International Transport Forum

Decarbonising Transport in India: Learning From Life Cycle Assessment

Workshop Summary

Decarbonising Transport • Initiative •

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The International Transport Forum

The International Transport Forum is an intergovernmental organisation with 63 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. The ITF is politically autonomous and administratively integrated with the OECD.

The ITF works for transport policies that improve peoples' lives. Our mission is to foster a deeper understanding of the role of transport in economic growth, environmental sustainability and social inclusion and to raise the public profile of transport policy.

The ITF organises global dialogue for better transport. We act as a platform for discussion and pre-negotiation of policy issues across all transport modes. We analyse trends, share knowledge and promote exchange among transport decision-makers and civil society. The ITF's Annual Summit is the world's largest gathering of transport ministers and the leading global platform for dialogue on transport policy.

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The "Life cycle assessment methods to support India's efforts to decarbonise transport" workshop was part of the ITF's Decarbonising Transport (DT) initiative, which helps governments and industry translate climate ambitions into actions. More specifically, the workshop and this workshop summary are part of the ITF activities developed in the framework of the NDC Transport Initiative for Asia (NDC-TIA).

The NDC Transport Initiative for Asia (NDC-TIA) supports the People's Republic of China, India and Viet Nam to define policies that may enable them to meet the objectives of their Nationally Determined Contributions (NDCs). NITI Aayog is the nodal agency working closely with the ITF on the NDC-TIA project development in India. The goal of NDC-TIA activities in India is to implement actions to mitigate GHG emission in the transport sector. The ITF's involvement in the NDC-TIA India project leverages the life cycle assessment (LCA) tool being developed in the Decarbonising Transport in Emerging Economies (DTEE) India project. The tool aims to help local research and academic institutions support the government in defining greenhouse gas (GHG) emission mitigation policies in transport. The DTEE project develops modelling tools that assess GHG emissions in transport and help elaborate policy strategies to mitigate those emissions. ITF member countries Argentina, Azerbaijan, India and Morocco are all participants in the current DTEE project.

Both the DTEE and NDC-TIA projects are funded by the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

Presentation slides from speakers are available at https://www.itf-oecd.org/life-cycle-assessment-india-decarbonise-transport-workshop.

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Acronyms

Acronym	Term
BECCS	Bioenergy with carbon capture and storage
BEV	Battery electric vehicle
CNG	Compressed natural gas
DAC	Direct air capture
ERS	Electric road system
EU	European Union
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model, by Argonne National Laboratory
GWP	Global warming potential
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
LCA	Life cycle assessment
NGCC	Natural gas combined cycle
PHEV	Plug-in electric vehicle
PV	Photovoltaic
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-Wheel

Glossary

Term	Definition
Cradle-to-gate	Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e. before it is transported to the consumer).
Tank-to-wheel emissions	Emissions generated from the use of transport vehicles. Also known as tailpipe emissions. It does not include well-to-tank emissions, which make up part of the total emission pathway (well-to-wheel).
Well-to-tank emissions	Emissions generated from the production and transport of fuel (or another energy source, such as electricity) for transport vehicle use.
Well-to-wheel emissions	The total emissions associated with transport vehicle use. Including well-to-tank (indirect) and tank-to-wheel (direct) emissions.

Workshop background and objectives

On 13-14 April 2021, the International Transport Forum (ITF), together with NITI Aayog, held a workshop entitled "Life cycle assessment methods to support India's efforts to decarbonise transport". This event brought together Indian and international experts to take stock of the existing transport life cycle assessment (LCA) work and explore how it can assist transport decarbonisation policies in India. The workshop also identified potential gaps and priorities that arise as new vehicle technologies, fuel types, and mobility services enter the mass market. The ITF had set the following workshop objectives ahead of the event:

- take stock of the available research and tools used to evaluate the life cycle emissions and energy use of alternative transport options
- identify what India-focused LCA studies are available today with relevance for transport decarbonisation
- explore how existing LCA frameworks accommodate the analyses of energy use and GHG emissions of emerging vehicle technologies, fuel types and mobility services
- elicit opportunities to build on existing India-focused LCA frameworks to develop a tool that can inform transport decarbonisation policy developments in India.

Starting from these objectives, the organisers prepared an agenda with 14 speakers in four sessions. The opening session focused on international experience from transport LCA research. The following three sessions focused on: India-specific transport LCA research on alternative fuel options; vehicle powertrains; and transport infrastructure. A total of 77 participants joined over the two-day workshop. The workshop was held virtually via Zoom. The full agenda is available in Annex-A.

The workshop facilitated the transfer of knowledge and experience on transport decarbonisation strategies. It also assessed the relevance of experiences developed in other jurisdictions for the case of India. The event helped establish connections between the ITF, local universities and research institutes to build a community of stakeholders with the capacity to support the preparation of an LCA tool that can inform policy making for decarbonising the Indian transport sector.

LCA is a methodology used to calculate the environmental footprint of services or products through all life stages, ranging from the sourcing of raw materials to the final disposal of the exhausted product. This environmental footprint can be evaluated for various impact categories, such as energy use, GHG emissions or emissions of local pollutants. It is usually specified for a comparable service unit, for instance, passenger-kilometre (pkm) or tonne-kilometre (tkm), in the case of alternative transport options.

