International Transport Forum

The Billion Dollar Question
How Much Will it Cost to Decarbonise Cities' Transport Systems?

Discussion Paper

Nicolas Wagner International Transport Forum, Paris

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The International Transport Forum

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Introduction

The urban population is growing rapidly in all regions of the world and this is expected to continue. This growth will require building more transport infrastructure to satisfy increasing mobility needs. This is particularly true in cities in developing countries, where there will be a demand for faster transport due to income growth.

Decisions made now about physical transport assets (infrastructure, vehicles and systems) will have important implications for decades. Most transport infrastructures were designed and built for a world of cheap and abundant fossil fuels, allowing for flexible and fast mobility, although carbon intense. With the urgency to act upon the climate challenge, there is a need to broadly redefine how cities organise their transport systems. This will have strong implications on how we plan infrastructures in the coming decades.

This paper estimates the investment needs in urban transport infrastructures and vehicles up to 2050. Although several forecasts have been produced during the last decade (see Box 1) our work differs from them on at least three aspects. First, it focuses only on urban transport while previous approaches considered transport infrastructures as a whole. This more sectoral approach allows a deeper understanding of the linkage between transport infrastructure investment, transport demand and urban policies. Second, it is a scenario-based approach where the need for infrastructure is estimated in different policy packages. Finally, it is a demand-driven approach where infrastructure levels depend on expected traffic. Rather than deriving the level of infrastructure from the level of income, it attempts to account for the complex interdependency between the demand for transport, in terms of passenger-km by modes, and the available supply of transport infrastructure.

The paper concludes that investing in a low carbon transport system is not necessarily more expensive and can even be more efficient, provided it is well coordinated with land-use policies. Under current policies, the needs for investment in urban infrastructure and public transport vehicles will remain high. Between 2015 and 2050, the average investment per capita is projected to be approximately USD 400 per year in high-income cities, while it ranges between USD 100-150 for upper- and lower-middle-income cities. Decarbonize the transport system would require investing 25% more, unless active polices to control urban sprawl are implemented. If that the case, the investment needs would decrease by 20%.

This paper is divided into five sections. After giving a quick overview of the methodological choices (first section), we assess the current situation in terms of infrastructure stock (second section). The third section presents a baseline forecast of infrastructure demand, while the fourth section deals with alternative policy scenarios. The last section discusses the possible consequences of the uptake of shared mobility services on infrastructure needs.

Box 1. Existing global assessments of transport investments needs

Most infrastructure forecasts rely on long-run elasticities to represent the relationship between infrastructure stock measures and GDP/income measures over time. These can be derived either as ratios (based on historical and/or cross-country benchmarks) or as coefficients in econometric models. In turn, elasticities are used to derive estimates of the level of infrastructure provision needed to satisfy consumer and producer demand, based on forecast levels of economic activity.

Econometric analysis by the World Bank (Fay and Yepes, 2003) define a model to predict how the evolution of GDP will affect infrastructure needs using GDP as a proxy for aggregate demand and controlling for underlying differences in economic and technological performance across countries. The model predicts the amount of infrastructure needs based on GDP forecasts for developing countries, which was equal to about USD 465 billion per annum – or 5.5% of developing countries' GDP over 2005-10.

A more recent study by the OECD, Strategic Transport Infrastructure Needs to 2030 (OECD, 2012), focuses on airports, ports, rail, as well as pipelines for oil and gas distribution. Based on a similar methodology, this report estimates that countries will need to invest USD 11.3 trillion between 2009 and 2030 (or USD 486.5 billion per year) in strategic infrastructure projects to meet increasing demand arising from enhanced trade and travel.

The International Energy Agency (Dulac, 2013) forecasts transport investments needs based on historical ratios of infrastructure per unit of traffic (i.e. vehicle kilometres for roads and train-km for railway tracks). They forecast that the investment required for the construction of new projects would be USD 43.4 trillion between 2010 and 2050 in a 4 degree scenario (4DS), or USD 1 trillion per year. This might go up to USD 98.8 trillion or USD 2.5 trillion annually if significant effort to shift to a low-carbon transport system.

Overview of the methodology

The general principle of our approach is as follows. Using geospatialised data sources, a detailed analysis of the current state of urban infrastructure is conducted. The stock of infrastructure is then forecasted using the ITF global urban passenger model. The model forecasts a transport demand (in passenger-km split among several transport modes) and converts it in a need for additional lane-km of roads and public transport lines. Several policy scenarios are tested leading to several estimation of the demand for infrastructure The infrastructure stocks (in lane-km) are turned into investment needs (in USD) using region specific ratios presented in Appendix 3.

Unless otherwise mentioned, all data presented in this paper are from author's own calculation based on ITF urban passenger model. All costs are given in constant USD 2010.

The scope of the study: cities of more than 300 000 inhabitants

This works focuses on the 1 692 cities over 300 000 inhabitants as listed in the *World Urbanization Prospects: The 2014 Revision from the United Nations* (United Nations, 2014). All results presented in the paper in terms of transport activity and of quantity of infrastructure are restricted to those cities. This choice was motivated by data availability issues: mobility patterns and infrastructure provision are poorly documented in middle and small sized cities, especially in the developing world.

Extrapolating these results to all cities, regardless of their population, should be done with caution. Cities with more than 300 000 inhabitants represent 56% of the total urban population and 65% of the Gross Domestic Product (GDP) produced by urban population. Although scaling up the results from population or GDP could give useful orders of magnitude, it should only be consider as very crude estimates.

The use of geospatialised data to quantify infrastructure stocks

In a work of such a scope, data availability is usually the main challenge. Infrastructure stocks are imperfectly known and when they are known, it is at an aggregated level with little detail on the infrastructure characteristics. This paper makes extensive use of OpenStreetMap (OSM) to obtain information about the road network and the public transport infrastructure at detailed geographical level in a comparable way. OSM is a collaborative project with the aim of creating a free, public map of the world. The content is contributed voluntarily, using geographic data from portable GPS devices, aerial photographs, and other free sources. The quality of this volunteered information has become increasingly high and is comparable to commercially produced maps. A recent assessment (Barrington-Leigh and Millard-Ball, 2017) shows that 83% of the road network is mapped in OSM and for more than 40% of countries — including several in the developing world — the coverage is exhaustive. Moreover, completeness tends to increase with population densities so urban areas are likely to be best mapped. For this study, the road and public transport network of each city has been extracted together with relevant information such as lane number, legal speed, and road type. Only paved roads were considered, mainly because the data on unpaved roads is unreliable. Additional data was collected on public transport networks and timetables from local transport operators under the GTFS format.

A point of attention is to carefully define what is meant by a city and its associated urban extent. Indeed infrastructure stocks are usually higher in city centres compared to suburbs, so that a larger urban area usually implies a lower density of infrastructure. As the definition of cities can vary greatly from country to country, objective comparative analyses cannot generally be obtained using administrative definitions of urban areas. Here we retain the OECD definition of an urban core based on population densities (Brezzi, Piacentini, Rosina, and Sanchez-Serra, 2012) and derive urban boundaries for the selected cities (including non OECD countries). The geospatialised transport networks have been clipped into these urban boundaries, thus offering a unique estimation of the stock of urban transport infrastructure.

Very little data is available to quantify the historical spending in transport infrastructure at the urban level. Although data has been collected during the last decades at the national level (see Box 2), there is no data available at the urban level. This is very unlikely to change in the near future. Investments at the local levels are usually scattered among several stakeholders, typically local authorities, regional and central governments, and sometimes the private sector. Even if they were to be collected, the very definition of urban area varying from country to country would make any meaningful comparison impossible.

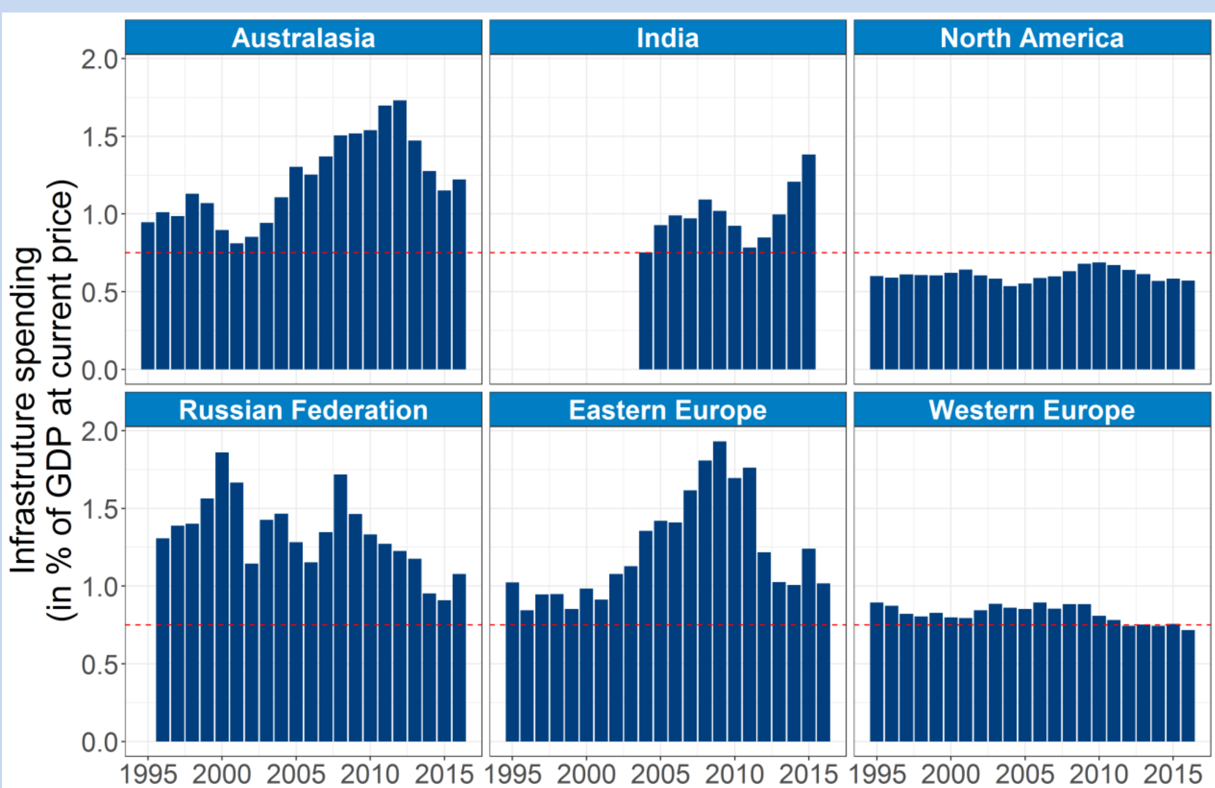
Box 2. Infrastructure spending in inland transport

In 2014, OECD countries spent on average 0.75% of their GDP on investment in inland transport infrastructure (road, rail and inland waterways). This figure is on a declining trend for the OECD as a whole, apart from a surge in spending in 2008 and 2009 because of the economic stimuli decided by many countries following the economic crisis. Part of the drop can be explained by a decline in interurban infrastructures, with most countries already having developed interurban transport networks and now focusing on selective upgrading and extensions. The share of transport infrastructure spending for developing countries is generally above that of developed countries. Most of these countries are developing their infrastructure supply in quantity and quality to reach levels observed in developed economies. From the countries for which we were able to collect official data – mainly upper middle income countries - it can typically go up to 2% in catching up periods (see Eastern Europe countries for example).

A large share of the investment is dedicated to road infrastructure. It is generally above 70% in developed countries and 80% in developing ones. In recent years, however, there is a trend of increased investments in railways in OECD countries, especially in Western European countries. In 2014, the rail share of inland investments in Western Europe was 41%, when it was only 30% in 2000. This reflects an ongoing political commitment of developing railways.

Information on spending on infrastructure maintenance is scarcer than on spending on infrastructure investment. This is partly due to the difficulty to draw a line between investment and maintenance spending. From the limited data available, it appears that the share of public road maintenance in total road expenditure is increasing. As the stock of infrastructure grows, it is natural that the effort to maintain this infrastructure increases as well. Despite that, observers in many countries have raised concerns about underfunding of infrastructure maintenance. We estimate the share of maintenance in road expenditure to be 25% and 40% in North American and European countries respectively.

