aviation (Sgouridis, Bonnefoy, & Hansman, 2011). The literature hints at plausible activity reductions in maritime and aviation transport but remains inconclusive on the overall magnitude and normative evaluation.

In total, the potential of activity reduction to mitigate climate change in transport — and their comprehensive economic evaluation (including co-benefits) — remains highly uncertain; the systematic evaluation of demand-side measures to reduce transport emissions on a global level remains scarce. For urban transport, existing studies suggest that 20–50% reduction in GHG emissions by activity reduction or shifted transport is possible between 2010 and 2050 compared to baseline development. If aviation and freight are also considered, demand mitigation is likely to be smaller.

Comparative Evaluation

Next, the aim is to more systematically compare the three scientific communities across certain criteria, such as model architecture, emphasis in the solution space, and strength and weaknesses. For this, a small database of 51 relevant publications, chosen with relative strict criteria, is developed and evaluated (see Methods). Due to the relative small size of the literature data base, results remain tentative but are indicative for further improvements of low-carbon future modeling in transportation.

The analysis of the different scientific communities reveals a number of differences (Figure 1(a–c); Table 1). The IAM community is dominated by economists, designing models that are synoptic, aggregate models, and in tendency more deductive than inductive, that is, relying more on models and certain assumption spaces but less on observed data (Table 1). IAMs operate economy-wide, envisage long time scales (up to 100 years), and focus on climate change mitigation across sectors (Figure 1(a)). Their narrative focus is on the decarbonization of the energy supply, which means for the transport sector a fuel shift from oil to electricity, hydrogen, and/or biofuels (Table 1; Figure 1(b)). Their scenarios operate in unknown futures, need to rely on a number of uncertain assumptions, and hence, they report a broad ranges of plausible scenarios. Transport-sector models, in contrast, operate on shorter time scales (20 or 40 years) and also address other transport objectives such as accidents and congestion (Figure 1(a)). Transport-sector models are more dominated by researchers with engineering and environmental sciences background (Table 1). These in tendency more inductive models emphasize efficiency improvements in transport technologies in this time frame, while also seeing important roles for fuel shifts and avoid and shift measures (Table 1; Figure 1(b)). The results of these two communities broadly agree on the relative importance of efficiency improvements, fuel shifts, and demand-side effects and/or measures for climate mitigation. Nonetheless, the IEA reports a plausible reduction of 30–40% GHG emissions in 2050 compared to 2005, whereas the IAMs see only stabilization at 2010 levels in their median model results under ambitious mitigation. The reason for this divergence is based on the different underlying baseline scenarios of growing demand (Figure 1(c)). The IEA sees not more than a doubling of overall transport demand between 2005 and 2050, but the IAMs report higher demand growth. IAMs project energy demand either by importing exogenous pathways or by endogenously, deriving it from population and income dynamics and equilibrium effects in economy-wide global energy markets, whereas the IEA scenarios are more grounded in recently observed trends. This methodological difference might explain the divergent baseline scenarios.

The gap between IAMs and transport sector models and place-based approaches is wider than that between the first two. This is obviously rooted in different spatial scope — global vs. place based — and often different objective functions: the place-based approach embeds climate change mitigation into a broader set of objectives such as congestion, air quality, and public health (Figure 1(a)). Geographers, public health researchers, and other non-physics nature sciences dominate these local inductive models (Table 1). The spatially dis-

