DECARBONISING COMMERCIAL ROAD TRANSPORT

TNO innovation for life

There is growing consensus among governments, businesses and consumers about climate change and the required energy transition. At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The agreement sets out a global action plan to put the world on track to limit global warming to well below 2°C. The aim is even to limit the increase to 1.5°C, since this would significantly reduce the risk of potentially devastating impacts of climate change on civilized life on this planet.

In the transport sector there is a growing attention for reducing CO_2 emissions, or *decarbonisation*, and the transition towards zero-emission vehicles. For example, ERTRAC, the European Road Transport Research Advisory Council, has set the objective[1] to achieve a 50% more efficient European road transport system between 2010 and 2030. Furthermore, the German Bundesrat has voted to ban new gasoline- or diesel-powered vehicles from German roads starting in 2030. Similar proposals are discussed in the Netherlands and Norway. After *"dieselgate"*, Volkswagen is radically shifting its strategy towards the development and mass production of electric vehicles. Tesla is building its first Gigafactory in Nevada for the mass production of lithium-ion batteries primarily for electric vehicles and is investigating where to locate new Gigafactories in Europe. BYD is starting mass production of battery-electric buses for the European market in Hungary. In January 2017, a consortium of 13 companies, including Toyota, BMW, Daimler, Honda, Hyundai, Shell and Total announced in Davos that they will invest 10 billion Euros to promote the use of hydrogen in the transport sector within five years. In the Netherlands, currently about 100,000 plug-in and all-electric vehicles are in use and about 25,000 charging stations are publicly available. In addition, more companies are adding a climate-change dimension to their strategic supply chain planning and site selection.

The Dutch government has developed a vision on sustainable transport fuels, called *"Brandstoffenvisie"*. Electrification of transport is seen as one of the major options to reduce the direct greenhouse gas (GHG) emissions from transport in urban areas. However, achieving substantial overall well-to-wheel GHG emission reductions with this approach requires a substantial increase of

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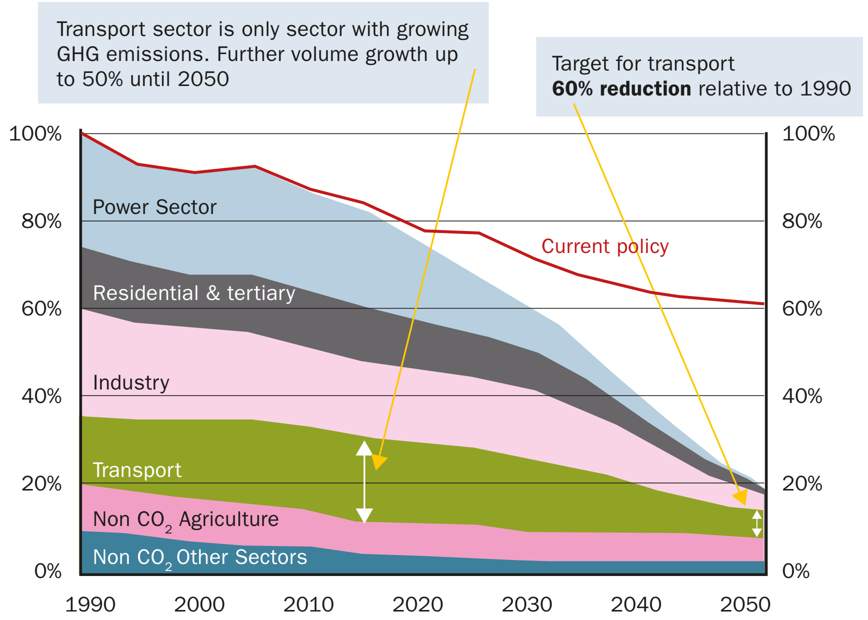
[1] *http://www.ertrac.org/uloads/documentsearch/id21/ERTRAC_SRA_2010.pdf*

renewable energy sources in power generation. The policy targets for the transport sector refer only to the direct tailpipe emissions from fuel combustion. Therefore, electrification of transport could transfer a part of the carbon footprint of transport activities to the energy production sector. Due to electrification, the energy and transport sectors become more integrated resulting in additional challenges as well as opportunities. The Dutch agreement on energy for sustainable growth (*“Energieakkoord”*) marks the start of the transition to a sustainable future in the Netherlands. Interestingly, the transition toward renewable energy sources also shows appealing examples of how costs of low-carbon technologies can rapidly decrease when markets develop and become more mature. In 2016, for example, there was considerable excitement when DONG Energy delivered a tender for the Dutch offshore wind farm *Borssele-1&2* with the striking price of €72.70/MWh, hereby beating the industry’s 2020 goal of €100/MWh by several years. Moreover, by late 2016, yet another record-breaking bid of €54.50/MWh was reached when a Dutch consortium, including Shell, won the tender to build the *Borssele-3&4* offshore wind farm in the Dutch North Sea. These examples show that the need to subsidize sustainable technologies can reduce more rapidly than expected once sufficient momentum and scale is reached.