LCA can yield comprehensive insights into the environmental performance of different transport choices. It reflects, for instance, the embedded emissions of rail infrastructure for a planned metro line, or the energy use associated with battery production for electric vehicles (EVs). It can be used to assess alternative fuels – accounting for the carbon intensity of electricity used to charge EVs – or to compare alternative production pathways for biofuels. LCA can also shed light on the environmental impact of emerging mobility services. As an example, it can quantify the energy used during the empty running of ridesourcing cars on their way to pick up passengers, or that of service vehicles used to charge and distribute dock-less scooters in cities.

In a nutshell, LCA provides more detail than, for instance, information on the fuel use per vehicle-kilometre alone and is a powerful tool to inform the design of policies to decarbonise transport. Well-designed policies can ensure that the developments in the transport sector are compatible with climate objectives and further stimulate economic growth and industrial competitiveness. These policies are more effective if policy makers take into account LCA characteristics during the policies' development.

Insights from workshop sessions

The speakers of the workshop's opening session were Jari Kauppila and Pierpaolo Cazzola of the International Transport Forum and Siddharth Sinha of NITI Aayog.

The International Transport Forum opened the workshop. It presented an overview of its activities under the Decarbonising Transport initiative, through which it also implements its India-related activities of the DTEE and NDC TIA projects.

NITI Aayog reiterated the timeliness and importance of the DTEE and NDC TIA projects for assisting a sustainable development trajectory for India's transport sector in response to increasing urban traffic and interregional travel. A key priority that emerged is the need to decouple the growth in transport activity from increased energy consumption, greenhouse gas (GHG) emissions and air pollution.

NITI Aayog also stressed that sound data is an essential prerequisite for effective policy making. While transport data is abundant in India, policy makers do not always consider available insights when designing policies. Siddharth Sinha singled out LCA as a particularly useful method to assist evidence-based, holistic policy making that avoids an unintended shifting of impacts from one life cycle stage of transport systems to another. NITI Aayog also stressed that the Covid-19 crisis is an opportunity to accelerate sustainable transport reforms. These can alleviate climate change impacts that are particularly threatening to India and other developing economies.

Session 1. International life cycle assessments for the transport sector

The first workshop session, chaired by Madhav Sharma of NITI Aayog, gathered insights from existing transport LCA studies that can assist decarbonisation programmes. It provided examples of international experience, with speakers from Europe and North America. The presentations featured insights on life cycle impacts of alternative transport options for vehicle technologies, fuels and transport infrastructure, thus setting the stage for the three subsequent sessions, placing those themes in the context of India.

Transport infrastructure life cycle assessment

In her presentation, Shoshanna Saxe of the University of Toronto highlighted the importance of conducting sound LCA studies for infrastructure. She provided a comprehensive overview of impacts that are not always reflected in conventional assessments.

Infrastructure is the cornerstone for any transport system and its design locks in the type of transport activity over very long time scales. This calls for a holistic assessment of infrastructure planning that does not simply evaluate the impacts of material choices but also considers the impacts of the resulting transport system. This could be, for example, an urban road network with energy-intense car use or a rail network with lower impacts per person-kilometre. Infrastructure projects also induce secondary effects with varying impact. For example, North American cities that had an inner-city tramway in the early 20th century tend to be more compact with high-rise buildings. In contrast, elsewhere, highway projects have induced urban sprawl and created more car travel and a larger carbon and energy footprint. Planners should consider these indirect impacts of their infrastructure choices in addition to those of material use. The latter are significant due to the high environmental footprint of, for example, cement and steel.

Most impacts of infrastructure projects incur during the construction phase and vary depending on the material used and the work required. Underground structures have the largest footprint. These impacts are usually averaged over the assumed infrastructure lifetime, which can be a factor of uncertainty. There are examples of infrastructure projects exceeding their lifetime expectations (e.g. London tube). Others required extensive maintenance works that represented a complete refurbishment after just 25 years due to flawed construction. Infrastructure's longevity reduces its average environmental impact. However, it also locks in transport systems over very long time scales. The selected infrastructure type usually determines the choice after the infrastructure's lifetime, as like-for-like replacements are common. For instance, a new road can induce a long-lasting car dependency. Saxe stressed that, in most cases, end-of-life assumptions are not meaningful for determining the endpoint for a transport system.

Determining the environmental impacts of conventional and alternatively fuelled vehicles through life cycle assessment

Ricardo teamed up with E4Tech and IFEU for DG CLIMA at the European Commission to evaluate the life cycle impacts of alternative powertrain choices and fuel options for light-duty and heavy-duty road vehicles. Sofia Amaral of Ricardo Energy presented insights from the study at the workshop. The research scope does not include transport infrastructure.

European regulations on transport energy use and emissions historically focused on tank-to-wheel (TTW) impacts. This is the case, for instance, for emission standards for light-duty and heavy-duty vehicles. Biofuels and other low-carbon fuels led to the need to consider well-to-tank (WTT) impacts in fuel assessments. Further, the footprint of the manufacturing and end-of-life phases of vehicles increased in relevance when electric vehicles (EVs) entered the market.

The study evaluated the impacts of 65 powertrain and vehicle type combinations in 14 impact categories and took into account temporal variations in annual steps from 2020 to 2050. The analysis focused on European Union member states. The study generalised vehicle options to enable policy options, i.e. the underlying LCA is not product-based.

