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Use of causal loop diagrams to assess future drivers and trends in South African transport

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Background: In view of limited funding, research and development (R&D) investment needs to be optimised for future impact. Road transport R&D is complex and vary from road materials, design and traffic control to safety.

Objectives: Future drivers, trends and technologies in the South African road transport sector were determined and rated. Causal loop diagrams (CLDs) were used to determine how they will influence the sector and potential future R&D focus areas.

Method: Literature reviews, stakeholder interviews and workshops assessed the prevailing state of the sector and identified and rated the drivers, trends and technologies that will impact it. A novel method for structured technology foresight using CLDs was used to analyse the interrelationship between these elements and to determine the gaps in knowledge and the technologies required to position the sector for the future.

Results: Eighteen mega-drivers, 28 industry drivers, 53 trends and 79 key technologies were identified and rated by 98 workshop participants. The CLD analysis provided insight into the characteristics of the transport system and enhanced the understanding of the complexity of the system. Research focus areas were identified to position the transport sector for the future.

Conclusion: Causal loop diagrams were used effectively to demonstrate the interrelationships between and influence of drivers, trends and technologies on the transport sector and to identify gaps in knowledge.

Contribution: The current and future drivers, trends and technologies in the transport sector were identified and CLDs used to assess the relationships between them which led to the identification of new focus areas for R&D.

Keywords: technology foresight; futures study; R&D; transport sector; causal loop diagram.

Introduction

Technological innovation drives economic growth and social development (Bessant et al. 2014:1), which emphasises the importance of investment in research and development (R&D) (Link 1993:2; Link and Scott 2013:15). Well-directed R&D is thus fundamental to developing sustainable and competitive industries.

Worldwide, there is an emphasis on the benefit, both economic and social, that can be obtained from R&D, particularly publicly funded R&D where funds are limited (Bessant et al. 2014:1). This is especially important in less-developed countries where resources are scarce and benefits from R&D must be optimised (Lazarotti, Manzini & Mari 2011:212; Rust et al. 2021a:19; Rust et al. 2021b:33).

Transport and the associated infrastructure act as drivers of the economy and social development and growth (Cigu, Agheorghiesei & Toader 2019:1–22; Ding 2013:312; Ng et al. 2018:292; Zhang 2013:24). This occurs through the effective movement of freight and people (Ng et al. 2018:292). Associated benefits of an effective transport system are job growth, poverty alleviation and the reduction of inequality (The World Bank 2014); hence, a well-planned R&D programme that delivers relevant solutions to current and future challenges is of vital importance to any country (Rust and Koen 2011:2).

The South African National Roads Agency SOC Ltd (SANRAL), a state-owned entity, initiated an R&D programme in 2019. South African National Roads Agency SOC Ltd envisaged that this programme needed to be developed in such a way as to ensure that the outcomes would apply to the future. This led to the development of a project plan to conduct a South African road transport sector foresight study that could inform and support the project portfolio of the ongoing R&D programme.

Transport-sector knowledge and technologies vary and can range from new materials and products, through new design methods, to software solutions (Rust 2010:87). A transport R&D programme will therefore be varied and complex, with many elements and interactions to consider. Such a programme must also be future proof and prepare the industry for participating fully in developments such as the 4th Industrial Revolution (4IR) (Rust and Sampson 2019:547).

Historic R&D programmes in the South African Road Transport sector have been focussed on solving short-term problems currently faced in the sector (Rust and Koen 2011:3). However, in view of the significant changes in the challenges the sector faces such as increasing traffic loading, climate change impacts as well as impactful changes in technology through, for example, the 4th Industrial Revolution (Schwab 2017), R&D should be focussed on positioning the sector for a challenging future.

This article describes a novel technology foresight process including the results of a desktop study to identify the drivers, trends and technologies that will impact the transport sector. The current nature of the transport sector was characterised and this was used to describe the current reality in the transport sector informing the definition of the drivers, trends and technologies that will influence the transport sector. The rating of the drivers, trends and technologies by participants in six workshops is then discussed. Causal loop diagrams (CLDs) are then used to analyse and depict the inter-relationships between the drivers, trends and technologies and to assess potential R&D opportunities.

Objectives and purpose of the study

The purpose of the study was to provide a futuristic view of the transport sector 15 years hence and to recommend to SANRAL the potential R&D focus areas that should be addressed to position the transport sector for the future. The objective of this study was to use a novel, structured technology foresight process to determine and rate the drivers, trends and technologies that will impact the road transport sector in the future and to analyse these using, *inter alia*, CLDs. This led to an improved understanding of the interrelationships between these elements and allowed for identifying potential gaps in knowledge required to position the sector for future challenges. These inputs will be used by SANRAL to structure their future R&D programme.