Despite the growing attention for low-carbon transport and renewable energy sources, there are still many challenges ahead and investments to be made to arrive at a path toward the climate goals for 2050. This is all the more so because full electrification currently does not provide a feasible route for decarbonising all modes of passenger and freight transport. Remarkably, the transport sector is the only sector of which GHG emissions in EU have grown between 1990 and 2015. Current and planned policies will largely fall short of the low-carbon transport targets towards 2050, as figure 1 indicates.



Source: Roadmap for moving to a cometetive low-carbon economy in 2050 (2012)

Fig. 1. EU GHG emissions towards an 80% domestic reduction.

THE CARBON PRODUCTIVITY CHALLENGE

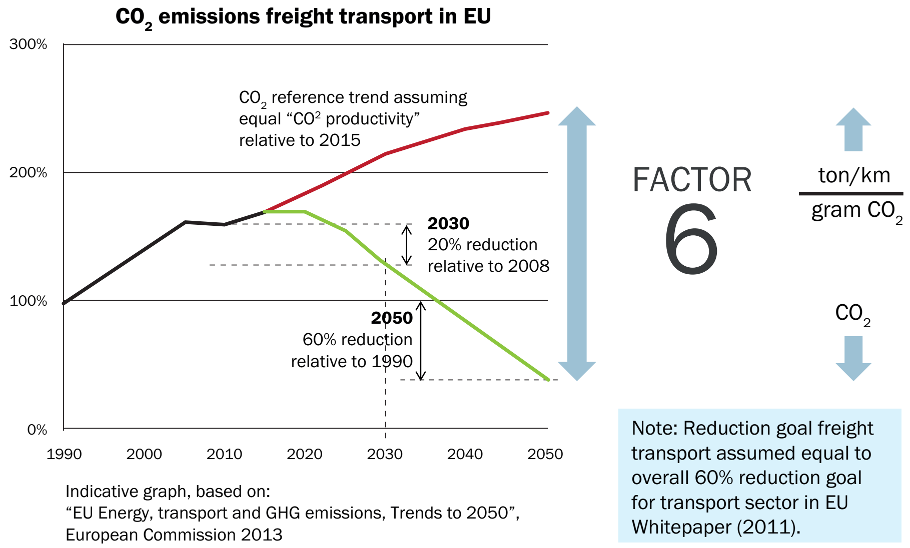
The EU has set itself a long-term goal of reducing greenhouse gas emissions by 80 to 95% in 2050 when compared to 1990 levels. To achieve the 80% goal, emissions from transport must be reduced to more than 60% below 1990 levels by 2050. However, since the new Paris agreement, the CO_2 reduction target for the transport sector is expected to be tightened towards perhaps 75% or more by 2050.
Any successful policy or action on climate change must support two objectives: reducing CO_2 emissions whilst maintaining economic growth. Assuming that economic growth will lead to a continued increase in transport demand, meeting the 2050 target for transport requires approximately a sixfold increase in “carbon productivity”: the amount of freight and passenger transport per unit of carbon equivalents emitted, i.e. t-km/CO_2e and p-km/CO_2e (see figure 2). This will require an integrated approach capturing available opportunities to increase energy efficiency in a cost-effective way, decarbonizing energy sources, accelerating the development and deployment of new low-carbon technologies and changing the logistics operations of businesses and behaviours of consumers.

To achieve a sixfold increase in carbon productivity, CO_2 abatement options are needed at all system levels, such as energy carriers, powertrains, vehicle, fleet, logistics operation, behaviour, and all transport areas, including passenger cars, buses, light commercial vehicles and medium/heavy-duty trucks in road transport as well as all other modalities such as inland shipping and rail. Consequently, designing a consistent package of measures, alignment of short-term and long-term action and dealing with uncertainties by adaptive programming become increasingly important.

A BRIEF VISION ON SUSTAINABLE ENERGY TECHNOLOGIES

From various scenario analyses it is clear that the long term CO_2 emission reduction targets for the transport sector can in principle be reached by a combination of curbing the growth in vehicle kilometres, the large scale application of extremely efficient vehicles running on sustainably produced energy carriers, and where possible a shift towards inherently more energy efficient transport modes.