Figure 1. Infrastructure spending in inland transport from 1995 to 2016



Note: OECD average is in red. Western Europe includes Austria, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, *Israel, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey and the United Kingdom. Eastern Europe includes Albania, Bulgaria, Croatia, Czech Republic, Estonia, Former Yugoslav Republic of Macedonia, Hungary, Latvia, Lithuania, Montenegro, Poland, Romania, Serbia, Slovakia and Slovenia. North America includes Canada, Mexico and the United States. Australasia includes Australia and New Zealand.

*The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Source: Adapted from ITF (2017a).

Forecasting infrastructure stocks from ITF transport model

ITF global urban passenger model is a tool that estimates and forecasts transport activities in cities at an aggregated level (Chen and Kauppila, 2017). It takes as input the main variables shaping transport demand, such as population growth, economic activities, the availability and quality of urban roads, and the efficiency of the public transport network. ITF urban model has been calibrated on a dataset gathered from various institutions and covering all the main regions of the world (see Appendix 4 for an exhaustive list).

For this study, the model was adapted in two ways:

- An extra-module was included to estimate the desired stock of infrastructure, measured in lane-km of roads and urban railways, from the outputs of the model namely passengers-km by road and public transport. The relationship was estimated based on an econometric analysis which is presented in the next section.
- A feedback loop was introduced to represent the interdependency of transport demand and transport supply. This is because transport demand is a driver of the infrastructure stock and vice versa.

The full description of the urban model is available in Appendix 2.

Transport infrastructure stock in urban areas: How large is the infrastructure gap between low- and high-income cities?

Road infrastructure

It is a known fact that road infrastructure stocks are lower in low-income countries. Among many others, the World Bank development indicators show a significant gap, with a road density of 20 km per 100 km^2 in low-income countries against 60 km per 100 km^2 in high-income ones (Group and others, 2017). The analysis presented in Table 1 and 2 show that this stays true at the urban level.

Table 1. Trunk roads stock in cities

Income group	Lane-km of trunk roads			
	Total	per 1 000 inhab.	per km^2	per million VKM
High income	348 480	0.61	1.15	0.076
Upper middle income	129 868	0.13	0.53	0.076
Lower middle income	25 433	0.04	0.25	0.055
Low income	1 331	0.02	0.13	0.059

Source: Author's own calculation based on OSM data.

The stock of trunk roads varies significantly between low- and high-income cities

For the purpose of the analysis, trunk roads have been defined as roads with dual carriageway speed limits over 70 km/hour. In rich cities, there is 0.6 lane-km of trunk road for every 1 000 inhabitants. This is 30 times less in a low-income city. These variations can partly be explained by population density: low-income cities are much denser; so the gap in lane-km per km^2 is lower. The level of traffic is the main driver of trunk roads stock. Low-income cities tend to have low traffic so the road occupancy, indirectly measured by the ratio between lane-km and vehicle-kilometres (VKM), is high. At first, traffic grows with wealth at a faster pace than the trunk network. Once a certain threshold is reached, vehicle-kilometres and the total length of expressways have the same elasticity to GDP and thus grow at the same pace, leaving the ratio between the two unchanged.

This last result recalls, on a global level, Down's "fundamental law of peak hour congestion" (Downs, 1962; 2005). It states that on urban commuter expressways, after any new investment in road capacity, roads will quickly return to the same level of congestion as before. Naturally, our simple, cross-sectional approach does not allow us to conclude on the causality of this relationship; the supply of road might increase to fulfil a growing demand, or, reversely, it might cause additional demand. Nevertheless, this finding complements the time series studies that Downs and others have been conducting on specific countries.

Table 2. Stock of local roads in cities

Income group	Lane-km of local roads		
	Total	per 1 000 inhab.	per km^2
High income	3 952 341	7.0	13.1
Upper middle income	2 528 239	2.6	10.2
Lower middle income	332 034	0.6	3.3
Low income	23 367*	0.3*	2.4*

Note: *estimated data, unpaved roads are excluded of the analysis
Source: Author's own calculation based on OSM data.

There is less variation in the stock of local roads

The remaining road network represents the largest share of the road stock with more than 90% of the total road network. The stock of local roads is less unequal. As expected, density of local roads is more stable across regions. The remaining variations are due to lower-income cities having a larger share of unpaved roads (unpaved roads being excluded of our analysis). Note that the values for low-income cities have been estimated by extrapolating them as a direct use of OSM data would have been unreliable. Indeed, the data coverage in low-income cities is poor and the distinction between unpaved and paved roads is often poorly reported.

The two following regressions summarise how roads stocks are affected by traffic levels and income. Both of them are under a log-log specification, so the coefficients are unitless and can be directly read as elasticities. As the table indicates all coefficients turn out to be statistically significant at 1% level, which is not surprising under a log-log specification with high number of observations and great variability in the quantity to be explained.

The first regression explains the length of the trunk road network (in lane-km), denoted as *TrunkRoad*, as:

$$log(TrunkRoad) = A + B * log(Area) + C * log(trafficDensity) + D * log(GDP\_CAP)$$

where *Area* is urban extent in km^2, *trafficDensity* is the number of vehicle-km par km^2 and *GDP_CAP* is the GDP per inhabitant of a city. The results of the estimations are statistically significant and are presented in the Table 3.

Table 3. Model for main roads

Variable	estimate	std.error	t-stat	p.value
A	-2.65	0.50	-5.28	0%
B	1.02	0.03	41.37	0%
C	0.36	0.04	9.12	0%
D	0.28	0.03	9.26	0%
Adjusted R-squared		0.727		

The second regression explains the length of the local road network (in lane-km), denoted as LocalRoad, as:

$$log(LocalRoad) = A + B * log(Area) + C * log(GDP\_CAP)$$

where *Area* is urban extent in km^2 and *GDP_CAP* is the GDP per inhabitant of a city. The results of the estimations are statistically significant and are presented in the Table 4.

Table 4. Model for local roads

Variable	estimate	std.error	t-stat	p.value
A	5.13	0.20	25.63	0%
B	0.35	0.02	14.02	0%
C	0.99	0.02	47.97	0%
Adjusted R-squared		0.728		

Mass transit infrastructure

When it comes to public transport, the first question is the one of availability. Globally, 75% of cities have no subway, tramway, light rail system or bus rapid transit (BRT). Availability again varies with wealth. Mass transit systems of any kind are more common in high-income countries while there is no subway supply in any low-income cities. Higher population densities also make the deployment of large-scale public transport systems more feasible. Within each income group, cities with mass transit tend to have a higher density.

There are fewer cities with mass transit infrastructures in developing countries. Where there are such infrastructures, the networks are usually very limited in size. The amount of km of subway per inhabitant is two times higher in high-income cities than in middle-income ones. When looking at a light system, defined in this study as tramway, light rail system or bus rapid transit, the ratio is even higher, close to 1:4. This reflects the significant investments undertaken in high-income countries in tramways during the last decade.

Surface rail infrastructure is specific. They are more common, with 60% of cities having some. On average, rail infrastructure stock is always significantly higher than other forms of mass transit infrastructure. However, this does not mean that these assets are actually used for urban transport. When it is actually used in urban transport, its utilisation rate is usually lower than the one of subway or light systems. On a sub-sample of cities for which timetable data are available, we found that the average frequency for local trains is approximately 25 trains per day while around 100 for subways and 75 for tramways.

Table 5. Mass transit infrastructure availability

Income group	% of cities with subway	% of cities with light system	Km of subway per 10^6 inhab. (for cities with subway)	Km of light system per 10^6 inhab. (for cities with light system)
High income	25%	63%	1.86	3.70
Upper middle income	13%	27%	0.93	0.93
Lower middle income	7%	14%	0.17	0.51
Low income	0%	3%	--	0.17

Source: Author's own calculation based on various data (see Appendix 1).

Transport investments forecasts in a business-as-usual scenario: Is the infrastructure gap likely to narrow?

Underpinning factors

The previous section showed that the infrastructure endowment is higher in wealthier cities because they are less dense, have higher traffic volumes and higher incomes per capita. In a business-as-usual (BAU) scenario, where no additional policies aiming at controlling transport demand and land use is implemented, the needs for infrastructure will strongly increase in developing cities. Three factors will underpin this growth.

Urban extension will cause significant challenges for urban mobility. One of the most likely global trends of the coming decades will be the process of urbanisation, especially in developing countries. It could change all aspects of urban life, and make the organisation of efficient transport in cities a challenge. In their World Urbanisation prospect, the UN (2014) expects that 66% of the population will live in urban areas by 2050. This will lead to a growth in demand for urban travel that will need to be accommodated.

If no stringent land control policies are put in place, urban density will globally decrease –by 5% by 2050.A statistical analysis of the ITF city database shows that the two main drivers of urban area are population and GDP per capita. However, urban areas increase at a slower pace than population, thus cities that are bigger in terms of their population also tend to be denser. On the other hand, cities with higher GDP per capita tend to be more sprawled out. Overall, the income effect more than compensates the effect of population, leading to a decrease in density when cities get wealthier. The density decrease is observed for all regions of the world, although to different degrees: it is particularly sharp in Asia, where the GDP per capita is expected to be a significant driver of urban expansion.

In a business-as-usual scenario, motorised mobility is set to grow strongly. The combined effects of urban extension, population and income growth will result in a surge in motorised mobility. Urban road traffic, measured as the sum of in car-km and motorcycle-km, will globally increase by 98% by 2050. In absolute value, most of the increase comes from upper-middle-income countries, with 3.7 trillion additional vehicle-km out of a total of 7.6 trillion. However, car use per capita remains higher in high-income countries because of more frequent use of alternative modes, in particular walking in developing countries.

Table 6. Variations of key drivers of infrastructure demand under a business-as-usual scenario

	Urban extent (in thousands of km^2)		Density (in thousands of people per km^2)		Road traffic (in trillion VKM)	
	2015	2050	2015	2050	2015	2050
High income	303	439	1.9	1.6	4.7	6.2
Upper middle income	247	486	4.0	2.9	2.3	6.0
Lower middle income	101	294	6.0	4.0	0.8	3.0
Low income	10	40	8.2	5.9	0.0	0.2

Source: Author's own calculation based on ITF global passenger model.

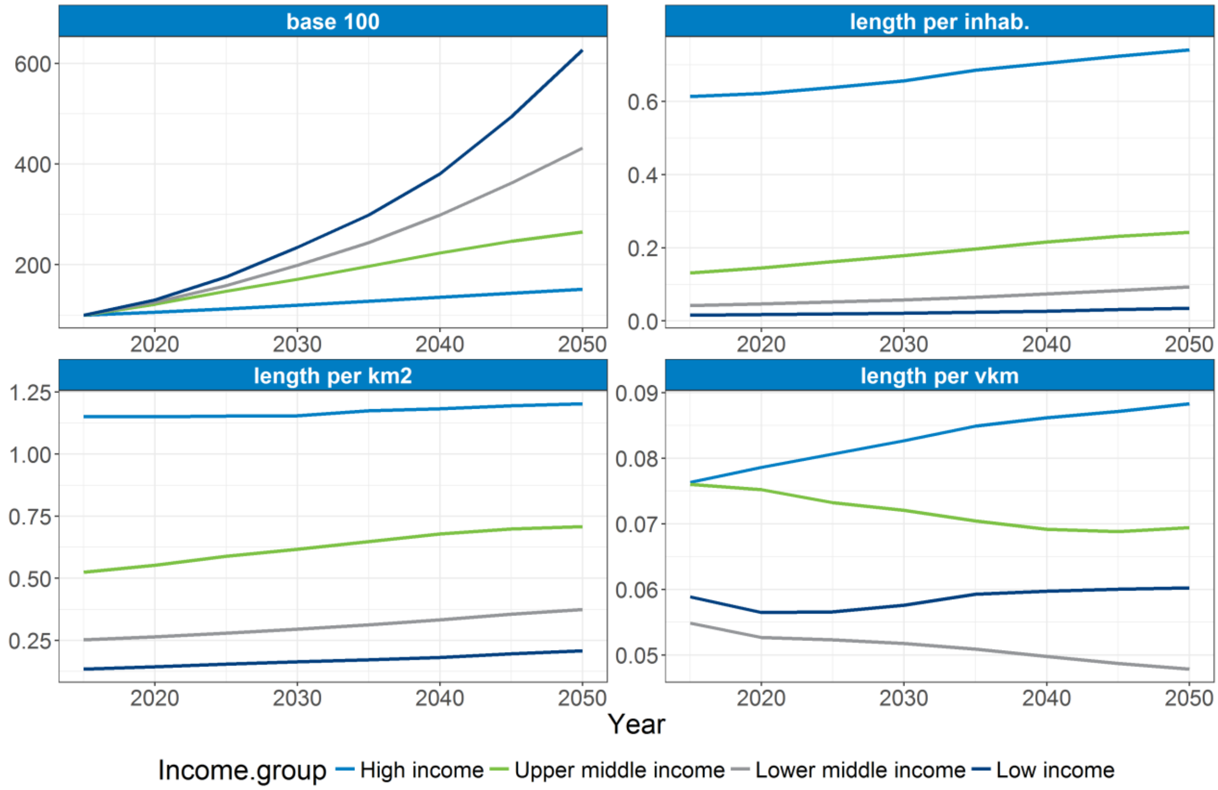
Infrastructure needs in a business-as-usual scenario: Trunk roads

To cope with additional traffic and larger urban areas, the road network will need to be expanded at a fast pace. In particular, the trunk network will double from 0.5 to 1 million lane-km between 2015 and 2050. In relative terms, the increase is stronger in low-income and lower-middle-income cities where the network is set to more than triple. This is especially true for Asian and African countries where the growth in population and traffic is sharp. In absolute value, however, most of the increase comes from upper-middle-income countries, where 43% of the additional lane-km will be built.