Findings on lifetime impacts from passenger cars showed that EVs overall have a smaller footprint than internal combustion engine (ICE) vehicles. However, EVs perform poorly in some impact categories, for instance, in terms of mineral use and human toxicity. EVs in Europe on average have a lower global warming potential (GWP) than ICE vehicles and these impacts are set to reduce over time as the power grid decarbonises. A sensitivity analysis identified the parameters of power mix, lifetime mileage and electric driving share of plug-in hybrid electric vehicles (PHEV) to influence findings the most. While EVs already provide net GWP reductions across EU member states on average, individual results differ according to a country's power mix. The lifecycle emissions of an EV in Sweden are just 25% that of gasoline ICE cars, while the current carbon intensity of Estonia's power mix prevents EVs from realising net savings.

Today, battery electric vehicle (BEV) powertrains perform best overall for medium-freight trucks and city buses, while electric road systems (ERS) are best placed to reduce GWP of heavy freight trucks.

Further standardisation of methodologies can help make studies more comparable.

Life cycle analysis of vehicle and fuel systems using the GREET model

Michael Wang of Argonne National Laboratory explained that the Greenhouse Gases, Regulated Emissions and Energy Use in Technologies (GREET) model framework consists of two modules: one to evaluate fuel cycles considering WTW impacts and; another for vehicle cycle modelling that calculates the life cycle footprint from the manufacturing to end-of-life phases. The model features four impact categories: energy use, GHG, pollutants and water consumption. It covers marine, rail and air transport in addition to road vehicles. For road vehicles, the model is capable of comparing a large number of powertrain-fuel combinations. GREET has a global user base that includes major corporations as well as government agencies and international organisations.

Several projects developed with GREET point to a number of interesting findings on electric vehicles. GHG emissions of vehicle batteries range from 100 kg CO_2e per kWh of battery in China to under 70 kg CO_2e per kWh in Europe. Aluminium production has the largest influence on variations of the final GHG emission level. This can be explained by the high electricity use of aluminium production, which, in China, comes from a comparably emission-intense power mix. The relative GHG performances of ICE vehicles, hybrid electric vehicles (HEV), PHEVs and BEVs across Chinese provinces vary with relative vehicle energy efficiencies and electric grid carbon intensities, and ambient temperatures (which effect on-road EV electricity consumption rates). With the current power mix, ICE vehicles perform better than EVs in ten Northern provinces and that HEVs can be an emission-saving alternative to BEVs and PHEVs in almost all Chinese provinces[1].

On biofuels, GREET distinguishes between four feedstock categories and eight fuel products. The model considers direct activities and indirect effects from farming, fuel production, fuel-use and land-use changes. The chosen feedstock has a strong impact on GHG emission results. In the case of ethanol, corn ethanol emits 57 g CO_2e per MJ of fuel, which compares favourably to 95 CO_2e per MJ for gasoline. Second-generation production pathways allow drastic emission cuts, with 8 CO_2e per MJ for ethanol from corn stover and even negative emissions for miscanthus ethanol with -4 g CO_2e per MJ. Most GHG emission impacts come from farming (e.g. fertiliser and energy use), which differ by location in the United States. Results for India would differ further according to characteristics of the country's agriculture sector.

From individual life cycle assessment towards a more holistic approach

Marta Yugo of Concawe outlined findings that largely build on the JEC Well-To-Wheels report (fifth version)[2], which focuses on the life-cycle impact assessment of fuels. She also presented upcoming Concawe research, which takes a holistic approach to assess decarbonisation pathways for the passenger car segment in Europe.

A diverse suite of low-carbon fuels and efficient power train technologies will be required to achieve the EU's net-zero targets for 2050 in the transport sector. The role of fossil fuels will decline as groups of gasoline-like and diesel-like fuels increase in relevance. Concawe identified ten fuel families that, together with 60 possible powertrain combinations, result in broad WTT ranges for different vehicle types. Liquid transport fuels can become an attractive option to complement EVs for reducing transport emissions. However, it will depend on the fuel feedstock and production pathway, as well as on the power mix that determines the GWP of EVs. LCA is a powerful tool to evaluate emerging low carbon fuels for which WTT emissions will be very case-dependent.

One of Concawe's research projects[3] evaluates which market constellations of alternative powertrain technologies (ICE, HEV, PHEV and BEV) can maximise emission savings under constrained battery supply in Europe. Current projections expect battery supply in Europe to reach between 0.3 and 0.5 TWh/year by 2030. Findings illustrate that expected battery supply may prevent a full switch to BEV by 2030, as this would require an annual supply of 0.8 TWh/year. PHEV can play a role in maximising WTW emission savings under a constrained battery availability of 0.5 TWh/year, with a market share of 60% for PHEV and 40% for BEV. However, the calculated benefits of PHEV having a 100km electric drive range are contingent on an electric driving share of at least 45%. If this cannot be reached, HEV would be better suited to maximise emission savings in concert with BEV.

Session 2. Life cycle assessment focusing on transport fuels in India

Session 2 highlighted that fuel switching can lower India's dependency on fossil fuel imports while reducing the carbon intensity of transport. The environmental impact of alternative fuels tends to concentrate on fuel production, which means that their potential to mitigate emissions depends on their WTT emission intensity. This session, chaired by Till Bunsen of the International Transport Forum, presented LCA research on conventional fuels and their low-carbon alternatives.

Life cycle assessment of fuels

Seema Unnikrishnan and Shilpi Srivastava of the National Institute of Industrial Engineering presented analytical results on electricity generation from gas and coal, as well as those of oil refining, highlighting which factors make these fuel types carbon-intensive. The carbon intensity of these fuels has implications not only for India's current car fleet, which consists almost exclusively of gasoline and diesel ICE, but also on the WTW mitigation potential of EVs if used with the current power mix.