For road vehicles, the current portfolio for efficient vehicles running on sustainably produced energy carriers includes (battery-)electric vehicles running on renewable electricity, fuel cell vehicles on hydrogen produced from renewable sources and efficient combustion engine vehicles running on low-carbon fuels. The latter include sustainably produced biofuels as well as synthetic fuels based on renewable energy. All options have their specific advantages, drawbacks and limitations, leading to the conclusion that it is likely that the future road transport system will contain a mix of all these



Indicative graph, based on:
"EU Energy, transport and GHG emissions, Trends to 2050",
European Commission 2013

Note: Reduction goal freight transport assumed equal to overall 60% reduction goal for transport sector in EU Whitepaper (2011).

Fig. 2. A sixfold increase in CO_2 productivity is needed to achieve CO_2 reduction targets in EU28.

technologies. Each technology in that case will be applied in specific (sub)sectors or niches where the benefits of the technology outweigh the disadvantages. It is at this stage not possible, and also not constructive to the transition, to make a blueprint indicating which technology will "win" in which application. Nevertheless, some conclusions can be drawn based on current insights in the various technological routes.

> "There is still significant potential for improving the energy efficiency of conventional vehicles"

Through improved engines, waste heat recovery, efficient gearboxes, increasing levels of hybridisation, improved aerodynamics, lower rolling resistance tyres and weight reduction, the fuel consumption and TTW CO_2 emissions of internal combustion engine vehicles can still be greatly reduced. Assessments in support of future CO_2 legislation for cars and vans show that reductions from the current fleet average of around 120 g/km to around 70 g/km in 2025 are feasible at acceptable costs. For long -haul trucks a 40% reduction of fuel consumption and TTW CO_2 emissions appears possible at net negative costs (ΔTCO < 0). This improved efficiency will help to reduce the demand for biofuels in applications where other renewable energy sources cannot be applied.

> "Electric vehicles are the preferred option for transport in urban areas"

Given that electric vehicles have zero-tailpipe emissions and that electric propulsion powered by electricity from the grid is the most energy-efficient route for converting renewable energy into kilometres driven, electric vehicles are a preferred option in all applications where limitations with respect to range, charging times and the need for charging infrastructure are acceptable. This will be the case mainly in the urban environment for a large share of the passenger cars, vans, city distribution trucks and city buses.

For passenger cars, projections of the development of costs and range indicate that EVs could compete with ICEVs beyond 2025. Latest projections by some industry experts indicate that battery cell costs may drop to $100 per kWh already by 2020. Strict post-2020 CO_2 standards for passenger cars and vans, below levels that can be reached with improved ICEVs only, will help to make sure that sufficient production volumes are reached to realise the required cost reductions and the broad supply of models that is needed to meet the demands of early majority consumers.

Conductive slow charging is currently the main option used for charging EVs, but is unlikely to suffice when EVs become the dominant vehicle technology in urban areas. In the coming decade, gaining practical experience with alternative charging infrastructure options, including fast conductive charging, inductive charging and possibly overhead wires for buses or trucks (“electric highway”), is paramount for determining the dominant design for the future charging infrastructure that can support the large-scale adoption of electric vehicles.

“Hydrogen is a significantly less efficient route for using renewable energy in transport, but is a relevant option for light-, medium- and some heavy-duty applications for longer distances”

Fuel cell vehicles on hydrogen are technically nearing maturity. They combine some of the superior driving characteristics of electric vehicles with a longer range, a short refuelling time and an energy infrastructure that is more similar to the current system based on gas stations. These are all important advantages from an end-user perspective. The energy chain from renewable electricity to the mechanical energy at the wheels, however, contains significant energy losses for electrolysis, compression or liquefaction and subsequent transport of hydrogen and for conversion back to electricity in the fuel cell on board the vehicle. Starting with a given amount of renewable electricity, e.g. from solar energy (photovoltaics) or wind turbines, a battery-electric vehicle can drive a distance that is a factor of 2 or more larger than for a hydrogen vehicle. As long as renewable energy is not abundantly available at low costs, this means that, from an overall energy perspective, hydrogen should only be used in applications where the drawbacks of electric vehicles are not acceptable. This could be the case with, for example, passenger cars in business applications, some truck segments or regional buses.