Between 2015 and 2050 the investment needs for new trunk roads will amount to USD 2 250 billion. Over half of this amount is spent in high-income countries although they account for 20% of the urban population and 30% of the lane-km to be built. Public works are labour intensive, so construction costs tend to be correlated with GDP per capita. Apart from new infrastructure, an extra USD 691 billion will be needed for reconstruction works, i.e. large maintenance operations.

In a business-as-usual situation, it is unlikely that the gap between low- and high-income cities will narrow significantly. In our simulation, both the lane-km per inhabitant and the length per km^2 remain nearly unchanged (see Figure 2). Furthermore, traffic density (i.e. the length of the network per unit of traffic) decreases in all cities but high-income ones. This suggests that road congestion will increase in those cities. Traffic will increase so fast that public finance will not allow coping with it by building enough high-capacity roads.

Figure 2. Increase of the trunk road network in a business-as-usual scenario



Note: In this graph as in following ones, base 100 means 2015 is taken as the reference year and is assigned a conventional value of 100.

Source: Author's own calculation based on ITF global passenger model.

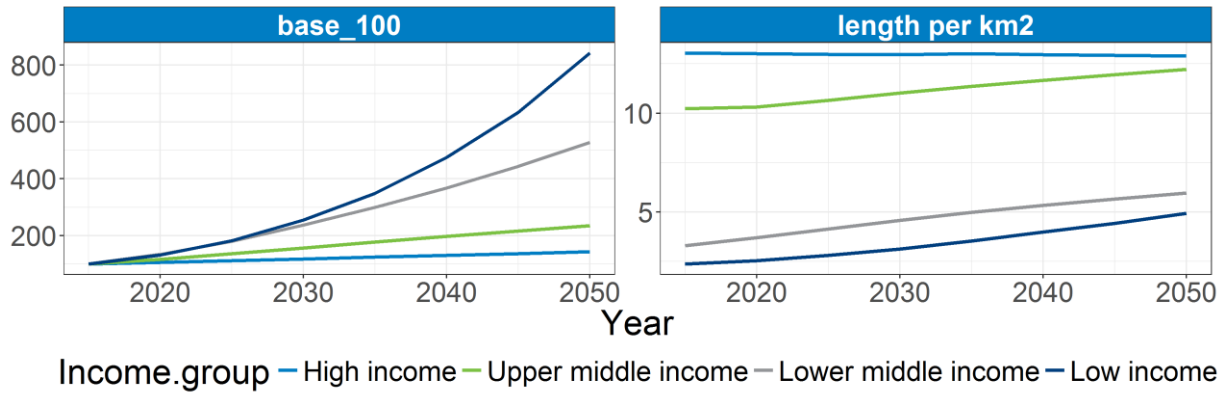
Infrastructure needs in a baseline scenario: Local roads

If no stringent land control policies are implemented, urban areas will double to accommodate the growth in population and respond to the demand for larger accommodations. To serve new neighbourhoods, 4.7 millions of lane-km will need to be built. An additional 2 million lane-km will be required to upgrade unpaved roads to paved ones, so that the total lane-km of local roads required is 6.7 million lane-km.

Here again, the increase in relative terms is stronger in low-income and lower-middle-income cities where the growth rates range between +300% and +500%. A convergence between developed and developing cities in terms of length of network per km^2 is observed but a gap remains. In 2050 the density of local roads is of 16 lane-km per km^2 in a high income city, while it is only five lane-km per km^2 in a low-income city.

Between 2015 and 2050 the investment needs for local roads will amount to UDS 1 010 billion. As they are the most subject to urban sprawl, lower-middle-income cities account for over half of this expenditure.

Figure 3. Increase of the local road network in a business-as-usual scenario



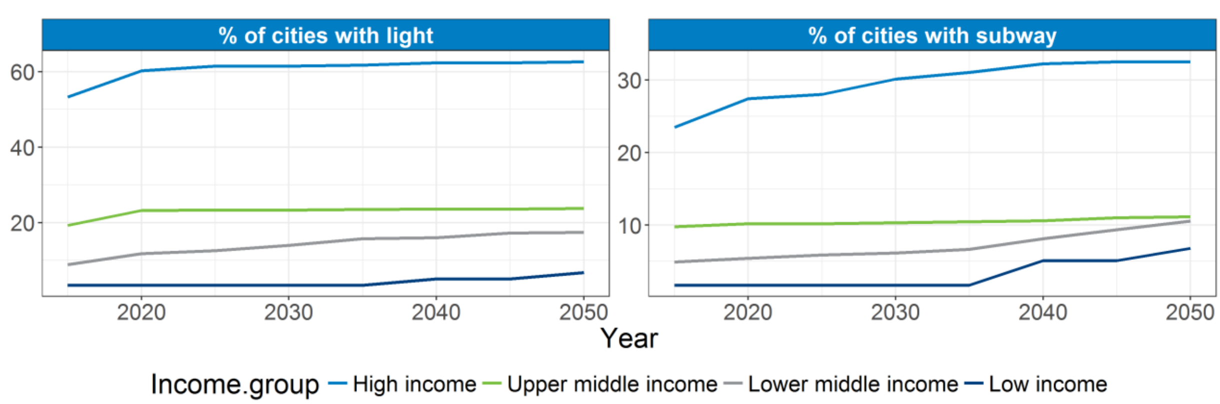
Source: Author's own calculation based on ITF global passenger model.

Infrastructure needs in a baseline scenario: Mass transit infrastructures

The growing wealth in cities might not necessarily result in a larger coverage by public transport. Developing cities are likely to sprawl, which will make the deployment of mass transit systems less feasible, cancelling the otherwise positive effect of income increase on mass transit infrastructure. In total, 101 additional cities would implement a mass transit service by 2050. It is only in high-income countries that the share of cities with underground transport services increases significantly; by 2050, nearly one-third of those cities, roughly the ones over 1 million inhabitants, will have an underground network.

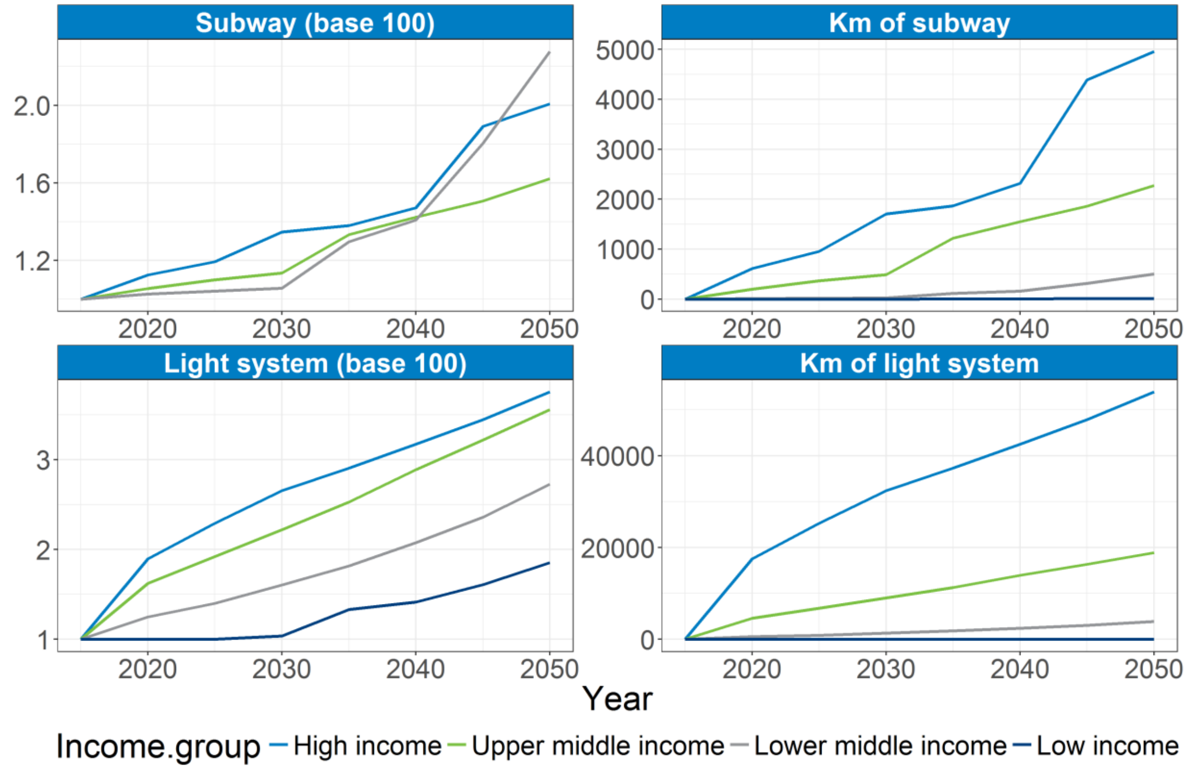
The network of light railways and BRT will witness the strongest growth and will triple everywhere except in low-income cities. By 2050, 77 400 km of new lines will be constructed, high-income countries accounting for two-thirds of the total. Although the percentage of cities served by a light system increases sharply in lower-middle-income cities, the size of the extent of their network will remain limited. The growth of the subway network will be less strong and is expected to double thanks to 8 680 km of additional lines that are, again, predominantly located in high-income cities.

Figure 4. Mass transit coverage in a business-as-usual scenario



Source: Author's own calculation based on ITF global passenger model.

Figure 5. Increase of the mass transit in a business-as-usual scenario



Source: Author's own calculation based on ITF global passenger model.