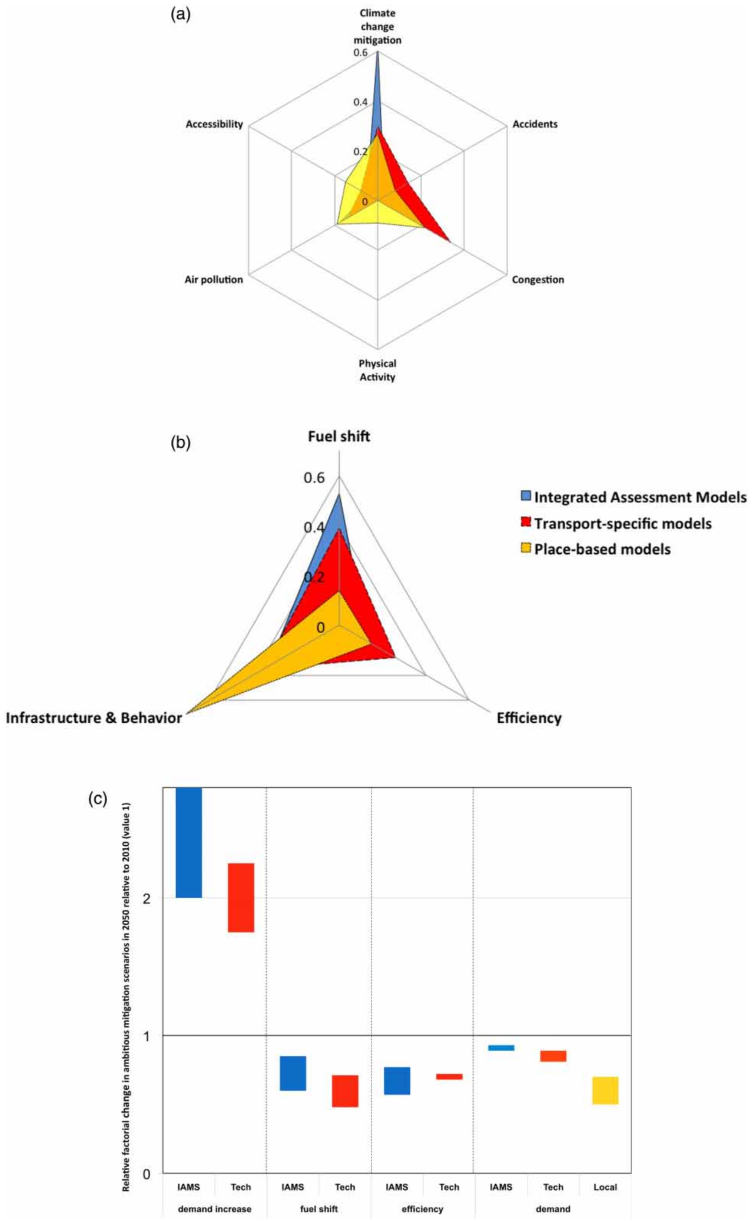

Figure 1. Comparison of modeling approaches. (a) Relative frequency of objectives in the literature reviewed (based on 51 publications, see Methods). IAMs are most focused on climate change mitigation, whereas place-based approaches display commonly multiple objectives and co-benefits. (b) Relative frequency in wording of solution options (based on 51 publications, see Methods). Place-based approaches focus on behavior and infrastructures, IAMs on fuel shifts (‘biofuels’, ‘hydrogen’, ‘electricity’) and transport-specific models on efficiency (‘fuel economy’, ‘modal shift’). See methods and SI for more detail. (c) Solution space. Solutions are broadly consistent between communities. Baseline assumptions explain the difference between IAMs and transport-specific models. Place-based approaches emphasize a relatively large potential in urban infrastructures and behavior. IAM ranges represents 25–75 percentile of AR5 scenarios (Edenhofer et al., 2014). ‘Tech’ ranges represent values from IEA (2009) and 2012 studies (with IEA, 2009 higher estimates in fuel shift compared to IEA, 2012a; but IEA, 2012a higher values in demand change). ‘Local’ is estimated by the author (see Box 1).

tinct perspective also leads to different emphasis on sometimes idiosyncratic infrastructure measures and behavioral options while considering technological change and fuel shift at best in a background scenario (Figure 1(b) and 1(c)).

Both global and place-based approaches have their shortcomings (Table 1). Global models, by necessity, consider demand and infrastructure changes generically, for example, by modeling a demand response on increasing CO_2 prices. But if local solutions lead in an emergent way to systematically new classes of transport behavior, a price elasticity approach would be insufficient to capture such local dynamics (price elasticities change dynamically with changing infrastructures and norms). In turn, place-based approaches, when blind to global and inter-sectoral dynamics, cannot analyze global mitigation pathways and are at risk of wrongly extrapolating local trends. For example, the current debate on 'peak travel' rightly observes that transport demand, especially but not only in urban areas in OECD countries saturates (Goodwin & Van Dender, 2013; Kenworthy, 2014; Metz, 2013; Millard-Ball & Schipper, 2011; Newman, Kenworthy, & Glazebrook, 2013).[5] But in some 'peak travel' literature, urban transport measures, such as the expansion of public transit and cycling infrastructures, are implicitly understood as the major instruments to mitigate climate change in transport. This view, however, ignores that most additional transport demand originates in developing countries, especially in Asia, and that the most rapidly growing mode is aviation, diminishing potential savings in automobile transportation.