Hydrogen may play a role as a buffer for excess renewable energy. Although the market price of excess renewable energy may be low (and at times even negative), this does not mean that hydrogen produced from excess electricity will be cheap. This will depend on the net capital costs of the electrolysis facilities that are only used part of the day. Furthermore, the future availability of excess electricity for hydrogen production should not be overestimated as this will be reduced by effective demand management in smart grids or by storage in alternative stationary options with possibly lower costs.

Similar concerns apply to power-to-gas and power-to-liquid options where hydrogen produced from (excess) renewable electricity is combined with captured CO_2 to produce carbon-based fuels that could replace natural gas and fossil petrol and diesel in conventional vehicles.

“Due to limited availability of sustainably produced biomass, the use of biofuels should be limited to long-haul applications in road freight, shipping and aviation”

Despite a “closed carbon cycle”, the well-to-wheel GHG emissions of biofuels are not zero. GHG emissions occur in agriculture, the production of fertilizer, and the production and distribution of the fuel. In addition, there are often significant GHG emissions resulting from so-called indirect land-use change (ILUC) as a consequence of the increased land demand for growing energy and food crops. In recent years, it has become clear that for some widely used biofuel routes, the WTW GHG emissions are actually higher than for the fossil fuels they replace. In addition, there are concerns about competition for land with the increased global demand for food production. Given that also other sectors will have an increasing demand for sustainably produced biomass in the coming decades, it is wise to assume that the availability of sustainably produced biofuels for the transport sector will be limited and not sufficient to replace more than a minor part of the current fossil fuel consumption. As a consequence, the consensus is that biofuels for transport should be reserved for applications where electricity and hydrogen are not viable options. In road transport this may include long-haul applications in freight transport. Within the transport sector as a whole, large-scale biofuel use is foreseen for shipping and aviation.

“Blend-in of compatible biofuels more likely than dedicated biofuels”

Regarding liquid biofuels, it is unclear which specific fuels will dominate in the future. However, given the increasing availability of options for producing biofuels that are compatible with fossil petrol and diesel, or even have premium fuel qualities, it becomes more and more likely that the increased use of biofuels will take the form of increasing blend-in ratios in petrol and diesel, rather than the use of dedicated alternative fuels that require specific engine adaptations.

“The role of natural gas, in the form of CNG or LNG, as a transition fuel should not be overestimated”

Compared to Euro VI for heavy-duty vehicles and the future Euro 6 with RDE (real-driving emissions) requirements for light-duty vehicles, the air quality benefits of natural gas compared to diesel have become very limited. Compared to petrol vehicles, air quality benefits were already limited to lower emission levels for some unregulated exhaust components. Direct emissions of CO_2 are somewhat lower than for petrol and diesel, but net WTW GHG emission reductions depend on the origin of the gas and the energy use and possible leaks in long-distance transport of natural gas, as well as on the amount of methane slip in engines running on natural gas. Gas in spark ignition engines leads to lower combustion efficiencies compared to diesel, although this could be partly overcome by higher compression ratios in dedicated engines. Dual fuel compression ignition engines allow the use of natural gas with diesel-like engine efficiencies. Using natural gas and diesel in RCCI (Reactivity Controlled Compression Ignition) engines, currently under development, could lead to further improvements in engine efficiency combined with inherently low exhaust emissions.

The WTW emissions of methane-powered vehicles can be significantly reduced by the use of biogas or synthetic gas produced from renewable energy and captured CO_2. The availability for use in transport of biogas with favourable WTW emissions, e.g. from waste or manure, will always be limited due to limited global feedstock availability and demand from other sectors. In addition, there is concern about creating a lock-in when natural gas would be used at a large scale as a transition fuel to bridge the gap between current petrol and diesel vehicles and the future upscaling of alternatives such as electric and hydrogen vehicles. We have only 35 years to complete the transition to a low-carbon transport system and resistance from both vehicle owners and actors in fuel supply infrastructure is to be expected if their vehicles and infrastructures would need to be phased out fifteen or twenty years from now.

The main routes for sustainable energy technologies in transport are starting to become apparent. However, the actual development and large-scale implementation of the needed innovations and abatement options requires a system approach that takes account of the characteristics of specific use cases and needs to consider technical, behavioral, logistical and business model innovations.

THE INCREASING NEED FOR A SYSTEMS APPROACH

This paper presents an application-specific systems approach which addresses the challenges mentioned above and is applicable to both commercial passenger and freight transport.