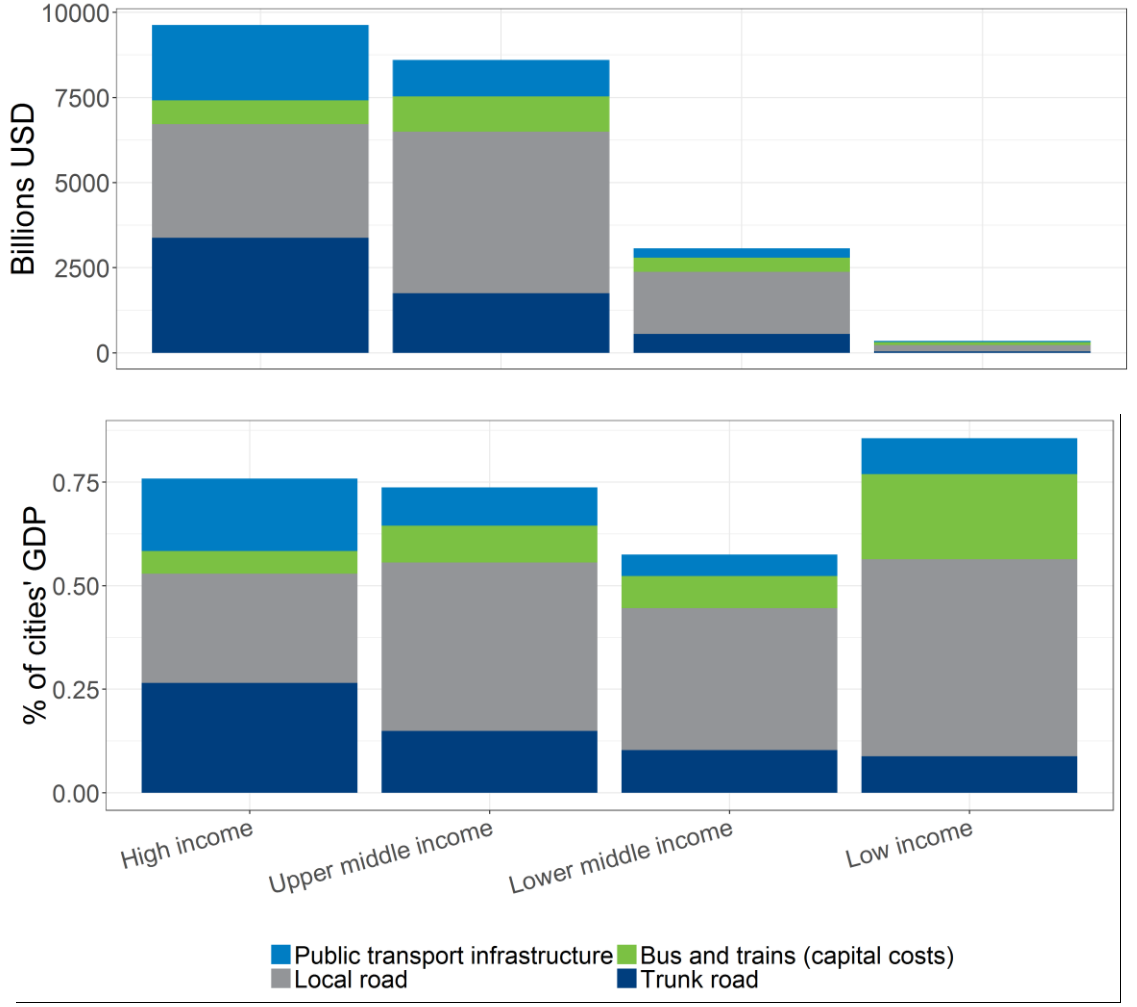
Summary of the investment needs in a business-as-usual scenario

Figure 6 presents the total investments in transport, including costs for public transport vehicles (buses and trains). Between 2015 and 2050, the average investment per capita is projected to be approximately USD 400 per year in high-income cities, while it ranges between USD 100-150 for upper- and lower-middle-income cities. Yet the effort in infrastructure investment, measured in % of a city's GDP, does not vary significantly with income levels. On average, cities spend around 0.75% of their GDP, regardless of their GDP per capita.

The largest share of the investment goes into local road construction, as for many cities the challenge will be to equip new neighbourhoods of a growing urban area. Note that our estimation includes road equipment such as road signalling, lighting and protective barriers, as well as sidewalks. These last costs are likely to represent a significant share of the total amount (see Appendix 3 for detailed assumptions on costs).

It is only in high-income cities that the investments in other types of infrastructure represent more than half of the total. Indeed, those cities will need to cope with a growing demand in mobility and thus to build high-capacity infrastructures.

Figure 6. Investments in the business-as-usual scenario in billions USD and % of cities' GDP



Source: Author's own calculation based on ITF global passenger model.

Alternative scenarios: To what extent can urban policies affect the demand for infrastructure?

The demand for mobility and infrastructure is affected by policy choices. Most transport infrastructures were designed and built for a world of cheap and abundant fossil fuels, allowing for a flexible and fast mobility, although carbon intense. Low-emission pathways require controlling transport demand and shifting it towards low-emission transport modes.

This part of the paper analyses how two policy packages may affect transport investments. It is divided in two sub-sections: the first sub-section defines the two scenarios, including the underlying assumptions, and presents the global results in terms of transport activity and emissions. The second sub-section is dedicated to the resulting infrastructure needs.

Two alternative policy scenarios

Below is a description of two scenarios which assess the impacts of various combinations of urban transport policies aimed at reducing CO_2 emissions: the Robust Governance scenario and the Integrated Land Use and Transport Planning scenario. Basically, these two scenarios represent stylised urban policies to move toward low-carbon mobility. While the first one is mainly a public transport orientated scenario, the second one also implements land-use policies. They have already been used in various ITF publications, in particular ITF's latest transport Outlook (ITF, 2017a).

The Robust Governance (ROG) scenario assumes that local and national governments seek to reach low-carbon mobility from three levers. First, they exploit demand-management instruments, mainly pricing and regulatory policies, to slow down the ownership and use of personal vehicles from 2020 onwards. Existing literature provides evidence on the effectiveness of rigorous pricing strategies to shift from personal cars towards modes with lower carbon intensities (see Greening, 2004). In this scenario, additional pricing policies targeting fuel prices, cost of vehicle ownership and use, and lower transit fares are implemented in all cities. Second, higher investment effort in public transport infrastructures is assumed, comparable to the one estimated for European cities. Finally, more stringent fuel standards are set and policies targeting higher market penetration of alternative fuels vehicles are implemented.

Table 7. Modelling assumptions for each scenario

Measure	Corresponding modelling assumption
High fuel price resulting from higher taxation or high oil prices	In 2030, fuel prices in each country correspond to a fictive oil price of USD 120 (real USD/bbl, 2005). The growth rates of oil price between 2030 and 2050 are assumed to be the same as in the business-as-usual (BAU) scenario
Increase in parking price	Parking prices are 50% higher than in the BAU
Decrease in public transport prices	Transit ticket sub-model estimates the elasticity of single transit ticket price with respect to GDP per capita for each region. The lowest regional price elasticity is used to determine the future transit ticket price of all the world cities
Regulation of car ownership and use	The elasticity of car ownership with respect to GDP per capita is lower than in the BAU
Improvement in the fuel efficiency of the vehicle fleet	Assumptions made in the latest 2°C Scenario (2DS) of the International Energy Agency (IEA) (when BAU is the 4°C Scenario)

The Integrated Land Use and Transport Planning (LUT) scenario assumes that, on top of the policies introduced in ROG scenario, a joint land-use policy is implemented. As land-use and transport planning decisions interact, it is widely acknowledged that better co-ordination and integration are a prerequisite for sustainable development (Geerlings and Stead, 2003). Higher population density and transit network density can effectively stimulate an increase in transit share and a reduction in trip distances, which then contribute to overall larger reductions in CO_2 emissions. Effectively modelling policies that mix land-use and transport instruments is challenging. Typically, transit-oriented development policies apply to neighbourhoods, so it is difficult to approach them in an aggregate manner. In this study, we modelled the potential benefit of integrated planning by assuming that urban sprawl is controlled from 2020 onwards. In practical terms, this means that urban area size remains constant for every city. Translating into quantitative terms, the average growth in urban density in the 2015-50 period ranges from 20% (European cities) to 83% (African cities), compared with overall decreasing urban density in the business as usual scenario.

The demand for mobility under the two alternative policy scenarios

The mobility levels under the three scenarios are presented in Figure 7. In the business-as-usual scenario, the market share of private vehicles remains stable, with around 70% of passenger-km. This is the result of two opposite trends: a slight decrease in high-income cities where the share goes from 75% to 70% and an increase from 55% to 60% in upper-middle-income cities. The share of public transport, motorcycles and non-motorised modes in developing countries are all projected to decrease until 2050, meaning that more residents of cities in developing regions will be shifting to private car use. At the end of the period, the private car is the dominant form of urban transport in all the regions of the world.

In both the ROG and LUT scenarios, there is a global shift toward public transport because of more stringent pricing policies and better public transport supply. Reduction in the share of cars already happens in 2030, except in China and India, where the mode share of cars continues to increase due to rapid income growth. By 2050, public transport becomes the dominant urban transport mode in every region except North America, where car share is still around 61%.

While the distribution of passenger-km between modes is similar in both scenarios, the total passenger-km is higher in the ROG scenario. The demand for transport is 38 trillion passenger-km in 2050 under ROG, 10% higher than in the BAU scenario. There are two main underlying reasons for that. First, there is a significant shift of non-motorised modes to transit. While the expansion of cities is likely to increase the length of the trips for urban residents, making walking and cycling less viable, the development of transit systems offers an affordable alternative in the ROG scenario and allows for longer trips. Second, the increase in accessibility provided by better public transport induces an increase in the total number of trips.

On the other hand, the mobility levels in the LUT scenario are comparable to the business as usual. LUT and ROG have more trips than in BAU due to induced demand. However trips tend to be shorter in LUT because of a more compact urban form. As a result of those two opposite effects, there is 35 trillion passenger-km in 2050 under the LUT scenario, the same amount as in a BAU scenario.

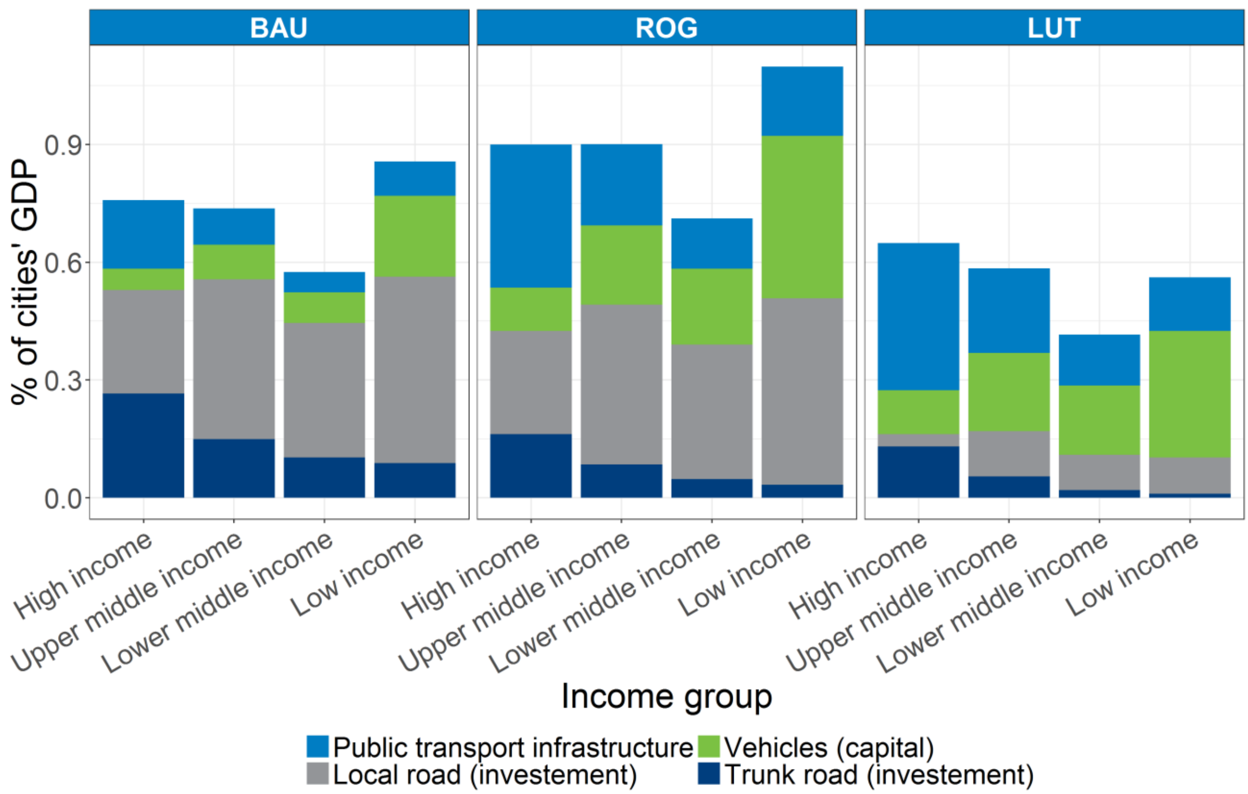
The investment needs under the two alternative scenarios

Overall, the analysis shows that a shift toward low-carbon mobility does not necessarily require higher investments. Although investments in public transport infrastructure are 170% higher in LUT and ROG than in the BAU scenario, this can be offset by a lower need for road infrastructure. Yet if not properly co-ordinated with land-use policy, an ambitious transport policy would lead to higher investment needs as shown by the results of the ROG scenario.