Reconciling Narratives

Recent publications aimed to narrow the gap between the different perspectives. Three aspects are central for an attempted reconciliation: resolution of the economy, resolution of technologies, and resolution of place-based behavioral and infrastructural considerations. The first two have been successfully integrated in IAMs. The transport demand models of the IEA constitute an example with lower economic resolution but with slightly more consideration of infrastructure and behavior. However, overall, the place-based results of mitigation options — originating in urban planning, infrastructure provision and behavioral change — remains largely unconsidered in global models. The systematic treatment of place-specific options in reducing global GHG emission in transport emerges hence as a major challenge for future modeling efforts (Pye, Usher, & Strachan, 2014; Schäfer, 2012). But the two communities already move toward each other. Three examples help to exemplify the tentative convergence.

First, the IEA models increasingly display and discuss modal shift and behavioral options. In the 2012 model results, 'avoid' and 'shift' options were reported independently, whereas in 2009 they were lumped together. California and US-specific studies relied on a model framework with high transport-technology resolution to identify both supply- and demand-side measures to achieve up to 80% in GHG emissions by 2050 (McCollum & Yang, 2009; Yang, McCollum, McCarthy, & Leighty, 2009) (Figure 2).

Second, Girod et al. (2013) combined the transport demand model approach by Schafer (1998) with IAM models and introduced behavioral categories, such as time budgets and luxury levels, to identify the contribution of overall behavioral change. Along the same lines, Waisman, Guivarch, and Lecocq (2013) use an Economy/Energy/Environment model to investigate 'behavioral' policies, such as the limitation of deployment of infrastructures for high-carbon modes, such

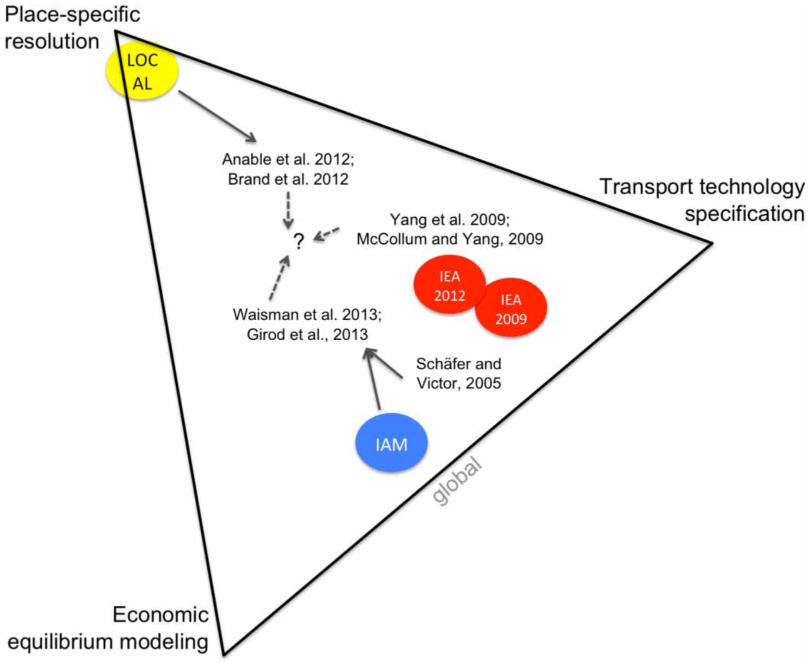

Figure 2. Different approaches toward modeling low-carbon futures tentatively reconcile behavioral and infrastructure options with transport technology models and economic equilibrium models. This development could enable a joint understanding of the different approaches for climate change mitigation, and the interaction between policy options and measures.

as airports, and a decoupling of mobility services from kilometers drive. The latter study finds that if behavioral options and infrastructure investments are implemented, a lower carbon price will be required for reaching climate targets. This result is of particular importance, as mitigation costs were predicted to be higher for the transport sector than for other sectors. Similarly, a regional example of an Economy/Energy/Environment model focuses on modal shift as a relevant mitigation strategy (Daly et al., 2012) (Figure 2).

While these approaches use a generic representation of the behavioral aspects of mobility, they make an important contribution toward recognizing the various behavioral dimensions. Waisman et al. (2013) point out that this approach remains insufficient to display the place-based specific effects, policies, and solutions.

Third, a few attempts were made to upscale the insights from place-based research and behavioral sciences. Specifically, Anable, Brand, Tran, and Eyre (2012), building on the model of Brand, Tran, and Anable (2012) identified lifestyle scenarios that are based on a cultural shift with rapidly changing social norms, complementing supply-side changes in technologies. Comparative analyses of place-based urban mitigation scenarios can help to demonstrate behavioral, infrastructure, and land-use contributions for global mitigation efforts (Creutzig et al., 2012) (Figure 2).