Low-carbon options and associated CO_2 abatement potentials, both technical and non-technical, are often ranked in marginal abatement cost curves (MACCs) from highest to lowest cost-effectiveness. A rational approach would be to start implementing these options starting with the least costly ones with the largest abatement potential. In practice, however, this exercise is not so straightforward. Obtaining objective and reliable insight into the reduction potential and costs of the various options is already a challenge. Moreover, in the selection and implementation of measures, many stakeholders are involved, with different interests and split incentives. One of the key challenges is to overcome the chicken-and-egg dependencies that hamper wide adoption of abatement options. It will be key to indicate which actions can be taken by which stakeholders and which benefits and first-mover advantages accrue to the early adopters. For example, if a number of leading municipalities and leading transport operators or logistics service providers together could develop a reliable transition path and guarantee a larger scale demand for zero-emissions vehicles in the next five years or so, producers could anticipate larger scale production and production costs could rapidly drop.
As targets become tightened and ‘low-hanging fruit’ options (e.g. start-stop systems, improved route planning, tyre pressure monitoring, etc.) have already been captured, moving away from fossil fuels to a combination of different low-carbon or biofuels or to clean energy stored in batteries and introducing more complex system innovations will become very challenging. In addition, the low-carbon trajectories are expected to result in many new relationships between different subsystems and policy areas which might become partially overlapping. For example, the increasing use of electric vehicles will require a more integrated approach of the transport and energy sectors. Further, many programmes or measures such as ‘smart mobility’ and ‘low-emission zones’ are primarily engaged from a congestion, accessibility or air quality perspective, while these also contribute to CO_2 reductions. Finally, the onset of automation may significantly affect the provision of transport and vehicle ownership models (i.e. Mobility as a Service and the Physical Internet).

In general, public and private stakeholders in commercial transport have a limited overview of how different short-term measures and action plans add up to the overall medium- and long-term GHG emission targets. Individual options, programmes and measures are implemented and evaluated, but assessments of whether the whole range of available short-term measures reinforce or diminish each other’s effects in view of the long-term low-carbon transition, are generally not consistently made.

THE MODELLING FRAMEWORK INCLUDES REFERENCE VEHICLES, VEHICLES STOCKS, MANY DECOMPOSITIONS, MISSION PROFILES FROM REAL-TIME MEASUREMENTS AND ENERGY EFFICIENCY CHARACTERISTICS FROM TESTING, REAL-WORLD MEASUREMENT AND SIMULATION.

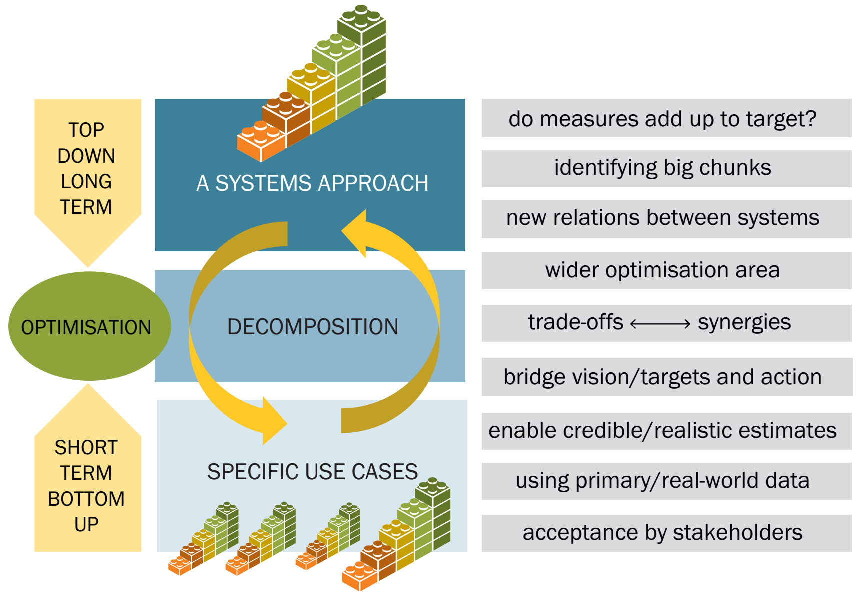


Fig. 3. The need and benefits of a systems approach.

The growing need to combine several complex abatement options requires governments, policy makers and decision makers in companies to exercise a more leading role. Roadmapping and adaptive programming are needed to orchestrate innovation, harvest synergies and avoid trade-offs, and achieve large reduction potentials. A **systems approach** enables to develop a coherent package of policies and abatement options for specific use cases on different system levels, such as passenger and freight vehicles, fuels, infrastructure, long-haul heavy-duty transport, city logistics and zero-emission bus transport (see figure 3 and figure 4).