In the ROG scenario, the demand for road infrastructures is lower, but the increased investments in public transport infrastructure and vehicle more than compensate it. Overall, the effort in infrastructure investment, measured in the percentage of a cities' GDP, increase by 0.2 points. In high-income and upper-middle-income cities, this is driven by more mass transit infrastructure. In particular, tramway networks in Asia would experience a steady growth with an increase of more than 700% from 2015 to 2050. In lower-income cities, investments are rather targeted at the acquisition of new buses.

In the LUT scenario, the increase in public transport supply is similar, but investments in roads are kept to a minimum. They mainly consist in reconstruction operations, i.e. large maintenance works for major roads. The investment effort in infrastructure is overall 0.15 point lower than in the BAU scenario.

Figure 7. Investments needs under the three policy scenarios



Note: BAU – Business-as-usual; ROG - Robust Governance; LUT - Integrated Land Use and Transport Planning.

Source: Author's own calculation based on ITF global passenger model.

Policy implications

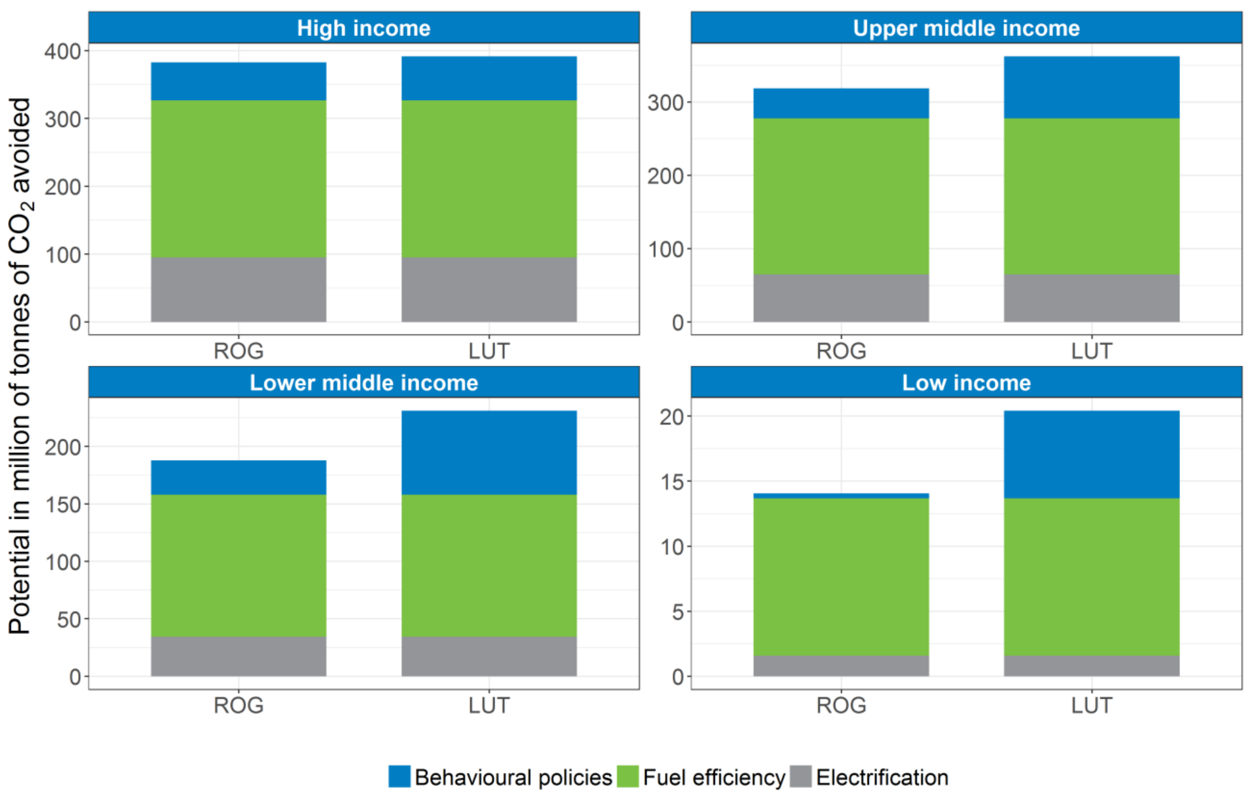
To achieve a 2 degrees scenario, investing in public transport infrastructure is not enough, it needs to be integrated into a wider policy package

Transport infrastructure investments are only a small part of the policy levers that will be required for decarbonising transport. Investing in public transport infrastructure will not be efficient without automobile use restrictions and co-ordination with urban planning. Full policy packages that go well beyond the sole public transport investment are required. Further, while they are not sufficient alone, fuel efficiency improvements and electrification have a large mitigation potential.

The ITF (2017a) showed that only the LUT scenario is consistent with the mitigation effort required to limit the global warming to 2 degrees Celsius. CO_2 emissions would decrease by 35% compared to 2015 levels (in contrast to a 20% increase in a business as usual scenario). In total, the mitigation potential of the measures in LUT is 1 000 tonnes of CO_2 avoided. Fuel efficiency and the electrification fleet represent 75% of the CO_2 emission avoided, while the remaining 25% comes from behavioural changes, i.e. from trip length reduction and modal shift.

In the ROG scenario, the emissions avoided thanks to the public transport development are 45% less than in the LUT scenario. The increase in the number of trips and the average travel distance, as well as the modal shift from walking and cycling to public transport, limit the impact public transport investments on CO_2 emissions.

Figure 8. Mitigation potential of the two alternative scenarios by categories of measures



Note: BAU – Business-as-usual; ROG - Robust Governance; LUT - Integrated Land Use and Transport Planning.

Source: Author's own calculation based on ITF global passenger model.

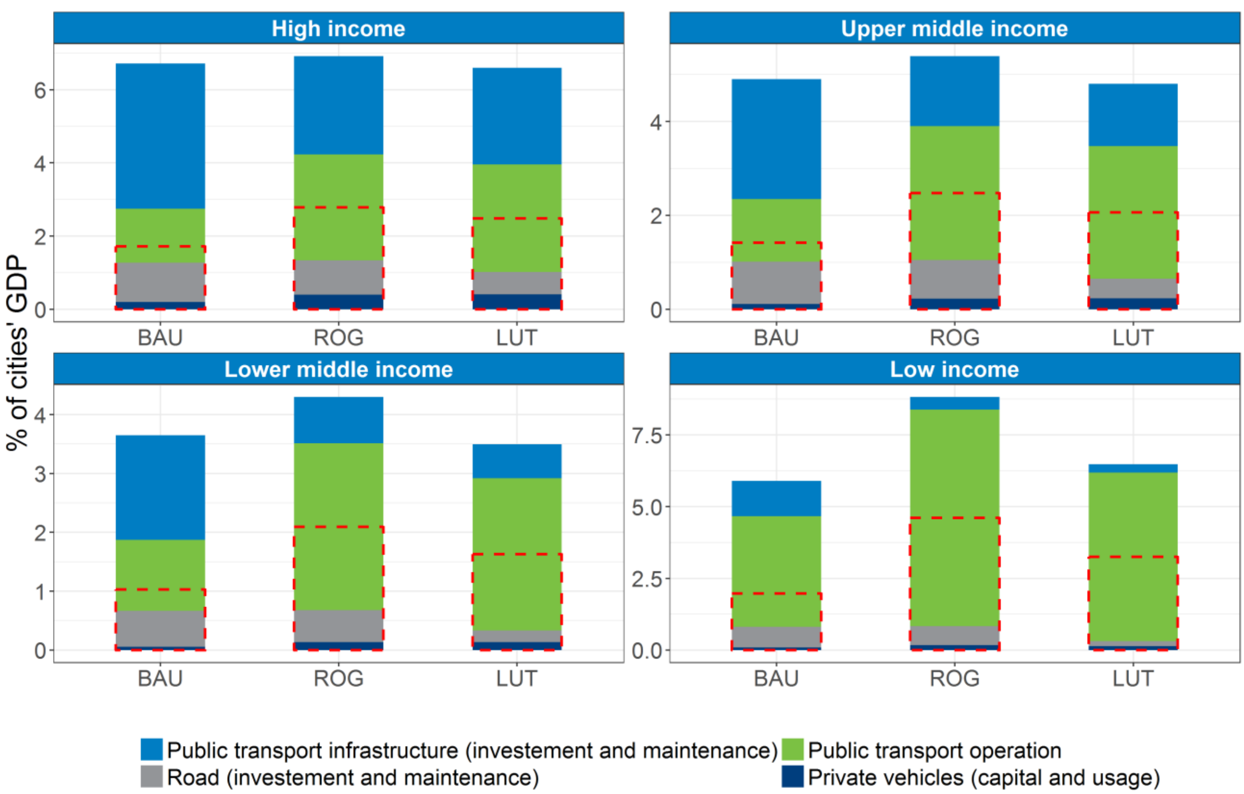
Different investment policies have implications on who will bear the costs of mobility

Policy choices in terms of infrastructure deployment have implications on the costs of transport and on who bears them. Transport infrastructures are long-lived assets characterised by high operation and maintenance costs. Local authorities often support a large part of the costs of public transport systems. If no public transport options are available, households might be forced to rely heavily on their car.

Figure 9 presents an estimation of the average cost of mobility between 2015 and 2050. Infrastructure costs include capital, reconstruction and maintenance costs. Usage costs include fuel costs, operation and maintenance and vehicle capital costs. As we take a socio-economic approach, taxes are excluded. The analysis shows that the total cost of transport does not differ between BAU and LUT scenarios, but their repartition is significantly affected.

If developing cities follow the same path as European cities for the development of their transport supply, the operations of their public transport network might become a financial burden. In European cities, public transport networks are well-developed and affordable, which require subsidies up to 60% of the total operation costs. Figure 9 includes a crude estimation of the costs borne by public authorities, depicted by the red dashed rectangles. It shows that the participation of the public sector increases sharply in the ROG scenario, with an increase of up to 75% in upper middle income cities. In the LUT, although the need for public money would still be greater than in the BAU, the increase is much more limited.

Figure 9. Complete transport costs between 2015 and 2050



Note: Estimation of the costs supported by the public sector are in red (assuming 50% of public transport funding in the alternative scenarios and 30% in the BAU). BAU – Business-as-usual; ROG - Robust Governance; LUT - Integrated Land Use and Transport Planning.

Source: Author's own calculation based on ITF global passenger model.

Targeted land-use policies can reduce transport infrastructure needs while increasing access in cities

Reduction of CO_2 emissions is just one aspect of transport policies. In many cities the most pressing challenges are local air pollution, congestion and affordable access to jobs and services. Our analysis suggests that the two last objectives are aligned with low-carbon mobility. In particular public transport has the ability to provide inclusive access to all where it is properly planned. As dense cities make public transport more efficient, targeted land-use policy can contribute to improving access.

Table 8 presents a simplified socio-economic assessment of the two alternative scenarios proposed in this study. It compares the costs of the different policies in terms of investments and operation costs with the business-as-usual scenario. Two non-monetary benefits are also included: the gains in terms of accessibility and CO_2 savings. Detailed assumptions are presented in Box 3.

The analysis shows that although the ROG scenario is overall more costly than the BAU, it induces a significant increase in access. Therefore it ends up with a positive socio-economic assessment, meaning that the underlining investments are good value for money. However, the LUT scenario is much more beneficial as it is able to provide a similar increase in access for lower costs. This simply reflects that it is easier and cheaper to provide transport services in a dense city.