One LCA study analysed the impacts per kWh of electricity along all life cycle stages from mining to generation for four power plants in India. Three of these power plants are coal-fired and one is a natural gas combined cycle (NGCC) power plant. The study scope excluded power plant construction. Results confirmed that the largest part of the footprint of generated electricity comes from the operation phase of power plants. Electricity from coal-fired power plants has GHG emissions reaching up to 1 kg CO_2e per kWh and stands out with a high acidification potential. The GHG emissions of electricity from the gas-fired power plant compared favourably, with just about 500 g CO_2e per kWh. One of the coal-fired power plants uses clean coal and stack emission control technology. It generates power with a GWP that is 10% lower than for the two remaining coal stations. The coal-fired power plants analysed in India were found to be more carbon-intensive than those in other countries on average.

The life cycle assessment of crude oil production in India includes everything from the recovery, transportation and refining of crude to the transport of the final fuel. Data for crude oil extraction and refining were complemented by information from the literature to assess the remaining life cycle phases. Findings confirmed that the refining phase weighs the heaviest on the footprint of fuel production. Transport also causes significant impacts, especially if trucks are used rather than marine or rail transport or pipelines. The type of crude oil also impacts the overall life cycle balance and, in the case of India, often comes from methane-rich reserves with high GHG emissions.

Scaling up low-carbon fuels in India will be necessary to mitigate environmental impacts from transport. Transport electrification should be coupled with grid decarbonisation programmes and avoid dependency on coal-fired power plants. The use of such power plants could limit benefits both in terms of GHG emissions and local pollution, as they are often located near cities.

Lignocellulosic ethanol: Life cycle assessment-based technology and policy evaluation

India's first biofuel policy dates back to 2003, when the country adopted a 20% ethanol blending rate target for 2017. Crop plants were explicitly excluded from biofuel production. The country revised its policy in 2018 after falling short of its target (India's blending rate is currently below 10%). It postponed the 20% target year to 2030. In addition, it made sugarcane and damaged or surplus grain supplies eligible for biofuel production. The government also supported the setup of 12 demonstration plants to test different production processes for lignocellulosic ethanol. Yogendra Shastri of the Indian Institute of Technology Bombay presented insights on the lifecycle impacts of two of these production processes.

One of the processes is DBT-ICT 2G Ethanol Technology, developed by the Institute of Chemical Technology (ICT) Mumbai. The process uses rice straw as feedstock. It also requires chemicals, enzymes and electricity and includes pre-treatment and hydrolysis to produce glucose. This is followed by fermentation and final distillation. The process is designed to produce up to 80 tonnes of ethanol per day.

The Indian Institute of Technology Bombay conducted an LCA study of this process that took a cradle-to-gate approach. It considered the production of rice straw, transport to the refinery and the refining processes for the functional unit of one litre ethanol produced. Inventory data were based on experiments on the production process and complemented by data on transport from the operating contractor. An LCA inventory database was used to gather information on process chemicals, electricity use and farming. The findings confirmed a GWP of 2.818 kg CO_2e per litre of ethanol, most of which came from electricity used in the production process (e.g. mechanical pre-treatment). Switching from India's carbon-intensive grid electricity to renewable generation would lower the GHG emissions of the produced ethanol to one-eighth. Another notable impact is the high use of water in the production process, where 27 litres of water are required to produce one litre of ethanol. This water use in the fuel production process comes on top of high water consumption in rice farming.

The GHG emissions of this ethanol production pathway compare favourably to results from another study on pathways with sugar cane bagasse. For these pathways, the GHG emissions per litre of ethanol would be at least 3.144 kg CO_2e. The use of steam is responsible for most impacts in this production process, as steam production in India typically relies on low-grade fuel.

The lack of India-specific inventory data can be a challenge to conducting LCAs on biofuels. There are also limited India-specific studies on fossil fuels available, which can make benchmarking difficult. An emerging research priority is LCAs on biofuels with grain feedstocks since the 2018 biofuel policy revision made them eligible. Such studies will rely on India-specific inventory data for agricultural processes, which are distinct from, for instance, those in the United States due to the prevalence of small-scale farming in India. It is also important to include LCA at the stage of biofuel process development. LCA studies are typically only conducted once a process is in place, which can be a missed opportunity for process optimisation.

Life cycle greenhouse gas emissions for algal biofuels: Effect of different CO_2 supply options

The Indian Institute of Technology, Roorkee, conducted an LCA of five alternative CO_2 supply options for algal biofuel production. Pratham Arora of the Institute presented the results.

Alga biofuel is a third-generation biofuel that can be used to produce various fuel products. It is easy to produce, grows in wastewater and farms can be built on land unfit for agriculture. A key input for algae production is CO_2, which is added to reactors to increase biomass growth. The research compared the GHG emissions of five alternative CO_2 supply scenarios for producing bio-crude from algae. The five CO_2 supply options use flue gas from 1) a legacy coal-based power plant (with 11.9% CO_2 content in flue gas); 2) a legacy natural gas-based power plant (about 4% CO_2 content in flue gas); 3) a purpose-built NGCC power plant; 4) a purpose-built biomass combustion power plant or; 5) a purpose-built direct air capture (DAC) system. These plants are assumed to be no farther than two miles from the biofuel production site. The production site grows algae in a bioreactor (in 60-day growth cycles followed by five days cleaning), processes algae sludge with hydrothermal liquefaction, transfers the resulting bio-crude to hydro-treating/hydro-cracking, and finally yields refined bio-crude. The functional unit was set to 1 MJ of refined bio-crude.