The systems approach is **application specific** in the sense that it builds on bottom-up data for specific uses cases resulting in estimates of feasibility, abatement potentials and costs of (packages of) abatement measures which are realistic and credible, and therefore accepted by the key stakeholders in these use cases. This will provide stakeholders with perspectives for action. Consequently, the wider optimisation area including different systems and system levels will enable to identify synergies, align short-term action plans and long-term targets, and develop more effective and efficient policies and abatement options.

THE TRANSITION REQUIRES A SYSTEMS APPROACH

TNO aims to support the proposed systems approach towards a zero-emission transport system by developing a toolset of methods and related simulation models specifically applicable for different use cases. TNO is seeking for ambitious and leading public and private partners to join this development and collaborate to set innovation priorities and harvest first-mover advantages. Starting point of the toolset is the combination of a vast body of in-depth scientific and technical expertise from TNO with the specific domain expertise and data from private and public partners. The development is backed by TNO's leading scientists, engineers, and market experts from various disciplines such as powertrains, automotive, logistics, renewable energy, etc. The expertise includes state-of-the-art technologies and socio-economic and technical assessments of technological advances and technology readiness of new options in time.
The toolset is envisaged to be a systems framework for selecting and matching affordable low-carbon options, policy measures and market opportunities as well as for the design and development of optimal system solutions and system controls.

There are three main categories of abatement levers, being the *demand* for transport, the *structure* of the transport and land use system, and the *efficiency* of vehicles and fuels (see figure 5). Next, the abatement options that physically bring about CO_2 reduction may comprise *technological* innovation (e.g. powertrains, vehicles, energy carriers, infrastructure and intelligent transport systems (ITS)), *behavioural* or social innovations (e.g. driving behaviour, travel behaviour, mode choice, car choice) and *system* innovations (e.g. improved network, improved routing, improved transit or transhipment, modal shift). Finally, there are policy measures that could push (e.g. road pricing, regulations, restrictions) or pull (e.g. fiscal incentives, exemptions, priorities, information and awareness, investments in quality of infrastructure) the adoption of technological, behavioural and transport and logistics system abatement options.

The toolset incorporates a multi-level energy optimisation framework in which the specific characteristics of the transport operator/user are matched with state-of-the-art technology insights, options and costs. The modelling framework includes reference vehicles, vehicles stocks, many decompositions, mission profiles from real-time measurements and energy efficiency characteristics from testing, real-world measurement and simulation.
One of the key challenges is to step-by-step move towards zero-emission vehicles in different areas of the transport sector in a cost-effective manner. Step-by-step refers to exploring the subareas in the transport sector that already are, or will in time

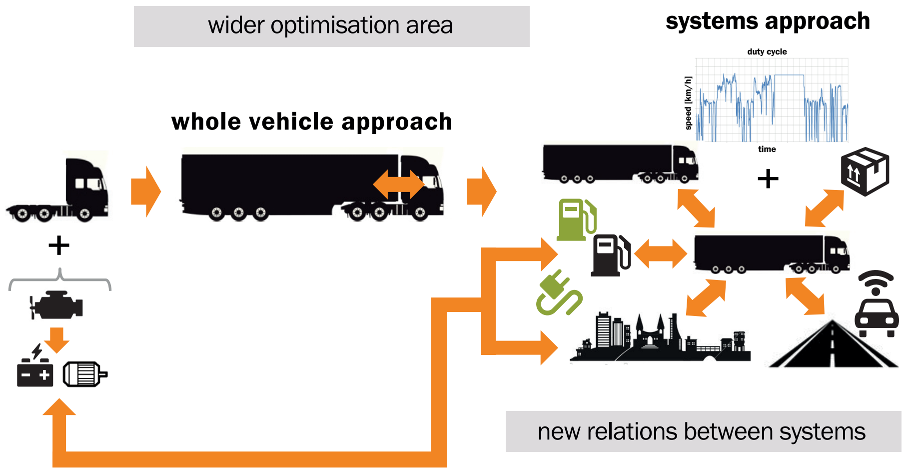


Fig. 4. Illustration of a systems approach.