Table 8. Socio-economic assessment of the two alternative scenarios (in trillions USD with a discount rate of 6% for 2015-50)

	BAU-ROG	BAU-LUT
Car use costs (including fuel costs)	11.0	12.0
Road infrastructure investments and maintenance	1.1	4.6
Public transport operation costs (including vehicle capital costs)	-13.8	-13.4
Public transport infrastructure investments and maintenance	-1.4	-1.5
Access gains measured as (new) users' surplus	5.5	7.6
CO_2 savings	1.9	2.1
Net benefit of the policies	4.3	11.4

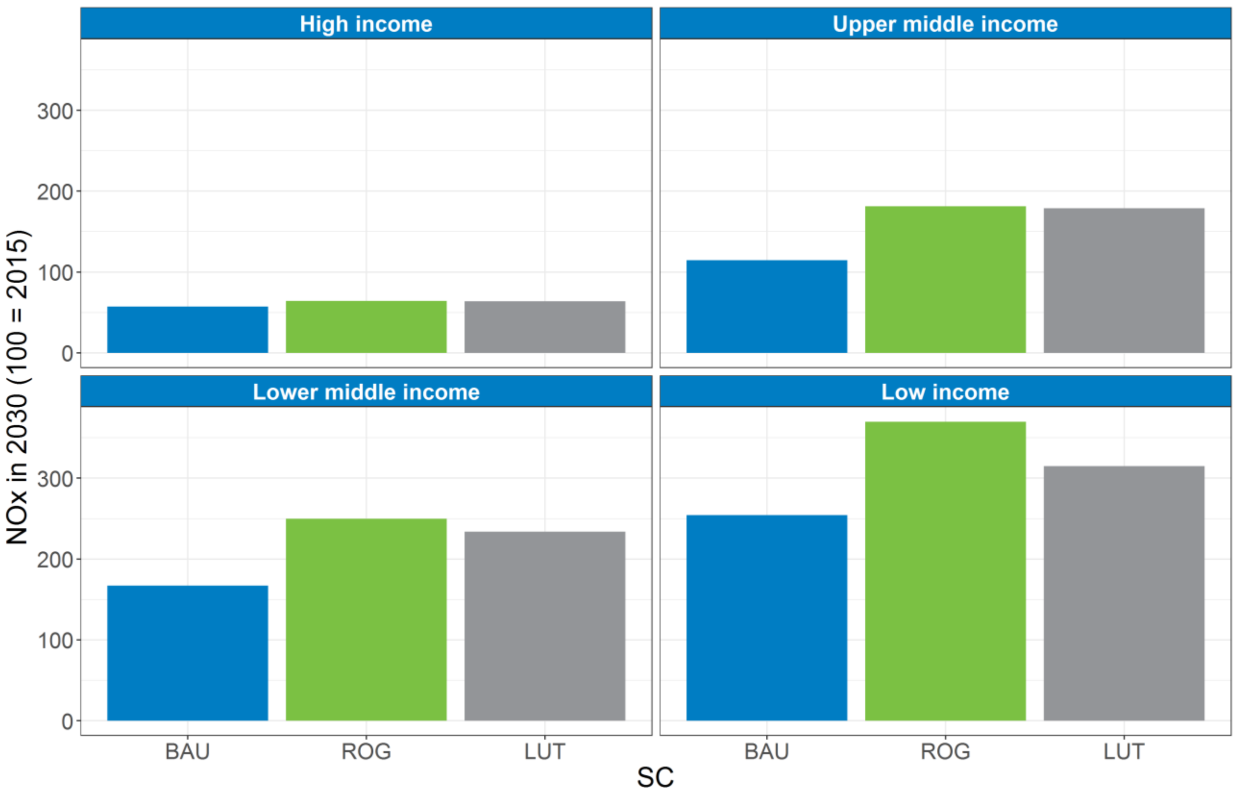
Source: Author's own calculation.

Achieving reduction in CO_2 emissions while maintaining air quality is challenging and might require additional investment in bus fleet

The effect of urban transport policies on CO_2 and local pollutants are not always correlated. Figure 10 presents the emissions of NOx resulting from the mobility levels of the three scenarios and using assumptions on the environmental performance of vehicles of the Roadmap of the International Council on Clean Transportation. This roadmap includes expected improvements in vehicle standards and their probable penetration in vehicle fleet until 2030. In both LUT and ROG, NOx grow more compared to the BAU scenario, because of increased bus travel that replaces car mobility. Diesel buses, which constitute the major share of bus fleets, have higher emission factors per passenger-km than passenger cars, and this relationship is not expected to decrease significantly in the near future, especially in developing countries.

This means that additional investment in cleaning the vehicle fleets are to be expected, although the actual technology is yet unclear. The fleet of electric (hybrid or battery) buses is rapidly increasing – e.g. battery-powered electric bus stock grew to about 345 000 vehicles in 2016, double the number in 2015 according to IEA electric vehicles Outlook (IEA, 2017) – they are still far too costly to be to be a cost-effective way to improve air quality and reduce CO_2 emissions (Guerrero, 2017).

Figure 10. NOx emissions in 2030 under the three scenarios



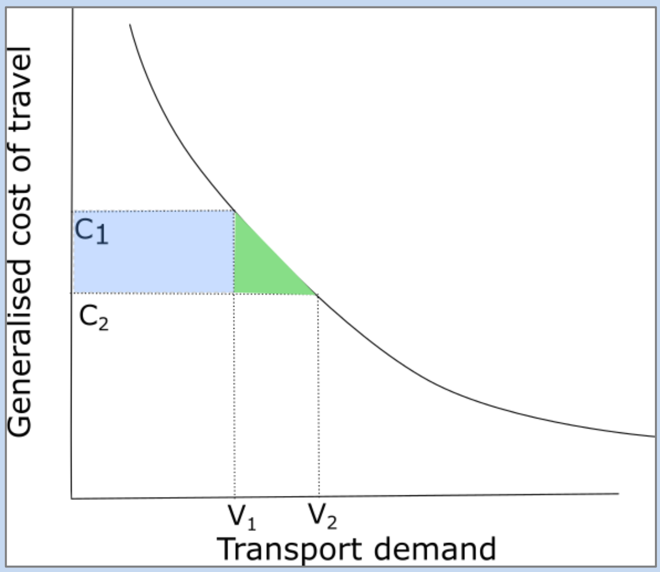
Note: BAU – Business-as-usual; ROG - Robust Governance; LUT - Integrated Land Use and Transport Planning.

Source: Author's own calculation based on ITF urban passenger model

Box 3. Assumptions for the simplified socio-economic assessment

Accessibility improvement and consumer surplus. When creating or improving new transport infrastructures, travellers will adjust their behaviour if cheaper or faster transport options become available. The benefit they derive from it is called the users' surplus and can be derived directly from the transport demand curve.

Figure 11. Principle of users' surplus estimation



A demand curve for public transport is presented in the figure above. If travel cost drops from C_1 to C_2, then public transport patronage is expected to increase from V_1 to V_2. The existing users, who were all willing to incur travel cost greater than C_1 before the improvement, now only incur a cost of C_2. Their change in user surplus is represented by the blue rectangle and can be simply approximated to $(C_1- C_2)*V_1$.

New users did not previously use the facility and thus did not have a previous cost of travel. Instead, their change in user surplus can be estimated by finding the area in green. It is often approximated by the formula: $(C_1- C_2)*(V_2-V_1)/2$.

An important result of transport economics is that users' surplus can be interpreted as the benefit from an increased accessibility (Koenig, 1974), rather than just money and time gains.

Discount rate. Costs are discounted with a yearly rate of 6% between 2015 and 2020. Note that as the benefits and costs are spread over the total period of assessment, the results obtained here are not very sensitive to the assumption on discount rate.

Carbon valuation. Carbon valuation is assumed to increase with time, starting from USD 50 per tonne in 2015 and going up to USD 100 per tonne in 2050.

A potential disruption: The rise of new shared mobility services and the implication on investment needs

Autonomous, electric and shared vehicles

Although limiting warming to 2°C has been a recognised target for several decades, there is a growing acknowledgement that more ambitious mitigation actions will be needed. The Paris Agreement commits to holding the average global temperature to "well-below 2°C" and recognises that avoiding 1.5°C of warming "would significantly reduce the risks and impacts of climate change." Yet recent ITF (2018b) work showed that current and foreseeable policies, as the ones modelled by the LUT scenario, will not suffice to achieve the international community's climate ambitions. Innovation and radical policy choices will be needed to decarbonise urban transport.

At the same time, many observers foresee that urban mobility will go through a dramatic transition. The convergence of electrification, car sharing and autonomous driving, offer the promise of a more efficient, cleaner and more inclusive mobility system, provided that policies guide these potential disruptions to work efficiently together.

The key element of this transition is undoubtedly the sharing aspect. Automation alone, i.e. a scenario where self-driving cars would be owned privately, would certainly result in an increased demand in car use. A range of non-drivers, such as young, older or disabled people, previously unable to drive a vehicle themselves, might want to start using automatic vehicles (Ticoll, 2015). Potential new users could also be attracted by the range of digital activities and entertainment on offer inside vehicles (Fraedrich, Beiker, and Lenz, 2015). A lower perceived inconvenience and time costs of driving with autonomous vehicles may favour urban sprawl.

On a similar note, even if deep electrification might be an option to decarbonise transport, most analysts agree that policies and technologies that reduce the need for individual transportation are required. They will make the deployment of new technologies more manageable and significantly reduce the required investment (IEA, 2016). Moreover, the full electrification of the vehicle fleet is unlikely to be a cost effective mitigation measure and might exceed the ability of governments to sustain the necessary incentives. As a simple example (Perissin Fabert and Foussard, 2016) finds that supporting battery electric vehicles have an abatement cost of more than EUR 400 per tonne of CO_2 avoided in 2050.

ITF conducted a detailed study on Lisbon (ITF, 2015) demonstrating that an electrified, shared and self-driving fleet of vehicles can significantly reduce the number of cars on city streets while offering the same levels of mobility as today. It also results in significant reductions of distances travelled, of congestion and of negative environmental impacts. The key technological enabler behind that is the advent of ubiquitous spatial location and communication technologies which allow designing very efficient demand-responsive services. Further studies have been conducted in other OECD countries (ITF, 2017b; 2017c), confirming that the original results hold in different contexts, albeit only in developed cities (see Table 5).

With respect to this paper, the main takeaways of this set of studies are:

- If massively adopted by car users, new shared mobility services have the potential to reduce traffic while providing transfer-free rides at a comparable price to public transport. However, this result is not true if the adoption rate is too low. There is a need for a critical mass of users so the services can be optimised efficiently to maximise occupancy rate and minimise detours to pick and drop users. When this is not the case, the service becomes costly to operate and can even result in increase in car traffic. This minimum market share depends on the urban form of the city and prevailing mobility patterns, but estimations show that a conservative assumption is 30% of the total demand.
- Even if 100% of car users were to switch to shared services, the impact on traffic can be somewhat limited. Indeed, shared services are likely to be operated by low capacity vehicles ranging from mini-vans to mini-buses. Therefore the shift of bus users to shared services will increase traffic wherever bus occupancy ratio is not unreasonably low (e.g. under 10 passengers per bus). In all case studies presented in Table 9, this was largely counterbalanced by the decrease in car traffic, but the maximum reduction in vehicle-km is 60% while in cities with already well developed public transport systems, such as Lisbon and Helsinki, the total traffic goes down by less than one-third.
- Based on stated-preference surveys, all studies concluded that users have a strong willingness to adopt shared mobility services as their main means of transportation. About 30% to 60% of the users would choose to shift to shared mobility services, if they were available. However, all things being equal, transit users are more willing to adopt the new modes than car users. This in line with existing research on user profiles of app-based on-demand ride services (Rayle, Dai, Chan, Cervero, and Shaheen, 2016).

Table 9. Results from ITF studies on shared mobility services in different cities

	Lisbon (Portugal)	Helsinki (Finland)	Auckland (New Zealand)	Lyon (France)
Reduction in VKM in case of full adoption by car and bus users	-25%	-33%	-60%	*NA*
Share of users willing to adopt shared mobility services	*NA*	63%	30%	43%

A tentative outlook

Building an accurate forecast of the impact of shared services on transport demand and infrastructure is challenging, given there is no feedback from a large scale experiment. Nevertheless, the following presents some first orders of magnitude based on previous ITF studies. We consider a simple shared mobility service operated with electric mini-buses of 8 to 16 seats. They are run under a street-corner-to-street-corner service, meaning that a passenger could potentially walk 200 metres to be picked up and must book 30 minutes in advance. The service is scheduled through a centralised dispatcher that matches supply and demand while minimising detour distances and travel times. Note that this tested solution does not intend to be prescriptive; it is rather an attempt to base simplified estimations on a service that seems to be emerging in the current market (for example LeCabPlus in Paris, Kutsuplus in Helsinki or Uber Express POOL in several cities).