Key Challenges for Transdisciplinary Advances

While attempted reconciliation suggests potential convergence of the different narratives, the contrasting of the different scientific approaches reveals three key challenges for further research across communities.

First, idiosyncratic aspects of urban transport mitigation options remain beyond the scope of global modeling efforts; and should not even be completely integrated. This perspective is based on two very different arguments. First, places are idiosyncratic and detailed solutions can and should not be up scaled to global or even regional levels. This argument needs to be taken seriously but is not insurmountable. A key challenge will be to synthesize the myriad place-specific case studies to evaluate their aggregate global contributions. A potential avenue to deal with the idiosyncratic observations on the one hand, and the global ambition on the other hand could be to construct typologies of places and their possible contribution toward mitigation in transportation (Baiocchi, Creutzig, Minx, & Pichler, 2015; Creutzig, Baiocchi, Bierkandt, Pichler, & Seto, 2015).

Second, as model structures and assumptions diverge considerably, a comparison may be futile. However, this perceived challenge can be turned into an opportunity. Comparing models across scales can be used for model validation. Model validation in scenario-building exercises typically includes testing of assumption, model structure, model behavior, and policy testing.[6] Aggregate global models typically have generic elements (such as a globally applied price elasticity). Its value can best be tested for validity by relying on models on lower spatial scales that include more explicit modeling of transport behavior. This could become a productive interface of the different narratives.

Third, the question of determining counterfactual demand growth scenarios deserves increasing scrutiny. For example, what kind of demand trajectory would emerge under high economic growth feeding the desires of a rapidly expanding global middle class, but considering congestion and place constraints? Research could also investigate how demand develops under starkly increasing fuel costs and urban policies that push a shift toward low-carbon modes worldwide.

Liberal and Welfarist Views on Low-Carbon Futures

The above discussion focused on addressing methodological challenges and assumption spaces for reconciling the different perspectives. But implicit normative assumptions might impose the greatest barrier toward convergence. A place-based analysis relies implicitly and explicitly on different objective function than a global analysis. Place-based studies often investigate urban transport in a multi-objective or co-benefit framework. The policy recommendations then are rooted in a certain idea of how a 'better' place looks like, suggesting infrastructure policies that de facto change preferences and policies that change commuting patterns overriding revealed preferences. In particular, the above discussion reveals that local studies see large non-monetized co-benefits in demand-side urban mitigation measures; in addition, the IEA points to $70 trillion saved in a corresponding global pursuit of 'avoid' and 'shift' measures.

This perspective, however, is highly problematic for the economically minded modelers who are used to the concept of revealed preferences; they understand the place-specific behavioral perspective to be welfarist if not paternalistic (for a comprehensive discussion of how behavioral economics impact normative views on transport policies see Mattauch, Ridgway, & Creutzig, in press). Furthermore, and more practically, a multi-objective analysis would require dealing with numerous complicated counterfactuals in systematic scenario making, leading to an exploding complexity of already highly complex models. And monetary quantification remains subject to high uncertainties. Hence, co-benefits and savings in infrastructure investments remain mostly unspecified as objectives in integrated assessments.

In turn, many place-based researchers reject the economists' 'liberal' objective of GDP maximization with minimal behavioral change because that is based in a simplistic if not unrealistic revealed preference assumption. It is argued that the 'revealed preference' approach is insufficient to evaluate welfare when infrastructure changes (Creutzig & Mattauch, 2013). The question is then how a shift in 'new' infrastructure provision be adequately represented in global models when observed price elasticities represent 'old' infrastructure settings. Also, the global models remain unable to see the complexity on the ground, which needs to be considered for both practical and tangible policy recommendations and results. Somewhat pointedly, one could see the place-based approaches as Copernican–welfarist (Copernican in their inductive nature, based on observations; welfarist in their implicit assumptions to 'know' how a better place looks like); and the global models as Promethian–liberal (Promethian in their understanding that technology can solve the climate change problem; and liberal in relying on