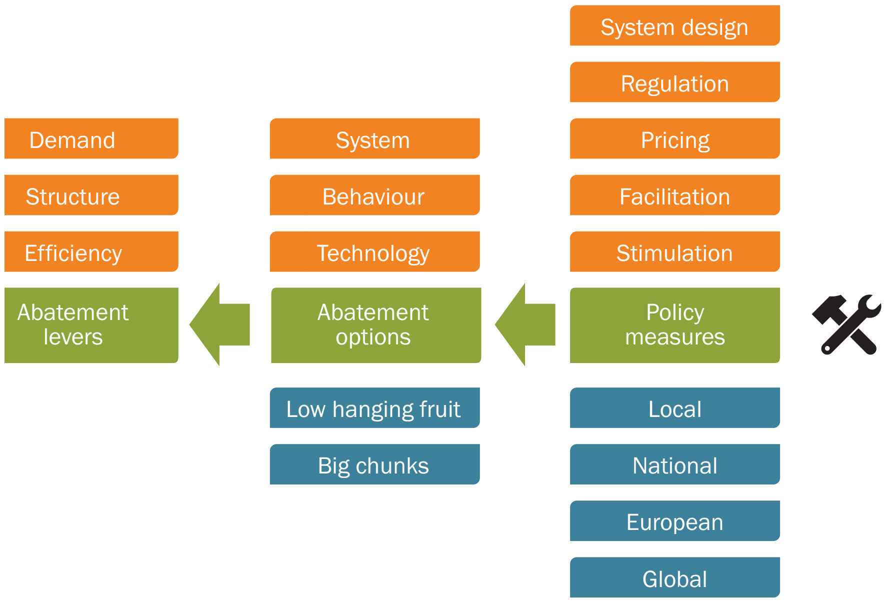


Fig. 5. Policy measures, abatement options and levers.

become, most favourable and feasible for the introduction of low-carbon or zero-emission options, while simultaneously taking into account the availability, specifications (e.g. energy use, range, price) and technological improvement of these vehicles/technologies in time. Often, alternative options are compared based on traditional transport and logistics system characteristics and constraints such as a diesel vehicle range, mileage and lifetime or concession period. Exploring the transition to zero-emission transport should therefore not only involve describing the current situation, but should also challenge and if possible reshape the boundary conditions and constraints of the current transport system or logistics operation in favour of easier and earlier adoption of electric vehicles or other low-carbon options.

Besides technical evaluations, a rational approach to assess the feasibility of abatement options for different applications includes an assessment of impacts on total-cost-of-ownership (TCO), as well as an evaluation of the value chain and associated business cases from a wider stakeholder perspective. The definition of TCO in this paper refers to the total cost of the operation of a vehicle fleet including aspects such as potentially required charging infrastructure, driver costs, etc. One of the main barriers for the mass adoption of zero-emission vehicles is related to their higher purchase price, capital expenses, depreciation rate and/or limited range. Higher initial costs have to be earned back during operation, either in terms of lower energy/fuel costs or possibly with lower maintenance costs or both. Another important barrier is the availability of charging infrastructure and the impact of large numbers of electric vehicles on the energy system in general.

The framework should enable assessment of the impact of changing and optimising transport and vehicle parameters such as more-efficient energy use to increase the range, shorter distance per trip, possibilities for fast charging, and higher daily mileage to maximize the savings, longer contract or concession periods to capture lifetime savings, etc. In practice, however, it is not just about the TCO. In fact, many stakeholders with different viewpoints and interests are involved. Important co-benefits of CO_2 abatement options for stakeholders are, for example, lower noise emission, reduced pollutant emissions (NO_x, PM), less congestion, energy security, increased operation time, increased customer satisfaction, and corporate societal responsibility.

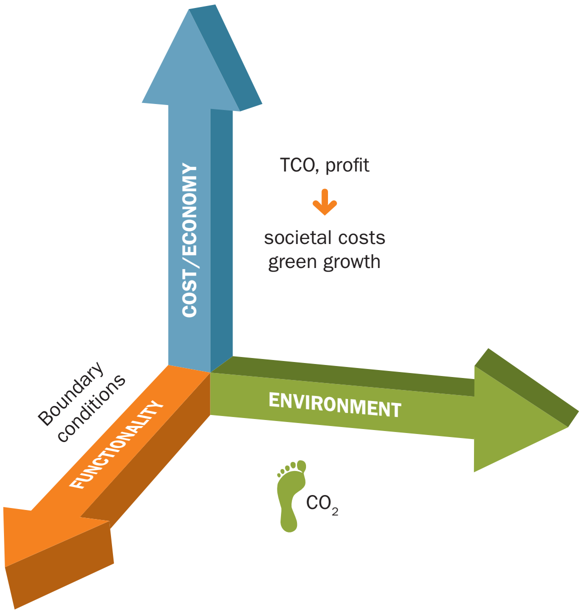
In addition, many other barriers and uncertainties play a role. For example, transport companies (carriers) may not invest in low-carbon options because any savings are directly passed on to the shipper, payback periods are considered to be uncertain or the logistics services could become less reliable. Alternatively, they may invest in low-carbon options to become *'lean and green'*, or to gain a competitive first-mover advantage which enables increasing their market share. Therefore, it is of vital importance to look at the whole value chain and take into account all stakeholders involved from technology development by suppliers, to technology adoption by service providers and to the end users or customers (figure 6). To overcome existing barriers and hesitations, the toolset enables to systematically assess and show the costs and benefits for companies and governments when moving towards low-carbon transport, either based on individual action or based on mutual interests with partnerships and gainsharing.