Literature review and conceptual framework

Nature of foresight

The core challenge in strategic planning is the uncertainty of the future (Ejdys et al. 2015:378). Technology foresight is often used as a tool to reduce uncertainty about the future and indeed create the future. It allows understanding of the forces shaping the long-term future to improve policy-making, planning and decision-making. Technology foresight is a strategic, forward-looking technology analysis to help prioritise research and is closely associated with the following fields (Andersen & Andersen 2014:278):

- **Futures studies:** Creative and imaginative thinking about the future.
- **Technology forecasting:** Using forecasting from the existing situation to predict future technology development.
- **Technology assessment:** An assessment of the result of introducing new technology into society.

Foresight deals with several aspects, including social development, economic development, policy and the impact of technological innovation (Hörlesberger, Kasztler & Wepner 2016). The term 'innovation foresight' (rather than 'technology foresight') is used to describe a greater emphasis on socio-economic aspects and their interaction with technology (Porter 2010:41).

In particular, technology foresight is a structured approach to determine emerging R&D and technology trends that will influence industry competitiveness, economic growth and social development (Georghiou 1996:360). Salmenkaita and Salo (2004) describe technology foresight as a:

> [*D*]eliberately structured process that combines the expectations of different actors towards technologies to plan the strategy of the future, considering the impact on the broader economic and social development. (p. 901)

Foresight can be conducted at various levels, such as sectoral (e.g. the road transport sector), using scenario development as a tool to prepare the sector for potential changes and assist in decision-making. It could also focus on future technologies, for example, assessing the aspects of science and technological development that will affect industry competitiveness and quality of life. It could even focus on a specific project (Hörlesberger et al. 2020:8). Ejdys et al. (2015) summarise the nature of foresight as follows:

> Technology foresight involves long-term views of technology-related developments, aimed at informing ongoing decision-making, and using a wide range of formal techniques, an interdisciplinary approach, the involvement of wide pools of experts but also stakeholders, and creating networks that promote a shared view of the developments discussed, along with joint commitment to the approaches or actions emerging from these exercises. (p. 378)

Foresight is not the forecasting of a situation at a particular point in time, but a structured process that, through various scenarios, allows for the understanding of trends under different circumstances, including unprecedented events and wildcards (Ejdys et al. 2015:379).

Purpose of foresight

Foresight can be used for several purposes, including (European Union 2005:22):

- to forecast developments and changes in the areas of society, environment, economy, technology and science, and create or adjust policy strategies to meet the challenges
- to define key areas of science and technology that are vital for economic development and hence should be prioritised for funding
- to elaborate pathways of technology application to create wealth and improve the quality of life while respecting environmental concerns
- to identify market opportunities for specific business or industrial sectors
- to set up collaborative programmes between industrial companies and the government
- to create enduring networks linking different interest groups such as scientists, policy-makers, industrial companies, funding agencies and specific stakeholders.

It must be remembered that foresight is concerned with a longer-term view of the future, with a time frame of between 5 and 30 years. It is a dynamic and developing process rather than a set of techniques and should integrate all potential stakeholders into a common view.

Foresight methodology and prerequisites

As stated above, foresight does not aim to forecast the future, but to create several scenarios that would assist in strategic decision-making about the future. These scenarios allow the understanding of trends under different circumstances, including unprecedented events and wildcards. The foresight process aims to build consensus among participants about these trends and the potential R&D focus areas that are important for the future.

Various methods and tools exist to assist with foresight studies. These include (Rust and Koen 2011:3):

- matrices such as morphological analysis and cross-impact analysis
- trend analysis, such as growth-curve modelling
- expert opinion through, for example, surveys and focus groups
- modelling using prediction algorithms and simulation
- logical and causal analyses
- road mapping
- scenario building
- economic analysis.

The nature of the road transport sector in South Africa

The South African transport system consists of many elements and players, which make it complex. It consists of a number of modes of transport and elements including road, rail, ports, pipelines, air transport, maritime transport, conveyor belts and cables, non-motorised transport (NMT) and minibus taxis (Ittman et al. 2016). Transport and transport infrastructure are essential for socio-economic development and are major drivers of economic growth. In 2018, the South African Transport Sector was still performing at reasonable levels (Ittmann 2018) although the Logistics Performance Indicator had decreased from 3.67 (world ranking: 23 out of 167 countries) in 2012 to 3.38 (world ranking: 33). A World Bank survey in 2018 ranked South African Transport infrastructure 38th in the world compared with a ranking of 19th in 2012, indicating a marked decrease in quality (Ittmann 2018). The rail system in South Africa appears to perform less well than roads and large quantities of freight that should be moved by rail are moved over long distances by road (Ittmann et al. 2016).