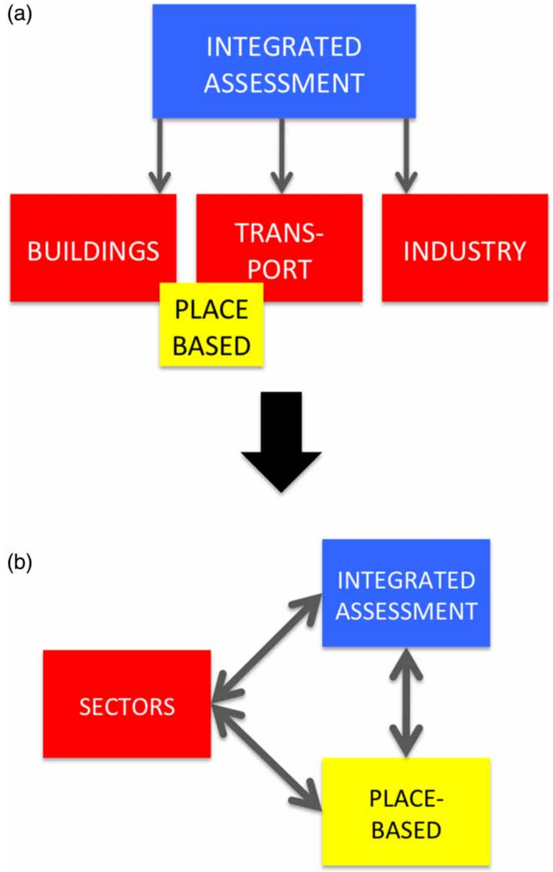

Figure 3. Potential evolution of hierarchical assessments (a) toward vertical assessments where place-based analysis is summarized with a systematic meta-analysis.

unqualified revealed preference approach). While many specific studies keep aspects of both extreme positions, it is useful to see these two divergent normative views underlying research. These views are rarely voiced, but they clearly underlie the few existing cross-community discussions, and cannot easily be solved. From this perspective of normatively diverging communities it follows that real collaboration on equal-par might be very difficult to achieve. Hence, an alternative, or perhaps complement, to attempted convergence and collaboration (Figure 2) could be a modular approach, where each community fosters its own assessment. That would correspond to the already available IPCC analysis of the IAM and technology models; and a systematic meta-analysis of place-based results, resulting in a typology of place-based solution strategies, that would be positioned at an equal level to the global modeling approaches (Figure 3).

Conclusion

The following conclusions emerge from the results and the discussion. First, at least three different epistemic communities investigate low-carbon transport futures from different perspectives. While scenarios and results are broadly consistent between these communities, each focuses on a different decomposition factor: the integrated assessment modelers favor fuel shifts, the transport-sector modelers have a high resolution on technological efficiency, and the place-based research focuses on demand-side solutions. A formal bibliometric analysis could further scrutinize these findings.

Second, the results from the place-based research point to idiosyncratic place-based solutions that can, if at all, be only very generically captured in global equilibrium models. That raises the important question whether global models display a bias in their solution space by representing the accumulated impact of local solution strategies by generic price elasticities or modal shift functions. The preliminary analysis of Box 1 suggests that the combination of fuel pricing, urban planning, and public transport and bicycle infrastructure provision could reduce urban emissions by 20–50% and help to mitigate climate change more than that assumed in many global models. Additionally, these idiosyncratic behavioral and infrastructure solutions often co-align with a broader objective function ('co-benefits', Figure 1(a)) that requires further analysis by specifying appropriate counterfactual scenarios. Bridging the gap between globally aggregate metrics and locally idiosyncratic but utterly important effects emerges as a key challenge in transport climate mitigation studies, similar to other sustainability challenges.

Third, the discussion reveals that a more horizontally structured assessment design, based on the identification of distinct communities, could elucidate diverging results, help identifying gaps, and ultimately improve allocating resources into modeling efforts to close these gaps. Specifying analytical frameworks and normative assumptions remains a crucial task for scientific modelers to enable a lucid communication at the science–policy interface.