To construct a quantified estimation, namely the SHARED scenario, we make the following, simplified, assumptions on top of the LUT scenario:

1. The market penetration of shared services increases from 2020 to 2030, with users switching from their main mode to the shared services according to Table 10. However, the service is implemented only if the resulting demand is at least 30% of the total passenger-km.
2. The global transport demand remains stable i.e. that the new mobility services do not induce additional trips or increase the length of existing ones. This is implicitly assuming that demand management policies are implemented. The wider range of mobility options offered by shared mobility services, would otherwise lead to a surge in demand resulting from conventional rebound effects.
3. There is a detour ratio of 1.5, meaning that to transport a single passenger for one kilometre, one needs 1.5 vehicle-km due to the distance travelled to pick up extra passengers and to empty journeys back to the depots. The average occupancy rate is assumed to be eight passengers per vehicle.

Table 10. Assumptions on the modal origin of shared mobility services' users

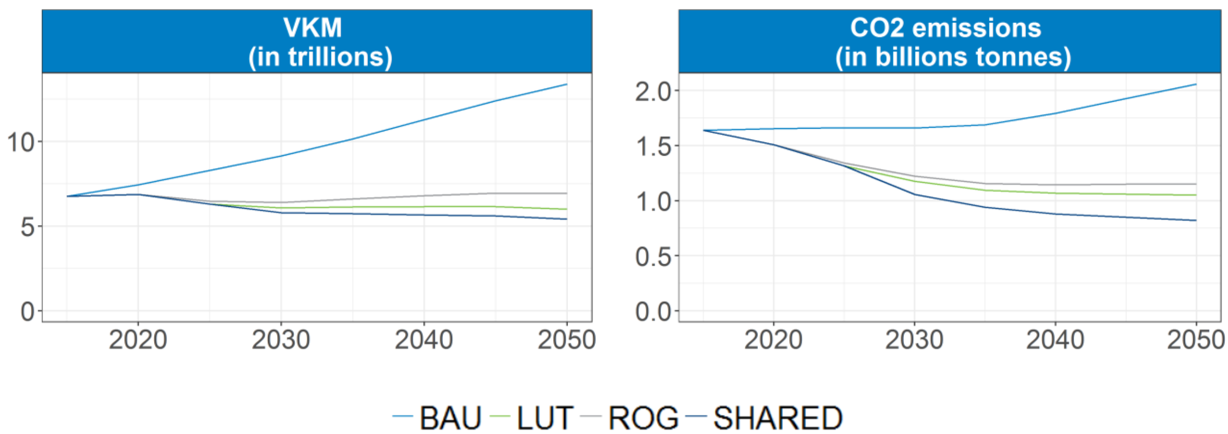
	Private vehicles (car and motorcycles)	Bus	Rail	Active modes (cycling and walking)
% of the users shifting toward a shared mobility service	20%	40%	10%	20%

Overall the impact of shared mobility services on traffic is small. First, because it is unlikely that large scale shared mobility services will appear in all cities. A recent ITF work (ITF, 2017d) has shown that a plausible pathway to large-scale adoption of shared mobility services would be to use bus users as early adopters, of the service, together with young and those living more remote areas without access to public transport. Deploying shared mobility services in a targeted way so they represent a better alternative to current bus services is indeed feasible. The increase of use in shared mobility services would gradually build the customer base needed to reach full efficiency of the system and then attract car users. In high-income and car-centric cities this pathway might not be feasible. In our forecast, 80% of the cities accounting for 84% of the total urban population have large-scale mobility services. It is mainly in medium-sized, car-centric, Northern American cities that the uptake of shared mobility services is not feasible. It is clear that those results should be taken with caution as they are built under strong and arguable assumptions. To the author's opinion, they highlight that the transition to a shared transport system might be hampered in cities where the willingness to share is too low. In these cases, alternative pathways would probably require some forms of disincentives for using private cars, at least temporarily, to support the growth of the service.

Second, the reduction in traffic caused by the modal shift from car to shared mobility services is partly counterbalanced by the replacement of buses by mini-buses. In 2050, this effect is especially strong, as the modal share of buses is particularly high. With 20% of the car users switching to the shared services, there is only a 10% decrease in road traffic.

The reduction on wheel to tailpipe emissions is more significant, with a decrease of more than 20%. An interesting policy aspect about shared mobility services is that they can easily by operated by shared electric services. Today, the total cost of ownership per kilometre for a private battery electric vehicle is already competitive with conventional cars if operated in fleets with intensive use. The main barrier is the vehicle range and the need for recharging stations. However ITF work showed that even with a range of 150 km this could be optimised provided that the vehicle allow fast charges of 30 minutes. Only 2% more mini-buses would be necessary for handling these recharging and range issues.

Figure 12. Traffic and emissions under different policy scenarios



The main impact on infrastructure will be a decrease in parking needs

In the so-called "SHARED" scenario, the need for road infrastructure will remain very similar to the LUT scenario. In term of space depicted to the movement of vehicles, the LUT is already rather optimised. As traffic levels are decreasing compared to nowadays in both scenarios, urban road infrastructure spending will mainly consists of maintenance and reconstruction works, except in fast growing cities. In the SHARED scenario it is likely that maintenance costs of trunk roads might decrease of a 1% to 3% due to lower usage.

But the main impact will be a smaller need for parking infrastructures. While in the LUT the need for parking might not change significantly, it is will be the case in the SHARED scenario. This is a direct consequence of those two stylised facts:

- The demand for parking spaces is essentially driven by car stock. There are currently between two and three parking spaces per car in cities. It is typically because parking in residential areas tends to be vacant during the workday, while parking at work is vacant at night. Although reduced car use might reduce this ratio, it is likely to stay over two.
- Car ownership will decrease in the SHARED scenario, not in the LUT. While studies have shown that public transport supply has an impact on car ownership, it is typically low. All things kept equal, the large public transport investment such as a major extension of the underground network might decrease car ownership by 1% to 3% (Mulalic, Pilegaard, and Rouwendal, 2015). A plausible explanation is that public transport services do not offer the same level of flexibility than personal transportation because of uneven coverage in space and time, so owning a car is still necessary for occasional trips. On the contrary some elements suggest that shared mobility services might have a more significant impact on car ownership. Car sharing schemes, whether point to point or free floating, lead to reduced car ownership with studies indicating five to 15

cars are replaced for each shared car added to the fleet (Barbora and Archer, 2017). In London, in a stated preference survey, 25% of non-car owners indicated they would sell at least one car if on-demand shared mobility services were available. Additionally 40% of non-car users would renounce buying a car and 37% would postpone buying one (Kamargianni, Matyas, Li, and Muscat, 2018).

The potential savings are not negligible. The cost of building and providing parking spaces is difficult to assess – it typically varies from several orders of magnitude depending if it is street, surface, multi-story or underground parking. A conservative value for surface level parking is USD 150 per square meter or USD 2 250 per parking spot (Dulac, 2013). In a BAU scenario, the car stock is 1.25 billion vehicles in 2050, leading to 3 billion parking spaces. If, with the uptake of shared mobility services, the 20% shift from car translates into a comparable decrease in vehicle stock, it would lead to 600 million parking spaces saved, accounting for USD 1.4 trillion. It also represents over 9 000 km^2, which is about the area of Paris, Washington and Beijing all together.

Besides the financial aspect, this will be an opportunity to reshape cities by providing additional public spaces. Huge amounts of space could be converted to other uses, from public parks to broader sidewalks, as well as commercial activities such as restaurant or kiosks. This conversion might be costly, but will contribute to citizen's well-being and improve cities' liveability. At the same time, with the rise of shared mobility services and the growth in urban goods delivery, road kerbs will more and more be used for pick-up and drop-off. Rather than the road itself, it is the complete street design that might evolve to accommodate new uses (ITF, 2018a).

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Appendix 1. Data sources

Data type	Description	Source
City list		
	Full list of cities with population above 300k by 2014	UN Habitat, Wolrd Urbanisation Prospects 2014
Mode shares		
	Percentage of trips (all purposes) by different type of modes	Various sources
	Main source	The EPOMM Modal Split Tool, http://www.epomm.eu/tems/result_cities.phtml?more=1
	Other miscellaneous sources	National Household Travel Survey
		Statistic year books
		Reports from local transport authorities
		Reports from different research institutes and organizations
		Union Internationale des Transports Publics (UITP), Mobility in Cities Database
Transport supply		
	Global road network	OpenStreetMap, https://www.openstreetmap.org/
	Global public transport network	OpenStreetMap, https://www.openstreetmap.org/
	Mobility in cities database	UITP
	World metro database	http://mic-ro.com/metro/table.html
	Rapid transit database	ITDP
	Public transport network and timetables	Various public transport operators and agencies based on the General Transit Feed Specification format (GTFS), http://www.transitwiki.org/TransitWiki/index.php?title=General_Transit_Feed_Specification
	Travel speeds	TomTom Traffic Index, https://www.tomtom.com/en_gb/trafficindex/
GDP		
	GDP, GDP per capita projection by country	OECD ECO department
	GDP by cell grid in 2010	LANDSAT

Data Type	Description	Source
Car ownership		
	Passenger cars per 1 000 inhabitant by country	IRF World Road Statistics 50th Anniversary (Data 2000-2011)
Transport prices		
	Transportation prices by city, e.g. gasoline per litre, monthly pass, one-way transit ticket, taxi per hour etc.	NUMBEO, open source, http://www.numbeo.com/cost-of-living/prices_by_city.jsp

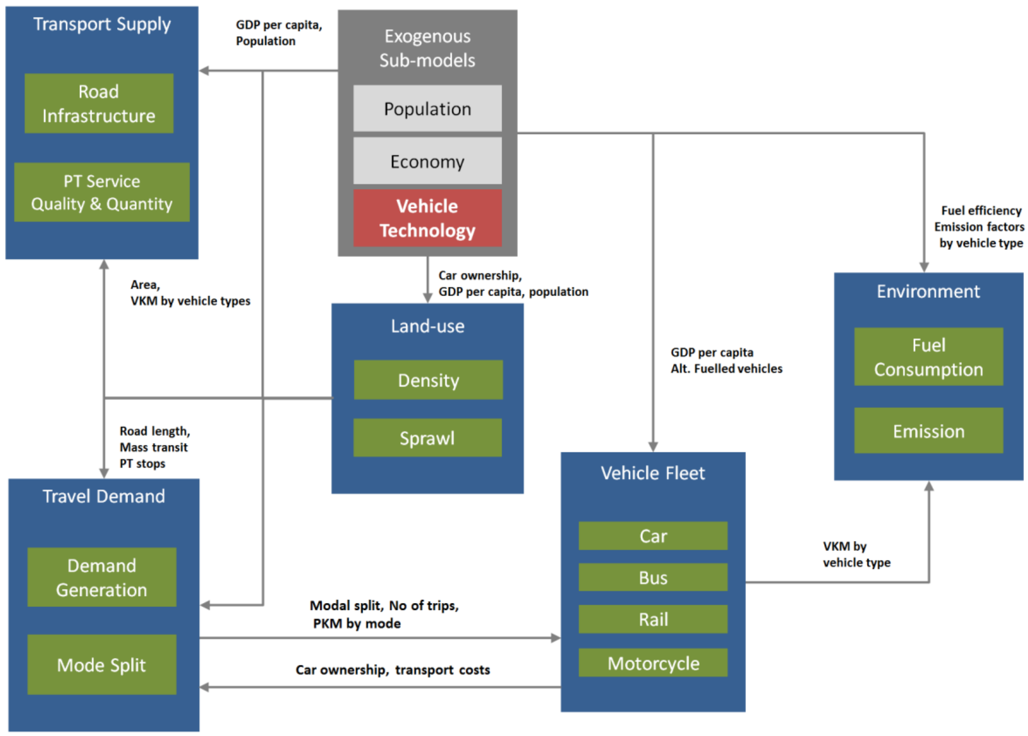
Appendix 2. Presentation of the urban passenger model

The scope of this study is all the urban agglomerations with population above 300 000, following the definition of UN World Population Prospects (2014 Revision). The full city list contains 1 692 cities. The general model structure comprises six sub-models. The transport system is composed by three highly interrelated sub-models: travel demand, transport supply and vehicle fleet. The dynamics among the sub-models play a fundamental role in the quantitative analysis. The interaction between land-use and transport system is represented as the land-use sub-model influencing the mode choice and vehicle ownership, and in turn being affected by the transport supply level. The exogenous sub-model contains the inputs of population, economy and vehicle technology providing exogenous drivers to the transport system. The outcomes of vehicle fleet sub-model feed into the environment sub-model to compute the CO_2 emissions. The sub-models are structured as in Figure A2.1.