The South African national road network comprises in excess of 22 197 km of highways and is managed by the South African National Roads Agency (SANRAL). The provincial road network and the metro and municipal road networks are managed by provincial and municipal road authorities respectively and comprise non-urban and rural roads and urban roads. This comprises 136 721 km of paved and 459 957 km of unpaved roads. There are also 454 609 kms of proclaimed gravel roads managed by provincial and municipal authorities. Post the coronavirus disease 2019 (COVID-19), transport infrastructure investment will play a key role in rebuilding the economy. South African National Roads Agency SOC Ltd spent R911bn on new projects and road maintenance in 2022 (SANRAL 2022). A significant portion of this expenditure is on road maintenance and the national network is in good condition with only 8.4% in a poor to very poor state (SANRAL 2022). Collection of toll fees remains a challenge. South African National Roads Agency SOC Ltd provided work on roads projects to 1933 small contractors during 2019–2020 with 80.2% of this work going to black owned enterprises. South African National Roads Agency SOC Ltd (2020) highlights road safety as an important aspect of its mandate and educational projects on road safety have reached 238 594 learners and 554 parents. Mobility and traffic management are equally important, and emphasis is placed on the Freeway Management System and associated Traffic Management Centres. South African National Roads Agency SOC Ltd also has a smart roads initiative that focuses on traffic management and safety improvement.

The South African Institution of Civil Engineering (SAICE) Infrastructure Report Card (IRC) of 2022 rated road infrastructure as follows (SAICE 2022), where A is world class and E is unfit for purpose:

- National roads: B+

- Provincial roads: D
- Paved metropolitan roads: D
- Other paved municipal roads: D-
- Gravel roads: E.

The National Household Travel Survey (NHTS 2020) indicated a number of pertinent characteristics of the South African transport sector:

- 76.0% of South Africans undertook trips 7 days per week.
- Nationally, average travel time has increased across all modes of transport.
- The main mode of transport that carries the largest share of workers is private cars, with the workers being the driver (36%), and taxis, which account for 28%.
- The estimated total number of workers' trips using public transport decreased from 5.4 million in 2013 to 4.7m in 2020. Taxis accounted for most public transport users.
- Walking all the way decreased from 18.5% in 2013 to 3.4% in 2020.
- More households selected a taxi as their usual mode of travel in 2020 (61.8%) than in 2013 (41.6%), followed by 18.9% of households who usually used a car or truck as the driver compared to 13.9% in 2013.

Transnet Planning (LTPF 2017) also indicated that the demand for freight transportation is expected to grow from 937 mt (2021 forecast) to approximately 1859 mt per annum over the 30-years period up to 2046. This 198% increase in volume implies that port, rail, road and pipeline infrastructure will require significant upgrades to handle the increased demand.

From the above analysis, it is evident that the transport sector has very specific characteristics (SANRAL 2021):

1. Roads are essential in stimulating the economy through improved people and goods transport as well as job creation.
2. Although the national road network is in relatively good condition, the provincial and municipal networks are in poor condition and are deteriorating fast.
3. At the provincial level, there are pockets of excellence where the roads are in good condition – the Western Cape is a case in point.
4. A backlog of road maintenance compounded by ever more scarce and costly road building materials.
5. There is dissatisfaction with the level of service from public transport.
6. The road safety record is of major concern.
7. A major challenge is the lack of funding (which also tends to be cyclical) and the lack of ability to spend the available funding effectively.
8. A significant skills gap in both public and private sectors.
9. A lack of sufficient capability in the state.
10. Ever increasing urbanisation with associated increased loading of infrastructure and congestion especially on metropolitan roads and inter-urban link roads.
11. Urbanisation and general traffic growth also contribute negatively to road safety and increase incidents as well as fatalities.
12. A lack of effective governance that can lead to corruption.
13. The transport sector is a major contributor to greenhouse gas emissions and its reduction will become a significant challenge in the near future.
14. A lack of effective service delivery especially to the poorest of the poor.
15. A lack of effective innovation or slow innovation, especially in the construction sector.
16. Technologies from the 4th Industrial revolution such as electric vehicles (EVs), autonomous vehicles (AVs), new age materials and artificial intelligence and machine learning will have a major impact on the sector, and the sector needs to prepare for this impact.

These characteristics are indicative of the complexity of the South African transport sector and emphasise the need for a focussed R&D programme that positions the sector for the future.

The South African National Roads Agency SOC Ltd research and development programme

In 2019, SANRAL started an R&D programme in line with its new strategy, Horizon 2030 (SANRAL 2017:3). This strategy focuses, among other aspects, on the use of technology and innovation to improve network condition, quality, capacity, mobility and road safety.