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Notes

1. the so-called autonomous energy efficiency improvement.
2. These models typically assume some price of carbon, by this making gasoline and diesel comparatively unattractive independent of oil resource availability.
3. In the IEA scenario, emissions are growing by about 100% from 2005 until 2050 in the baseline scenario. A 57% reduction in emissions in 2050 from 2050 baseline hence corresponds to 14% reduction in emissions from 2005 emission levels.
4. Population density is only correlated but causally only weakly connected to transport GHG emissions. While Newman and Kenworthy (1989) see population density as a major factor explaining transport energy use, Mindali, Raveh, and Salomon (2004) reveal that urban population density loses explanatory power if other variables such as per capita car km are included. Specific metrics, such as job density, remain statistically important. Ewing and Cervero (2010) indicate that more specific urban design metrics explain the proxy effect of population density. Urban economics help to understand that the high correlation between higher population density, less car travel, and more public transport is jointly driven by higher relative fuel prices (Creutzig, 2014).
5. The economic downturn even led to a reduction in per capita car travel in countries like the USA. But the saturation started well before the economic downturn, possibly caused by saturating car ownerships in households and the natural limits of suburbanization and exurbanization: further distance for commuting becomes prohibited by travel time costs.
6. A good example of policy testing the 2050 Pathway calculator of the UK (https://www.gov.uk/2050-pathways-analysis) that enables an immediate visual check of outcomes by changing policy assumptions.

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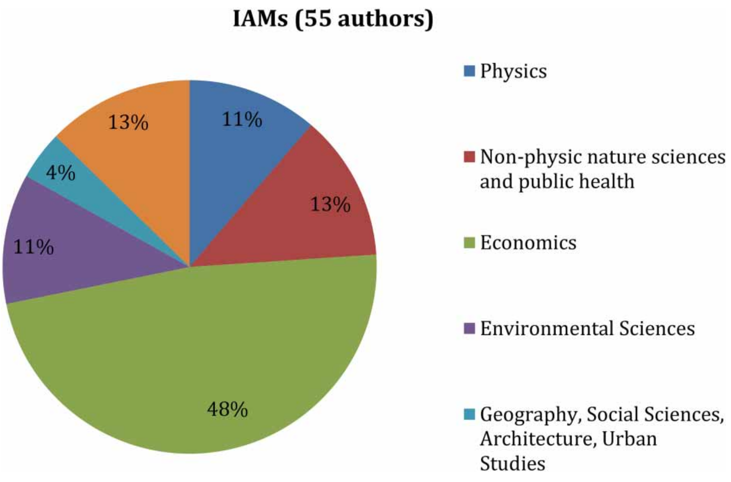
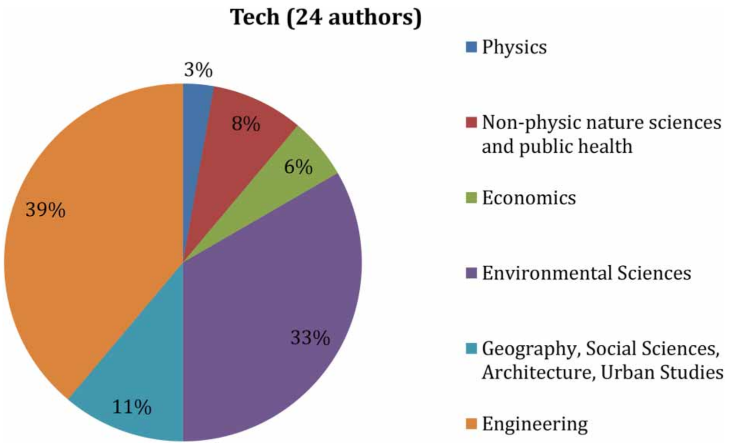
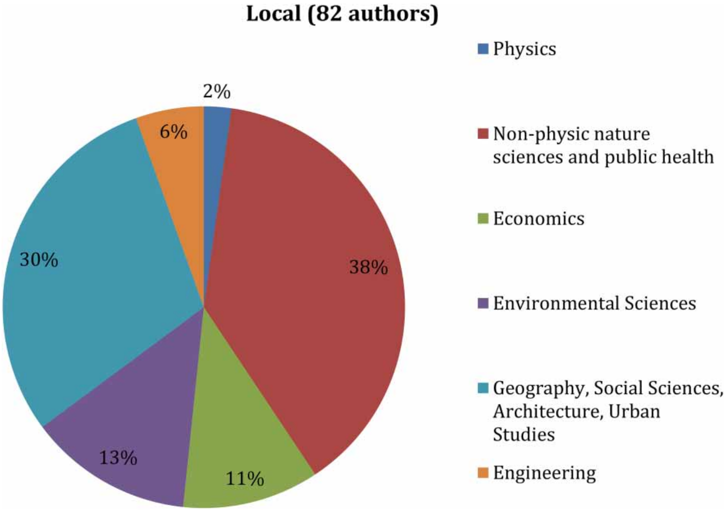
Appendix. Author statistics of the different communities






Local (82 authors)
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6%
30%
38%
13%
11%
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Economics
Environmental Sciences
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