The biomass combustion plant using bioenergy with carbon capture and storage (BECCS) produced bio-crude with negative GHG emissions. Among the remaining processes, the one supplied with CO_2 from a coal-fired power plant performed best, with 60% less GHG emissions than conventional gasoline. The two processes with NGCC power plant and DAC performed comparably poorly, the latter due to high electricity use.

All these production pathways currently do not exist at scale, and high costs place significant barriers to their prospects for commercial application.

Waste-derived alternative energy for the transport sector

Brajesh Dubey of the Indian Institute of Technology, Kharagpur presented laboratory-based research projects on the life cycle impacts of second- and third-generation biofuels. He focused on processes that use waste biomass as feedstock and, more specifically, on two completed LCA research projects[4].

The first study calculated emissions from algae biofuel production using an open-air raceway pond with CO_2 supply from flue gas. Findings confirmed that the cultivation of algae, especially energy needs in this production phase, have the largest impact on the GHG emissions of the final fuel.

A second LCA study evaluated the environmental impact of oleaginous yeast-based biodiesel and bio-crude production, a third-generation biofuel using waste.

An ongoing project explores whether hydrochar produced from waste materials such as lignocellulosic biomass, food waste or agricultural waste can substitute coal in electricity generation.

Today, EVs in India cannot effectively reduce GHG emissions. Their power mix does not allow them to. More than half of their power mix comes from coal-fired power plants, while only 37% comes from renewable energy. LCA is a sound tool to evaluate the WTW performance of EVs and to explore how they can contribute to a low-carbon transition. EVs can lead to significantly lower GHG emissions if charged with carbon-efficient electricity.

Session 3. Life cycle assessment of vehicles in India

The session, chaired by Vatsalya Sohu of the International Transport Forum, explored how factors such as vehicle design, powertrain choice and manufacturing processes determine the footprint of alternative vehicle options. Speakers identified India-specific particularities that influence energy use and GHG emissions from public transit and private vehicles.

Life cycle assessment of lightweighted ICEs and BEVs: An India perspective

Passenger cars are a growing mode of transport in India. They are expected to reach a market size of ten million per year in 2030. Cars are also a key source of air pollution, responsible for 11% of all PM emissions. Indian policy makers support vehicle electrification to reduce impacts, and previously had aimed at a 30% EV fleet share by 2030.

Krishna Upadhyayula of Umea University presented the LCA study[5] that compared the life cycle impacts of three alternative vehicle types – lightweight ICEs, BEVs and compact BEVs – against the benchmark of regular ICEs. Impacts were evaluated for a lifetime mileage of 150 000 km for ten impact categories. The assessment considered impacts in two target years: 2018 and 2030. Assumptions for the power mix for electricity generation considered a 71% fossil fuel share for 2018 and 56% for 2030, based on analyses of the International Energy Agency. The results covered four scenarios with varying shares of the considered vehicle types within the car fleet.

Findings showed that lightweight ICEs have a 17% lower GHG emissions and fossil fuel depletion potential than regular ICEs. However, their footprint is larger for some other impact categories, including metal depletion. Findings also showed that benefits from electrification are limited to compact BEVs with a 2030 power mix, which realise reductions for both GHG emissions and fossil fuel depletion.

The 2018 power mix prevents BEVs from realising impact reductions due to the high carbon intensity of electricity. Scenario results showed that in 2030, compact BEVs could reduce sector-wide emissions by 5% if they reach a 35% fleet share. In addition, BEVs benefit from continuous power sector decarbonisation during their lifetime, which can yield further emission reductions than shown in the results. Vehicle lightweighting is an attractive bridging technology to reduce impacts from conventional ICEs if the power mix prevents BEVs from realising benefits.

Life cycle analysis of road transport vehicles in India

An overview of LCA research compares alternative powertrain options, namely compressed natural gas (CNG) ICEs with PHEVs for buses and gasoline ICEs with BEVs for cars. The research also compares the life cycle impacts of using aluminium instead of steel as vehicle body material. Arghya Sardar of the Technology Information Forecasting and Assessment Council presented the research.

The study focusing on buses dates back to 2012 and represents one of the earliest research projects on the topic in India. It defined a bus with a 600 000 km lifetime mileage as its functional unit. The modelled PHEV bus has an electric range of 100 kilometres and a daily operation distance of 200 kilometres. An energy intensity of 1 700 MJ per kg was assumed for battery manufacturing, while the carbon intensity of the grid was set at 800 g CO_2e per kWh. The assumption for WTT emissions of CNG was set at 29% of its TTW emissions. Findings confirmed that PHEV buses can realise 22% GHG savings over their lifetime compared to their counterparts running on CNG, whereas lifetime emissions of PHEV buses reach about 800 tonnes of CO_2e. The researchers also compared gasoline ICE vehicles with BEV cars, whereas they confirmed that a BEV car with 56.5 tonnes CO_2e has a lower life cycle GHG emission impact than a gasoline car with 79.2 tonnes CO_2e.

Replacing steel with aluminium to manufacture car bodies can save emissions and energy in the long term. For a BEV, findings confirm that while the aluminium body has a higher embedded energy use due to the energy intensity of aluminium production, it realises net energy savings over the vehicle lifetime due to an improved fuel economy. However, GHG savings only occur if vehicles reach a very high lifetime mileage.