The programme comprises several focus areas associated with roads and transport, namely:

- future transportation and technical innovation
- transportation planning, public administration, management and economics
- pavements
- asset management
- traffic
- road safety
- geotechnical, structures, drainage and hydraulics, and the environment.

The nature of the research and innovation in the programme varies from product development such as new materials, to social sciences related to road safety.

Research methods and design

Process

Rust and Koen (2011:3) suggested a conceptual novel approach for foresight analysis in the South African road transport sector comprising the following steps:

1. describing the current reality and challenges
2. envisaging the desired future within specific scenarios
3. through back-casting from the future, determining the network of R&D activities and interventions required to move from the current reality to key solutions that will create the desired future.

The process, which was used in this study, was phased as depicted in Figure 1.

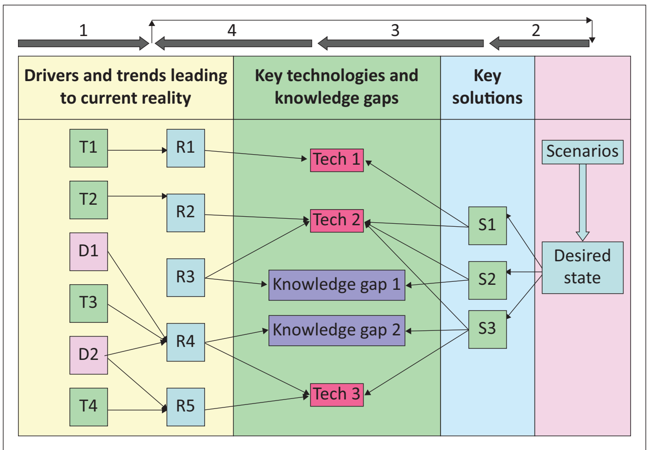
The process comprised drivers, trends, realities, events, actions and future outcomes that form an interactive network. It called for, firstly, the development of a description of the current reality for the roads and transport industry. Secondly, it jumped forward into the future to develop potential future scenarios for the sector. The third step was to conduct a backwards analysis (back-casting) to determine the potential paths of interventions and activities that were required to take the industry forward to the required future outcomes. The elements of the network can be weighted (using ratings from a user group) and statistical analysis conducted to determine the most likely paths for reaching the desired future state. This approach was used in this study.

Current reality analysis

A current reality analysis can determine the state of the road transport sector in South Africa, as well as its characteristics, challenges and opportunities. In this study, this information was accumulated through:

- a desktop study
- eminent thinker interviews
- workshops with stakeholders in the industry
- a questionnaire to evaluate and rate the characteristics, challenges and opportunities in terms of importance.

The information was then analysed and compiled to form an overall picture of the current state of the industry as depicted by the 16 significant characteristics of the transport sector in South Africa. The main current drivers and trends in the transport industry were also identified. **Causal maps** were used to analyse the interrelationship between the drivers, trends and technologies to determine interdependencies and identify the main causal loops that form the characteristics of the transport system and its environment.



Source: Rust, F.C. & Koen, R., 2011, 'Positioning technology development in the South African construction industry: a technology foresight study', *Journal of the South African Institution of Civil Engineering* 53(1), 2–8

FIGURE 1: Phased approach to foresight study.

Scenarios

In future work, the process will then leapfrog into the future and sketch potential future scenarios. This will lead to at least three or four likely scenarios, based on a set of main future drivers and trends.

Desired state

Based on the scenarios and future drivers, trends and technologies, the desired future state of the industry will be determined. This will be described in focusing on the characteristics of the desired future state and how they link to the current 16 characteristics of the transport sector.

Determining desired outcomes and key solutions

The desired outcomes and key solutions to take the industry to the desired future state will be determined by:

- analysis of the results of the desktop study and technology road mapping, if required
- interaction with stakeholder groups using online workshops and a survey
- evaluation and rating of the outcomes and key solutions by stakeholders.

Key required technologies and knowledge gaps

The last step in the process will be to determine the key technologies that need to be developed and knowledge gaps that need to be addressed to develop the key solutions that will migrate the transport industry from the current reality to the desired future. This information can define potential R&D projects for the SANRAL R&D programme.

Data sources

The following data sources were used:

- A comprehensive desktop study on drivers, trends and technologies that will influence the road transport sector.
- Interviews with six (four local and two international) eminent thinkers in foresight and the transport sector.
- Interviews with seven industry leaders and members of the youth sector (<35 years of age).
- Six stakeholder workshops to augment the data and rate the drivers, trends and technologies in terms of importance and relevance to the sector. These workshops were attended by 98 participants from public sector, private sector and academia.