The main assumptions are summarised below.

- The population is projected by replicating the UN Habitat approach to project the urban population from 2030 to 2050.
- A sigmoid curve is used to forecast the GDP growth rates for the cities. The relationship between the national share of urban population concentration and the national share of urban GDP concentration follows an S-shaped curve.
- Urban transport supply, including road provision and public transport supply, are derived from regression analysis.
- The modal split of each city is modelled via a multinomial logit.
- A sigmoid curve is used to forecast the passenger car ownership and assumptions to infer the share of other type of vehicles.
- CO_2 intensities and technological pathways by mode for converting vehicle activities into CO_2 emission are taken from IEA Mobility Model (MoMo)

Figure A2.1. Traffic and emissions under different policy scenarios



Transport supply

In the model the transport supply is described by four variables: the local and main road length; the public transport stops; the availability of mass transit. The equations for the estimation of the road network length and total number of public transport stops (bus, metro, tram, BRT, etc.) are the following:

$$mainrdLen_i = a_1 * area_i^{\beta_1} * gcap_i^{\beta_2} * VKM_i^{\beta_3}$$

$$localrdLen_i = a_2 * area_i^{\beta_4} * gcap_i^{\beta_5}$$

$$ptStops_i = a_3 * pop_i^{\beta_6} * area_i^{\beta_7} * gcap_i^{\beta_8}$$

Where $mainrdLen_i$, $localrdLen_i$, $ptStops_i$, pop_i, $area_i$, $gcap_i$ and VKM_i are total road length, total number of public transport stops, urban area size and GDP per capita of city i, respectively. β is the estimated coefficient for each variable.

The availability of mass transit depends on population density and GDP per capita and is modelled with a logistic regression on those two variables. The length of mass-transit infrastructures are derived directly from the VKM using VKM to lane-km ratios and distinguishing between light and heavy mass-transit.

National car ownership

The historical car ownership (passenger car per 1 000 inhabitant by country) data is collected from IRF with a time span from 2000 to 2011 that includes 169 countries of the world. The conceptualisation of the passenger car ownership model follows the study by (Dargay, Gately and Sommer, 2007). We built a passenger car ownership model that explicitly models the car saturation level as a function of observable urbanisation rate of each country. The elasticity of passenger car ownership with respect to per capita GDP follows an S-shaped curve, with car ownership rising slowly with income while income remains low, accelerating while income goes through medium levels, and slowing down again as incomes reach high levels.

$$carOwn_i=\frac{b_n+exp(u*uRate_i)}{1+exp(-gr_j*(gcap_i-m_j))}$$

Where, i is the country, n is the continent, j is the income group, $uRate$ is the urbanisation rate, $gcap$ is the GDP per capita, b_n denotes the constant term of the saturation level, u is the coefficient for urbanisation rate, gr is the growth rate, and m is the midpoint of the curve.

Car ownership is modelled as the dependent variable in the first instance, based on urbanisation rate and per capita income. The predicted car ownership is then treated as an independent variable in the development of mode share models.

Transport costs

Transit ticket price per trip is also collected from the same data source. A regression model is estimated to predict the transit ticket price in the future. The formulation is:

$$ptFare_i=c_j*gcap_i^{\beta_7}$$

Where $\mathrm{c_j}$ is the constant term of country group j, β_7 is the estimated coefficient of GDP per capita.

Parking price is collected from the a parking rate survey carried out by Colliers International in 2011 (Moore, 2011). Daily parking cost $parking_i$ is a function of car density (cars per square kilometre) $\mathrm{carDens_i}$ and public transport stop density (number of public transport stops per square kilometre) $ptDens_i$:

$$parking_i=d*carDens_i^{\beta_8}*ptDens_i^{\beta_9}$$

Mode choice

Existing studies show that the aggregated mode share for each city is a function of urban development status, including urban scale, geography, economy, land use, personal behaviour and public policy (He et al., 2013; He, Meng, Wang and He, 2011; Norley, 2015). It aims to answer the questions on what the impacts of urban development policies are related to socio-economic development, car ownership, urban structure, road supply, public transport provision and pricing indicators on the aggregated modal split of a city. Mode shares are the parameters which are sensitive to the urban development policies. It is an alternative to the usual individual-based or trip-based behavioural logit models used in travel demand modelling. A standard multinomial logit model is applied, with following specifications:

$$P_{ni}=\frac{e^{U_{ni}}}{\sum_j e^{U_{nj}}}$$

$$U_{C_i}=ASC_C+\beta_{cown}*carOwn_i+\beta_{fpx}*fPrice_i+\beta_{pk}*pPark_i+\beta_{rds}*rDens_i$$

$$U_{PT_i}=ASC_{PT}+\beta_{ptds}*ptDens_i+\beta_{mast}*mass_i+\beta_{tpx}*ptFare_i+\beta_{pds_{PT}}*popDens_i$$

$$U_{W_i}=ASC_W+\beta_{pds_W}*popDens_i+\beta_{gcap_W}*GCAP_i$$

$$U_{B_i}=ASC_B+\beta_{pds_B}*popDens_i+\beta_{gcap_B}*GCAP_i$$

$$U_{M_i}=ASC_M+\beta_{pds_M}*popDens_i+\beta_{gcap_M}*GCAP_i$$

where ASC is alternative specific constant, β 's are the estimated coefficients, $fPrice$ is the fuel price, $pPark$ is the parking cost, ptFare is the transit ticket price (single trip), $rDens$ is the road density, $ptDens$ is the density of public transport stops, $mass$ is the availability of mass transit mode, $GCAP$ is GDP per capita, and C, PT, W, B, M are car, public transport, walk, bicycle, motorcycle indices respectively.

The data set contained 247 observations, with an average weighted mode share in value of 42% for car, 30% for public transport, 18% for walk, 6% for bike and 3% for motorcycle. The calibrated model has $\rho^2 = 0.279$, showing a satisfactory explanatory power of the mode choice, and all the variables are statistically significant.

The values for the calibrated parameters, such as the preference factors, are plausible and in line with other studies that suggest higher preference for personal car as compared to public transport and bicycle to be the least preferred mode. All the coefficients are statistically significant. The calibrated coefficients indicate that car ownership and road density have positive impacts on car use. Positive impacts of transit stop density and the availability of mass transit are found to positively impact the use of public transport. The pricing variables, namely fuel price, parking cost and transit fare, are found to have negative impacts on the use of corresponding mode. We find urban density to contribute positively to the ridership of public transport and the use of non-motorised modes and the values of the coefficients are higher in for the public transport, followed by walking and cycling. GDP per capita uses as a proxy for income level is found to have negative impacts on the use of motorcycle and non-motorised modes. This finding is in line with the existing studies that increasing income leads to the growing demand for faster and more convenient transport modes.

Trip rates and distances

The average trip rate in this study means the number of trips per day per person considering all trip purposes. In trip generation analysis, the approach involves setting up the model to represent the relationship between trip rates and the socio-economic characteristics. In this study, we used a simple regression analysis to find the relationship between the observed average trip rates from the household travel surveys and the GDP per capita.

Average travel distance is defined as the single trip distance regardless of trip purpose. We used the observed sample trip distances to establish a relationship between average distance by private vehicle and the urban area size. We also obtained average differences in travel distance between different modes, such as average travel distances by public transport are 45% longer than car, distance of a bike trip is usually around 32% of a car trip distance. Based on available data, we made such a simplified average value for all cities over our study time period. If more and better data are collected in the future, the trip rates and trip distance estimations will be enhanced. The methodology will be further improved by including more explanatory variables on travel distances by mode, such as land-use mix, population density, and possibility, which evolve over time as well.

Vehicle technology and CO_2 emissions

The transport scenarios are translated into CO_2 emission scenarios by applying transport technology paths. The technology assumptions and emission calculations are taken from the IEA's MoMo model and the Energy Technologies Perspectives. The scenario used for the BAU is the four degree scenario (4DS) in the World Energy Outlook, which corresponds to a context in which broad policy commitments and plans that have been announced by countries are implemented. Under this scenario fuel economy standards are tightened and there is progressive, moderate uptake of advanced vehicle technologies (IEA, 2013 and Dulac, 2013). The result is a slow but sustained decrease in fuel intensity of travel and carbon intensity of fuel for all vehicles. In general, such a decrease is higher within the OECD region.

Appendix 3. Cost assumptions

Road infrastructure costs

The cost of a new road varies significantly depending on terrain, the level of traffic expected, the type of roadway, and whether civil works included bridges or tunnels. Yet an order of magnitude, even rough, of the costs remains a useful indication. Road infrastructure costs have been split into three categories: construction of new infrastructure and reconstruction and operation and maintenance (O&M) of existing, older infrastructure. Reconstruction and upgrade costs differ from annual O&M expenditures as they generally include civil works such as road strengthening, surface reconstruction and rehabilitation, and shoulder widening.

Construction costs

Unit costs are expressed as United States Dollar (USD) per lane-km. All values were standardised to USD 2010. Unit costs were collected from various sources with the objective to cover projects from various regions of the world and average by regions. Only projects of new infrastructure (i.e. excluding upgrades) were considered and, wherever possible, costs overruns were included. Table A3.1.1 summarises the average values of this analysis.

Table A3.1. Sources for trunk roads unit costs

Regions	Main sources
Africa	AFRICON, 2008 World Bank, 2006
Asia	World Bank, 2006
EEA + Turkey	European Court of Auditors, 2013
Latin America	World Bank, 2006
Middle East	*Not available*
North America	WSDOT, 2002
OECD Pacific	Nichols, 2013
Transition	World Bank, 2006

Most of the observations come from large interurban projects. Tow correction ratios, based on expert judgement, have been applied to values of Table A3.1. Urban trunk roads are more costly than interurban ones, due to higher land costs and to the difficulties of civil work in urban setting. Urban trunk roads are thus assumed to be three times more costly. Local roads, as they are designed to receive less traffic than trunk ones, are less costly. Local roads are assumed to be four times less costly than trunk ones.

Table A3.2. Unit costs assumptions for interurban trunk roads (in thousand USD 2010 per lane-km)

Region	2015	2030	2050
Africa	320	380	450
Asia	790	970	1 190
EEA + Turkey	1 650	1 810	1 980
Latin America	580	650	760
Middle East	610	670	740
North America	1 910	2 040	2 180
OECD Pacific	1 410	1 540	1 670
Transition	630	740	840

Road reconstruction and operation and maintenance costs

Reconstruction usually happens within a time of several decades. Here it assumed that a trunk road is fully reconstructed every 40 years, a value which is rather conservative as very intensively used traffic roads can be reconstructed every 20 years. No reconstruction cost was assumed for local roads.

Operation and maintenance (O&M) costs cover small civil engineering works that happens on close to yearly basis. O&M represents between 1% and 5% of capital costs, with an average of 3% regardless the region (Dulac, 2013). As O&M costs will typically vary with the intensity of usage, we estimated a relationship of O&M costs using an explanatory variable the ratio *(total VKM)/(lane-km of the network)*. As no city-level data is available, this was done on national level data. We found an elasticity of 0.3 and corrected the relationship so the average maintenance costs across cities would be 3% of the capital costs.

Public transport infrastructure costs

Our main data source is Codatu (2009) which provides construction costs for different types of public transport projects as a function of the level of income (through a linear relationship). The actual assumptions are presented in the Table A3.3 below.

Table A3.3. Constructions costs for mass transit infrastructures

Infrastructure type	Value for countries where GDP/hab. is USD 10 000	Additional cost per USD 1 000 of GDP per hab
Underground	USD 65 million per track-km	USD 0.8 million per track-km
Light transit modes (tramway or BRT)	USD 15 million per track-km	USD 0.3 million per track-km

As for roads, reconstruction operations were assumed to be conducted every 40 years. The O&M costs are assumed to be respectively 2% and 3% of the capital costs for underground, tramways and bus rapid transit.

The operation of bus networks also requires some forms of infrastructures (e.g. stops, depots or maintenance centres), although the actual scope is ifficult to define. It was assumed that they amounted to 20% of the vehicles costs.

Others costs

Fuel and vehicle costs (both capital costs and maintenance) are taken directly from MoMo, the mobility model of the International Energy Agency (IEA, 2018).

The costs of operating a line (in particular staff costs) are taken from (Codatu, 2009).

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