Scaling up renewable energy generation can further enhance the GHG savings of electric vehicles. India-focused LCA studies would benefit from better availability of inventory data for vehicle materials.

Life cycle analysis of transport options

Rangan Banerjee of the Indian Institute of Technology, Bombay focused on LCA research that considers the vehicle performance, alternative production routes and storage solutions of hydrogen vehicles. The support for alternative transport technologies in India is often determined by their ability to reduce urban pollution, which is a policy priority.

The study looked at the life cycle emissions and energy use of two hydrogen vehicle types: fuel cell electric vehicles (FCEV) and hydrogen ICE vehicles. It compared them against the benchmark of a small-size gasoline ICE passenger car. This benchmark vehicle emits 180 g CO_2e per km and consumes 2.6 MJ per km.

The study considered four alternative pathways for hydrogen production: steam methane reforming, photovoltaic (PV) with electrolysis, wind power with electrolysis, and biomass gasification. Of these processes, steam methane reforming consumes the most non-renewable energy (182 MJ per kg of hydrogen), followed by, in descending order, biomass gasification, PV with electrolysis and wind power with electrolysis. Steam methane reforming also has the highest GWP with 12.8 kg CO_2e per kg of hydrogen produced. This is one order of magnitude higher than the 0.98 kg CO_2e per kg hydrogen produced via wind power with electrolysis, the most efficient of the five considered processes.

Findings confirm that FCEVs perform better than hydrogen ICE vehicles. The latter use three times more energy per kilometre. The footprint difference of the hydrogen production pathways considered is also visible in the result per vehicle-kilometre. With the more efficient FCEV powertrain, vehicles relying on hydrogen from steam methane reforming reach a WTW emission value of 122 g CO_2e per km. The vehicles relying on the pathway with wind power and electrolysis reach only 43 g CO_2e per km. Overall, hydrogen vehicles relying on electrolysis pathways come with a smaller environmental footprint than both gasoline ICE and hydrogen vehicles relying on steam methane reforming. However, high operation costs limit their cost competitiveness.

Results on the life cycle performance of a proposed hyperloop project between Pune and Mumbai show that the energy use of this transport technology is at about 110 kJ per pkm, which is evenly split between infrastructure and vehicle operations. This energy intensity is higher than that of rail with about 30 kJ per pkm and that of air travel with about 70 kJ per pkm.

Session 4. Life cycle assessment of transport infrastructure in India

India's transport infrastructure has strongly expanded in recent years, keeping pace with economic growth and urbanisation, and will continue to do so in the future. Taking this into account, the session – chaired by the International Transport Forum's Elisabeth Windisch – focused on studies that evaluate the embedded emissions and energy use of road infrastructure and rail projects in India and how they influence the life-cycle performance of alternative transport modes.

Life cycle assessment for National Highways of India

Sharif Qamar of TERI spoke about the life cycle impacts of India's National Highways system until 2030 and its climate resilience.

The National Highways system carries 30% of India's passenger transport activity and about half of all freight transport. The research relied on available inventory data for 860 kilometres of road to evaluate the impacts of construction, maintenance and operation of road infrastructure. This sample is a good representation of the national network's average.

Findings on the life cycle impact of infrastructure confirm that the vast majority of embodied emissions comes from material use. Substituting high-carbon materials for low-carbon ones is an effective strategy to reducing the embedded emissions of infrastructure. Preventive maintenance can lead to significant advantages as well, reducing impacts of intensive repair works. Well-maintained roads also help vehicles save fuel.

Planned network extensions until 2030 are expected to increase infrastructure GHG emissions from construction and maintenance to over 31 Mt CO_2e. However, these emissions are dwarfed by those from vehicle use in the operation phase, expected to reach 248 Mt CO_2e by 2030.

Emissions from vehicle operations on the National Highways system are currently split evenly between passenger transport and trucks. The expected growth of aggregate emissions (from construction, maintenance and operations) to 278 Mt CO_2e by 2030 represents a 126% increase from 2016 levels, the study's baseline year.

One option for reducing the GHG emission growth from vehicle operations is to accelerate the implementation of stricter fuel economy standards. Doing so could achieve an estimated 15-20% savings by 2030. Other policy interventions include using large-capacity trucks for freight transport; scrapping old, inefficient vehicles; and scaling up transport electrification and low-carbon fuels.

Integrated life cycle assessment toolkits for sustainable transport infrastructure

Krishna Prapoorna of the Indian Institute of Technology, Tirupati presented an LCA study[6] that looked at the impacts of different concrete material types. The study underlined the potential benefits of using porous concrete. The assessment considered cradle-to-gate impacts of concrete materials considering current conditions of design life. However, future studies will be aimed at cradle-to-grave LCA approach when the materials have served the entire design life of 20-25 years.

The study compared the impacts of a porous concrete[7] with regular concrete of Portland cement. It also compared on-site mixing with ready-mix concrete. For the porous concrete, data was collected from the contractor, who had constructed a testing segment, and secondary sources were consulted for inventory data for the Portland cement. The functional unit was set at a one-kilometre single-lane road.

Findings confirmed that, in addition to benefits from reduced water-runoff, the porous concrete's embedded emissions were 3% lower than those of the concrete from Portland cement.

Comprehensive environmental performance evaluation of Mumbai Suburban Railway using life cycle assessment

Amar Shinde of Manipal Institute of Technology presented an LCA study that compares Mumbai Suburban Rail with alternative transport services. Its scope includes the impacts of infrastructure for and operation of suburban rail, metros, taxis, buses and auto-rickshaws.