Thus, qualitative and quantitative research methods were used in a mixed model.

This article describes the first part of the process, focussing on the definition of and rating of the drivers, trends and technologies as well as their interrelationships. Analysis of the data identified a number of initial focus areas for R&D to position the sector for the future.

Ethical considerations

The study was based on literature review and analysis as well as workshops with professionals and as such did not involve any testing of animal or human subjects. Ethical clearance to conduct this study was obtained from the CSIR ethics committee (No. 1002/58600/2018/P1.4).

Results and discussion

Drivers, trends and technologies in the transport sector

The data and information collected, including 16 key characteristics of the transport sector, were analysed and assessed to determine the primary drivers that will influence the future of the transport sector. The following categories were used:

- megadrivers (global): primary mega-drivers and secondary megadrivers
- industry drivers
- trends
- technologies.

As part of the process, interviews were also held with four local and two international eminent futures thinkers, as well as seven local industry leaders and representatives of the youth sector. Their inputs were used to expand the list of drivers, trends and technologies identified in the desktop study. The drivers, trends and technologies were rated for importance and relevance by workshop participants and the results are given below. A 5-point Likert scale was used for the rating and the average score was normalised as a percentage.

Global mega-drivers

Global mega-drivers are defined as powerful, transformative macroeconomic and geostrategic forces that shape our world and our collective futures in profound ways. They are structural 'shifts' that have a longer life span than 'trends' and have an irreversible impact on and consequences for the world (Blackrock 2022; PWC 2016:32). Examples include climate change, urbanisation and globalisation. The identified mega-drivers, their link to the 16 key characteristics of the transport sector and their ratings are given in Table 1.

The above evaluation indicates the importance of addressing the skills gap, the energy crisis, increasing urbanisation that overloads infrastructure, resource scarcity such as water, climate change and sustainable development. The relevance ratings followed the same patterns as the importance ratings.

Industry-level drivers

Local transport industry drivers are specifically relevant to the local transport sector and directly affect the South African transport sector. They exist at a lower level than mega-drivers and are connected to them. Examples include cyclical and reducing funding for infrastructure, the need for job creation and the need for road safety. The list of identified industry-level drivers is given in Table 2 ranked by importance. The scores have been normalised as a percentage. Their link to the 16 key characteristics of the transport sector is also indicated.

TABLE 1: Mega-drivers ranked by importance rating.

Mega-driver	Characteristic	Importance (%)	Relevance (%)
Skills and capacity development particularly among the youth and in technical or engineering fields with emphasis on 4IR skills	8, 9	90.8	88.2
Increasing energy crisis that impacts on the economy and social development	13	88.6	87.7
Urbanisation and population migration. Increasing population particularly in urban areas places pressure on housing, transport and utility infrastructure	10, 11	85.5	89.5
Increasing resource scarcity other than energy such as water and food	4	82.5	81.1
Greenhouse gas emissions and climate change; the emission of GHGs that leads to climate change and impacts on global warming and weather change	13	81.1	82.5
Sustainable development and environmental protection, water scarcity, sustainability of ecosystem services that provide food, water, materials, energy and the ability of the environment to absorb waste products.	13	81.1	80.3
Changing political landscape (Power shifts from west to east) and South African political fluidity and challenges	3, 12	79.4	82.0
Fourth Industrial Revolution and an innovation economy including autonomous vehicles, 3D printing, advanced robotics, advanced materials, the IOT, sensors, blockchain technology and synthetic biology.	16	78.9	80.7
Poverty, hunger and inequality based on race and gender – legacy of exclusion. Including access to mobility	5, 14	77.6	75.0
Cyclical nature of the economy; long-term fluctuations of economic activity and therefore ability to fund infrastructure	1, 7	76.3	82.0
International, regional, local conflict such as the war in Ukraine that impacts on the economy and resource availability for example oil and bitumen	-	75.4	78.5
Increasing globalisation exacerbated by the 4IR, digitisation and enhanced IT	16	70.2	76.3
Increasing demand for social infrastructure, housing and services due to current backlogs in, for example housing and sanitation exacerbating poverty	2	70.2	75.0
Increasing youth disillusionment entering the workforce in an employment ice age	8, 14	66.7	70.6
Ongoing threat of infectious diseases and health crisis such as COVID-19. South African health sector under severe strain	-	58.3	65.8
Demographic shifts and social change due to ageing populations, social cohesion, citizen action, and changes in behaviour such as work-from-home	11	58.3	61.8

IOT, Internet of Things; 4IR, 4th Industrial Revolution.