> **TNO CALLS FOR BOTH PUBLIC AND PRIVATE STAKEHOLDERS IN THIS SECTOR TO JOIN FORCES AND TOGETHER DEVELOP THE NEXT STEPS TOWARDS ZERO-EMISSION COMMERCIAL TRANSPORT.**

The TNO toolset enables to develop a low-carbon roadmap with perspectives for action by different stakeholders, see figure 7. The design and optimisation stages should be repeated for every next step on the roadmap as new information about the availability, costs and performance of zero-emission vehicles, other abatement options and the transport or logistics context may require to adjust the roadmap. This will result in adaptive programming.

COOPERATION IS KEY

As is evident from the above, the transport sector is facing a major and complex transition towards sustainable transport fuels, zero-emission vehicles and increased logistics and operational efficiency. Finding and implementing feasible, effective and affordable pathways for realising a sustainable transport system requires a systems approach. This is especially true for commercial transport of passengers and goods, which operates in a complex environment with stringent requirements for costs and profitability and strict operational boundary conditions set by demands and interests of customers and a wide range of other stakeholders. An integral systems approach, widening the optimisation area for increasing efficiency and functionality and lowering costs while taking account of relevant application-specific characteristics, is believed to result in cost-effective and accepted solutions. But no transport company, logistics service provider, government body, or research institute, can realise this on its own.



CO_2 needs to become a **system optimisation target** for:

- design of supply chains & logistics networks
- optimisation of logistic operations

What can be achieved:

- within existing systems and boundary conditions?
- By widening systems and modifying boundary conditions?

Wider optimisation area

Fig. 6. Optimisation of cost, functionality and the environment.

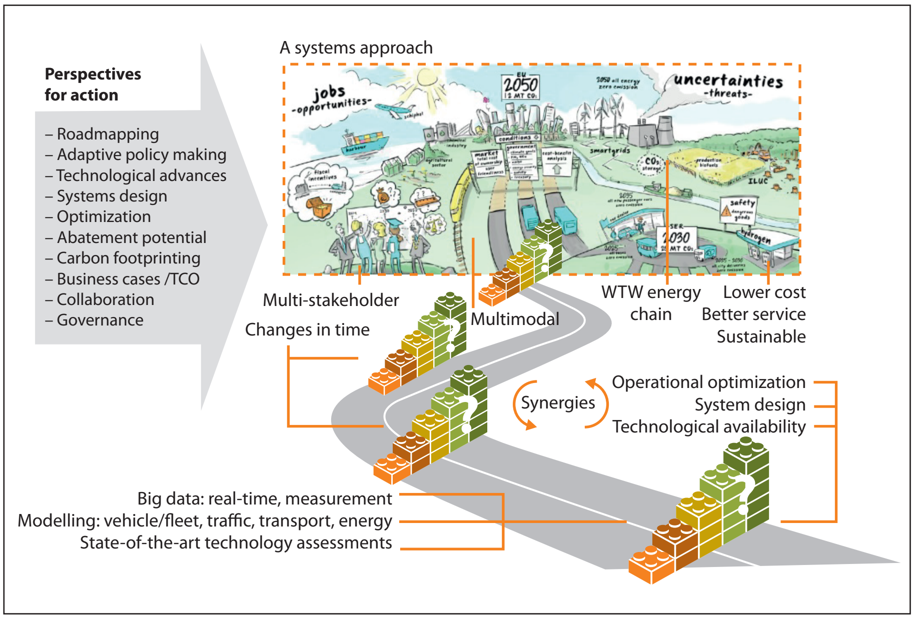


Fig. 7. Systems approach framework.

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LIVING ENVIRONMENT

As part of the Living Environment theme, we apply ourselves to devising innovations for vital urban regions. We work together with partners to create solutions for today and opportunities for tomorrow to enhance the viability, accessibility and competitiveness of these urban regions.

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