Construction began on the Mumbai Suburban Rail in 1964. Today, the network is comprised of about 1 000 track kilometres on three lines. The study's system boundary includes the construction and maintenance of railway infrastructure, the manufacturing of coaches, and train operation. Inventory data was obtained from the regional transport authority, the train coach manufacturer, and the two operators of the rail services. The study assessed six impact categories, including GHG emissions. Both vkm and pkm were used as functional units. This allowed for the evaluation of the influence of load factors on the life-cycle impacts of different modes. Results confirmed that the Mumbai Suburban Railways service operates at 6.2 g CO_2e per pkm on average, of which about 90% can be attributed to the operation phase. This low GHG emission impact is also due to the very high load factors of trains, which can reach six passengers per square metre in peak hours when trains operate at up to 190% capacity.

Buses operate, on average, at about 18 g CO_2e per pkm, which comes almost exclusively from tailpipe emissions and emissions arising during fuel production. The performance of buses also depends on the Bharat emission standard for local pollutants, whereby traffic on vehicles meeting the high Bharat VI standard performs best in terms of GHG emissions. Specific GHG emissions from bus use also depend on the powertrain, whereby an efficient CNG ICE bus with over 15 g CO_2e per pkm performs worse than an efficient diesel ICE bus with just over 12 g CO_2e per pkm.

A comparison of buses with other modes shows that their GHG advantage depends strongly on the load factor. For example, shared auto-rickshaws break even in terms of GWP with a bus that carries only 28 passengers. Taxis have the highest emission intensity of the considered modes yet still break even with a bus that has just over ten passengers.

Workshop conclusions

Pierpaolo Cazzola of the International Transport Forum closed the workshop. He recapped the outcomes of the two workshop days and provided a brief outlook on NDC-TIA project's next steps.

A key takeaway from Session 1 was that LCA is used successfully today to inform transport policy making, as demonstrated in Europe and the United States. The session also reflected on some potential limitations and emerging research priorities for the methodology, for instance, to better account for infrastructure choices that can lock in GHG emission trajectories over very long time scales.

Presentations in Session 2 reiterated the need to reduce the carbon intensity of India's energy mix to enable transport carbonisation. The impact of the high carbon intensity of grid electricity does not only reduce the benefits of EVs but also impacts the performance of biofuel production pathways that require electricity. India's 2018 biofuel policy reform points at increasing production volumes that will also use grains and sugarcane as feedstock. There is an emerging research priority to better account for India's production practices when evaluating the WTT performance of these fuels. Another aspect related to liquid fuels is to explore whether the crude oil benchmark differs between India and other regions due to imports from oil-producing countries with methane-rich reserves.

The life cycle impacts of electric vehicles have been on the research agenda for some time in India. Presentations in Session 3 showed that results are not static, due to changes in the power mix and the accelerating developments of the EV industry. Existing LCA studies on vehicle electrification and others on the use of hydrogen tend to focus on passenger cars and buses. Two- and three-wheelers may emerge as a research priority. These vehicles come with a low electrification barrier and own a large modal share in the Indian transport sector, making them important for sector-wide energy use and GHG emissions.

Presentations in Session 4 confirmed that most impacts of transport systems come from the operational phase, which holds for both road and rail transport. Investing in infrastructure that promotes public transit appears particularly effective in reducing impacts per pkm, as these modes are used at higher load factors than private cars.

The interest in the workshop demonstrated that there is an active transport LCA community at Indian universities and research institutes. Transport policy and planning ought to leverage this expertise. The International Transport Forum will support related efforts as part of its India activities under the DTEE and NDC TIA projects.

Following the workshop, the International Transport Forum will start developing a comprehensive LCA toolkit tailored to the Indian transport sector. The ITF will use insights from the experts who contributed to the workshop and leverage the existing capacity in the Indian research community.

The objective is not only to support the Indian government in developing strategies for transport decarbonisation but also to help build additional capacity in Indian research and academic institutions and to support the Indian government in its efforts to take action on GHG emission mitigation in the transport sector.

The ITF will engage with local research entities through in-country meetings and the development of one or more sub-contracting arrangements. Key activities will include data collection and processing, as well as modelling. The ITF hopes that involving the Indian research community in this context will create a thriving environment for research institutes and universities, stimulating their interest in developing curricula that integrate courses on transport modelling with an LCA approach.

In addition to the development of contracts, the ITF will also encourage local research partners (starting with those able to support formative activities) to integrate courses on transport modelling (including LCA) in the development of the curricula offered to their students. This could be complemented by opportunities for secondments, internships (e.g. for PhD students) and prizes (e.g. for the best research on a given subject).

Notes

1 Gan et al. (2021), "Provincial Greenhouse Gas Emissions of Gasoline and Plug-in Electric Vehicles in China: Comparison from the Consumption-Based Electricity Perspective", Environmental Science and Technology, Vol. 55/10, 6944-6956
DOI: 10.1021/acs.est.0c08217.

2 Prussi, M., et al. (2020), *JEC Well-To-Wheels report v5*, EUR 30284 EN, Publications Office of the European Union, Luxembourg, doi:10.2760/100379, JRC121213.