The ranking indicates the importance of building a capable state and the associated improved governance. This will, in

TABLE 2: Industry-level drivers.

Industry-level driver	Characteristic	Importance (%)
Need to build a capable state	3, 8, 9, 12	95
Public sector governance	12	91
Sustaining road condition	1, 2, 4	91
Need for safe, secure and reliable public transport	5, 6	88
Loss of skills and need for human capital development	8. 9	85
Integrated logistics planning	10, 11	84
Need for improved road safety	6	84
Oil and bitumen shortage and price increase	4, 15	82
Safety and security in general	6	81
Cyclical funding with impact on industry capability	1, 7	80
SANRAL role in industry, relationship with other departments	8	76
Need for rural access and mobility	5, 14	75
Resource efficiency	15, 16	75
Climate change impact on road infrastructure	13, 15, 16	74
Need for job creation in the transport sector	2, 14	73
Sectoral support to innovation and entrepreneurship in SMMEs	2, 14	71
Advanced and smart technologies in transport	15, 16	69
Regulation and legislation in transport	8. 9, 12	69
Short-term investment in roads – post COVID-19 recovery	2, 7	69
Green transport	13	68
Changes in the nature of transport demand for mobility	5, 10, 11,	65
Occupational health and safety	6, 12	59
Impact of land reform	-	56

SANRAL, South African National Roads Agency SOC Ltd.; SMMEs, small, medium and micro-enterprises.

turn, influence the ability of the public sector to maintain and improve the condition of the road network and to improve public transport which also rated highly. A factor that was also highlighted in the interviews is the loss of skills in the transport sector and the associated need for human capital development programmes. Improved logistics, road safety and a bitumen replacement also ranked highly.

Trends

Trends are emerging patterns of a systemic response or consequence to a mega- or industry driver that is likely to affect society. It has a general tendency to develop or change over time. A trend may be strong or weak, increasing, decreasing or stable. There is no guarantee that a trend observed in the past will continue in the future (EFP 2022). Examples specific to South Africa include the declining condition of infrastructure, increasing traffic volumes and congestion, and transformation of the transport industry.

For the SANRAL R&D programme, 52 trends were identified. To facilitate analysis and evaluation, through data reduction, the trends were grouped into 21 categories. A comprehensive list was provided in the desktop study report (SANRAL 2021:253).

The rating of the trend groups was conducted to determine the importance of the trends as well as their potential impact on the road transport sector. The results are given in Table 3 ranked by importance and normalised as a percentage. Their link to the 16 key characteristics of the transport sector is also indicated.

TABLE 3: Trend groups ranked by importance.

Trend group	Characteristic	Importance (%)	Impact (%)
Transport infrastructure condition and growth	1, 2, 4, 7	96	95
Increasingly weakening South African economy	1, 2, 7	93	92
Need for increase in road infrastructure investment	1, 2, 4, 7	87	86
Young population unequal and unemployed	14	83	78
Increasing traffic congestion	10	80	84
Advances in road safety, for example safe system approach	6, 11	77	76
Transport sector change and transformation	15	77	80
Skills development for 4IR technologies	8, 9, 16	76	75
Impact of climate change, for example adverse weather events	13	76	75
Dissatisfaction with public transport	5	75	79
Localisation of technologies	15, 16	74	71
Smart transport, for example mobility on demand, sensors. IOT	16	73	70
Modified construction methods such as low water use	15, 16	69	71
Smart road pavement materials for example self-healing, nano materials	16	69	70
Green transport and roads	13, 16	68	67
Advanced vehicle technologies, for example EVs and AVs	15, 16	64	62
Micro mobility (such as ‘rent and leave’ scooters)	16	58	61
Travel pattern changes caused by, for example work-from-home	16	58	62
Smart roads for, example energy harvesting, embedded sensors	13, 16	57	59
Protection of personal information	15	57	54
Shared economy of service provision rather than ownership	10,11	55	58

EVs, electric vehicles; AV, autonomous vehicles; IOT, Internet of Things; 4IR, Fourth Industrial Revolution.

Similar to the case of the drivers, the condition of the road infrastructure is a high priority and this is linked to the weak economy and the need for increased funding. The weak economy also has a secondary impact on unemployment, especially related to the youth. Operational challenges such as traffic congestion and changes in the nature of transport, with the associated impacts on road safety, also rated as important. The impact of new technologies and the 4th Industrial Revolution was rated in the middle of the group.

Technologies

Technologies are usually the response of science and engineering to addressing drivers and trends or result from unconnected blue-sky developments that have an application in the transport sector. Examples include artificial intelligence and smart materials.

For the SANRAL R&D programme, 79 key technologies and knowledge packages were identified that follow from the trends and drivers or result from current blue-sky research that will have a bearing on the transport sector. Detail is given in a SANRAL report (SANRAL 2021:254). Similar to the trends, and for ease of analysis, the technologies were grouped into

20 categories and then rated by the participants for importance as well as ease of implementation as indicated in Table 4.

Many of the primary and secondary mega-drivers affect one another or have a relationship with others, as depicted in the systems diagram in Figure 2. The drivers can be clustered as follows:

- environmental cluster
- economy cluster
- technology cluster
- socio-political cluster
- a ‘world cluster’ that groups several global mega-drivers that have a broad impact.

TABLE 4: Technology groupings rated for importance and ease of implementation.

Technology group	Importance (%)	Implementation (%)
Road safety technologies and methods: Safe System Approach; Road safety data management techniques	89	85
Bitumen replacements (green bio-binders);	76	74
Modelling and software: Building Information Modelling (BIM), Machine learning prediction models, Big data; Digital twinning;	76	86
Asset management technologies: Smart asset management through advanced sensor technologies.	76	79
Smart materials: Low water usage technologies, self-healing roads and embedded sensors in materials;	75	74
Sensors in vehicles: Sensors and Internet of Things; vehicle-to-vehicle and vehicle-to-road communication;	75	81
Waste materials: Plastic roads and recycled waste materials;	74	82
Smart transport technologies: Mobility as a service (MAAS); AI for traffic light control; blockchain; smart mobility	74	77
Robots and drones: Monitoring of traffic flow and events, infrastructure inspection	73	83
Modified materials: for example nano-modified materials, bio-based stabilisation and bio enzyme stabilisation, green materials	72	77
Mobile phone technologies: use of cell-phone sensors, for example accelerometers to determine road conditions and traffic flow	72	83
Smart vehicle technologies: Electrical vehicles; Advanced battery technologies; Wireless inductive charging; Autonomous vehicles; alternative fuels	72	75
Artificial intelligence and machine learning	70	77
Smart roads and sensors: In-road sensors; self-sensing and self-adapting pavements	69	72
Advanced construction technologies: 3-D printing; intelligent compaction; and off-site manufacturing;	69	70
Remote sensing: Remote sensing – Satellite imagery; LIDAR and VLP for ITS systems; Passive radiometric sensing;	69	78
Advanced and alternative transport systems: Personal Rapid Transport Pods; Hyperloop; Hydrail and driverless freight trains;	62	52
Energy technologies: Electrified roads Energy harvesting in roads;	61	53
Visualisation and modelling: Gamification; Extended and augmented reality	60	75
Smart surfacings: Rollpave surfacings for roads; Super-slab system;	60	65

Relative importance was given to the use of new technologies to address road safety; a bitumen replacement; new modelling techniques that include self-learning models based on machine learning techniques; asset management and preservation, smart materials and smart transport technologies. The ease of implementation of the technologies should be considered in strategic decision making.

LIDAR, light detection and ranging; VLP, visible light positioning; ITS, intelligent transport systems.

To develop an understanding of the linkages between the drivers, trends and technologies, CLDs were used.

Causal loop diagram analysis

Systems can be simplified and presented as a CLD to portray the key message observed from the conceptual systems model of a complex system (Pegasus Communications 2011:5). A CLD shows only the dominant feedback loops or specific causal connections between variables in the conceptual systems model. This is an effective way to portray the simplified message that can be obtained from analysing the system and its interactions. Causal loop diagrams can be a ‘reinforcing loop’ or a ‘balancing loop’ (Senge 1990:25; Rust 2009:33).

Causal loop diagrams can become very complex if too many variables are used in the same diagram. According to Pegasus Communications (2011:5–7), ‘creating CLDs is not an end onto itself, but part of articulating and communicating deeper insight about complex issues’. Causal loop diagrams should tell a story based on a theme to portray a specific message.

Causal loop diagrams were used to analyse the mega-drivers and trends defined above. Figure 3 shows a high-level CLD of the interactions between primary and secondary mega-drivers.

The main loop in the diagram, depicted by the brown arrows, shows the following flow:

- Increasing globalisation (MD3) and the 4th Industrial Revolution (MD7) have a significant impact on demographic shifts and social change (MD16). This is clear from the change in social behaviour such as the use (and abuse) of social media, increasing work-from-home behaviour and changes in the demand for mobility, among others.
- This driver then affects urbanisation and population migration (MD2), with people flocking to cities for access to technology and new jobs.
- However, the move towards the 4th Industrial Revolution creates greater inequality. This is because of a lack of skills in new technology jobs and a lack of access to technology (particularly among the poorest of the poor), which increases the need to reduce inequality.
- This places more emphasis on the need to eradicate poverty and hunger (MD4), which is exacerbated by events such as the COVID-19 pandemic.
- The need for poverty and hunger eradication (MD4) accentuates the demand for social infrastructure, services and housing (MD14), among others.
- In combination, these drivers change and, to a large extent, define the political landscape (MD9), which is also influenced by local and international conflict (MD18).
- This leads to a specific emphasis on socio-economic development and infrastructure (MD19), particularly in

rural areas where poverty is rife and accelerates the move to urban areas for better job opportunities and services.