3 https://www.concawe.eu/wp-content/uploads/4.-The-optimal-vehicle-electrification-level.pdf

4 Yadav,G., B. Dubey and R. Sen (2020), "A comparative life cycle assessment of microalgae production by CO2 sequestration from flue gas in outdoor raceway ponds under batch and semi-continuous regime", *Journal of Cleaner Production*, Vol. 258, https://doi.org/10.1016/j.jclepro.2020.120703.
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5 Upadhyayula, V. et al. (2019), "Lightweighting and electrification strategies for improving environmental performance of passenger cars in India by 2030: A critical perspective based on life cycle assessment", *Journal of Cleaner Production*, Vol. 209, pp. 1604-1613, https://doi.org/10.1016/j.jclepro.2018.11.153.

6 Singh, A., P. Vaddy and K. Prapoorna Biligiri (2020), "Quantification of embodied energy and carbon footprint of pervious concrete pavements through a methodical life cycle assessment framework", *Resources, Conservation and Recycling*, Vol. 161, https://doi.org/10.1016/j.resconrec.2020.104953.

7 This concrete type was developed at IIT Tirupati and tested on a small driveway segment. It reduces some disadvantages of sealed surfaces, for instance, through reducing run-off of rain water and better heat-retention.

Annex A. Workshop agenda

13 April 2021, 13:55 – 18:00 CEST/ 17:25 – 21:30 IST

<table>
<tr><td>5 min</td><td>Meeting start – connection to Zoom platform</td></tr>
<tr><td>40 min</td><td>Opening by International Transport Forum and NITI Aayog</td></tr>
<tr><td colspan="2">Speakers will introduce ITF's Decarbonising Transport initiative and its activities focusing on India. An overview of India's policy priorities for the transport sector and opportunities for LCA insights to aid decarbonisation efforts will then set the scene for following sessions.

Speakers:
• Jari Kauppila, International Transport Forum
• Pierpaolo Cazzola, International Transport Forum
• Siddharth Sinha, NITI Aayog</td></tr>
<tr><td>90 min</td><td>Session 1: International life cycle assessments for the transport sector</td></tr>
<tr><td colspan="2">The objective of this session is to gather an overview of existing LCA work with relevance for transport decarbonisation. It focuses on assessments of transport infrastructure, vehicle technologies and transport fuel types. Speakers will take stock of current research themes and emerging priorities.

Chair: Madhav Sharma, NITI Aayog

Speakers:
• Shoshanna Saxe, University of Toronto
• Sofia Amaral, Ricardo
• Michael Wang Argonne National Laboratory
• Marta Yugo, Concawe</td></tr>
<tr><td>10 min</td><td>Break</td></tr>
<tr><td>90 min</td><td>Session 2: Life cycle assessment focusing on transport fuels in India</td></tr>
<tr><td colspan="2">Fuel switching can lower India's dependency on fossil fuel imports while reducing the carbon intensity of transport. The environmental impact of alternative fuels tends to concentrate on fuel production, which means that their potential to mitigate emissions depends on their well-to-tank emission intensity. This session presents LCA research on conventional fuels and their low-carbon alternatives.

Chair: Till Bunsen, International Transport Forum

Speakers:
• Seema Unnikrishnan and Shilpi Srivastava, National Institute of Industrial Engineering
• Yogendra Shastri, Indian Institute of Technology, Bombay
• Pratham Arora, Indian Institute of Technology, Roorkee
• Brajesh Kumar Dubey, Indian Institute of Technology, Kharagpure</td></tr>
<tr><td>10 min</td><td>Conclusion of Day 1</td></tr>
<tr><td colspan="2">Recap of the workshop sessions of Day 1.</td></tr>
</table>

14 April 2021, 10:55 – 14:30 CEST/ 14:25 – 18:00 IST

5 min	**Meeting start – connection to Zoom platform**
10 min	**Introduction to Day 2 of workshop**
Reporting of outcomes from sessions 1 and 2 and their link to Day 2 of the workshop.	
90 min	**Session 3: Life cycle assessment of vehicles in India**
This session will explore how factors such as vehicle design, powertrain choice and manufacturing processes determine the footprint of alternative vehicle options. Speakers will also identify India-specific particularities that influence energy use and GHG emissions from public transit and private vehicles. Chair: Vatsalya Sohu, International Transport Forum Speakers: • Krishna Upadhyayula, Umea University • Arghya Sardar, Technology Information Forecasting and Assessment Council • Rangan Banerjee, Indian Institute of Technology, Bombay	
10 min	**Break**
90 min	**Session 4: Life cycle assessment of transport infrastructure in India**
India's transport infrastructure has strongly expanded in line with economic growth and urbanisation in recent years. This session focuses on studies that evaluate the embedded emissions and energy use of road infrastructure and rail projects in India and how they influence the life-cycle performance of alternative transport modes. Chair: Elisabeth Windisch, International Transport Forum Speakers: • Sharif Qamar, TERI • Krishna Prapoorna, Indian Institute of Technology, Tirupati • Amar Shinde, Manipal Institute of Technology	
10 min	**Conclusion of workshop**
This session will allow the ITF and NITI Aayog to summarise earlier sessions.	

Decarbonising Transport in India: Learning From Life Cycle Assessment

This publication presents a summary of the workshop “Life cycle assessment methods to support India’s efforts to decarbonise transport” organised by the International Transport Forum and the National Institute for Transforming India (NITI Aayog) in April 2021. Seventy-seven international and Indian experts took stock of existing work on assessing life-cycle emissions in transport and explored how current knowledge can support India’s policies to decarbonise transport. The workshop also identified policy priorities and potential regulatory gaps arising from new vehicle technologies, fuel types and mobility services entering the mass market.

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