- It all affects the demand on the economy, increasing its cyclical behaviour (MD6), particularly at sector level, and exacerbating the lack of sufficient funding for development because of political shortcomings and influence.
- Lastly, this leads to more social change (typically unrest), demographic shift (MD16) and more urbanisation, among others, intensifying the reinforcing loop into a vicious circle, thus affecting sustaining humanity and neglecting environmental protection.

For the SANRAL R&D programme, five cluster CLDs were developed (environmental cluster, economy cluster, technology cluster, socio-political cluster and a 'world cluster'). The economy cluster CLD and the technology cluster CLD are discussed below, as examples.

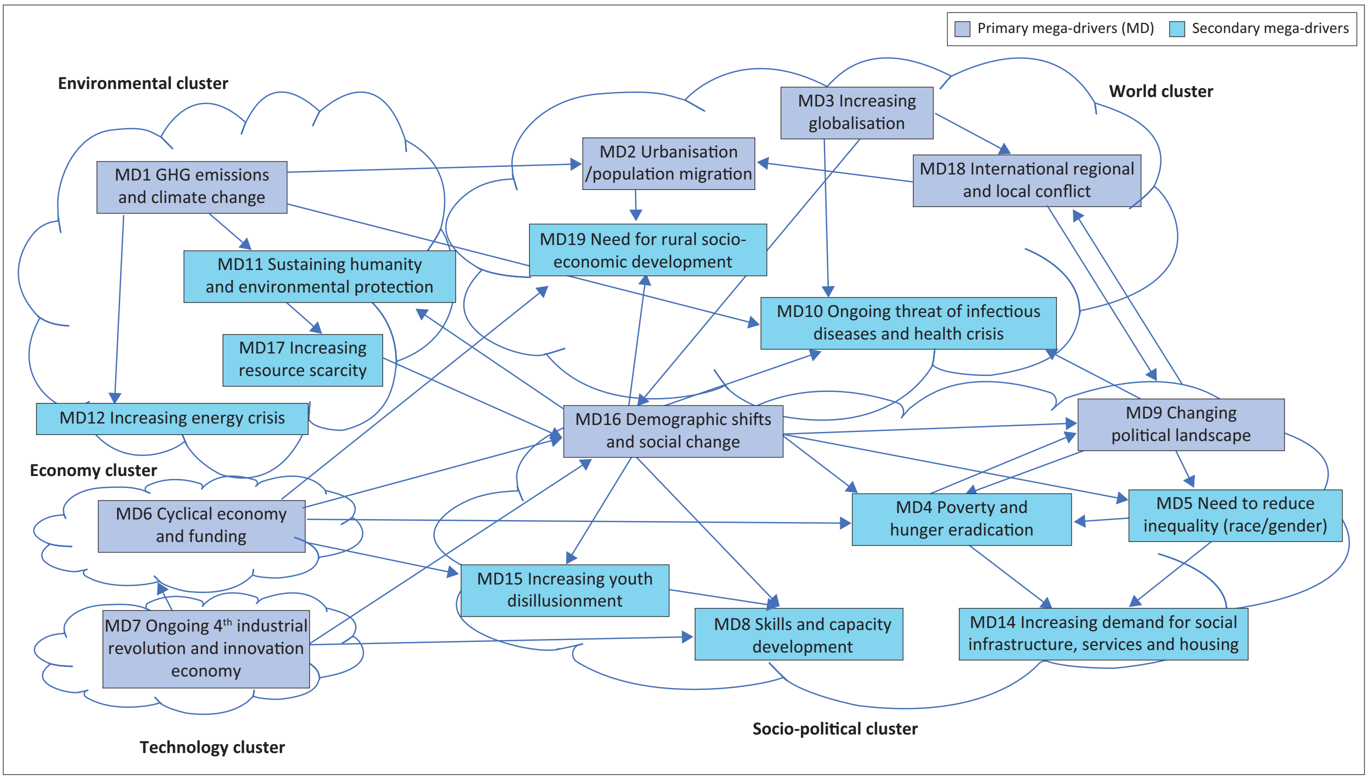


FIGURE 2: The mega-driver systems diagram with clusters identified.

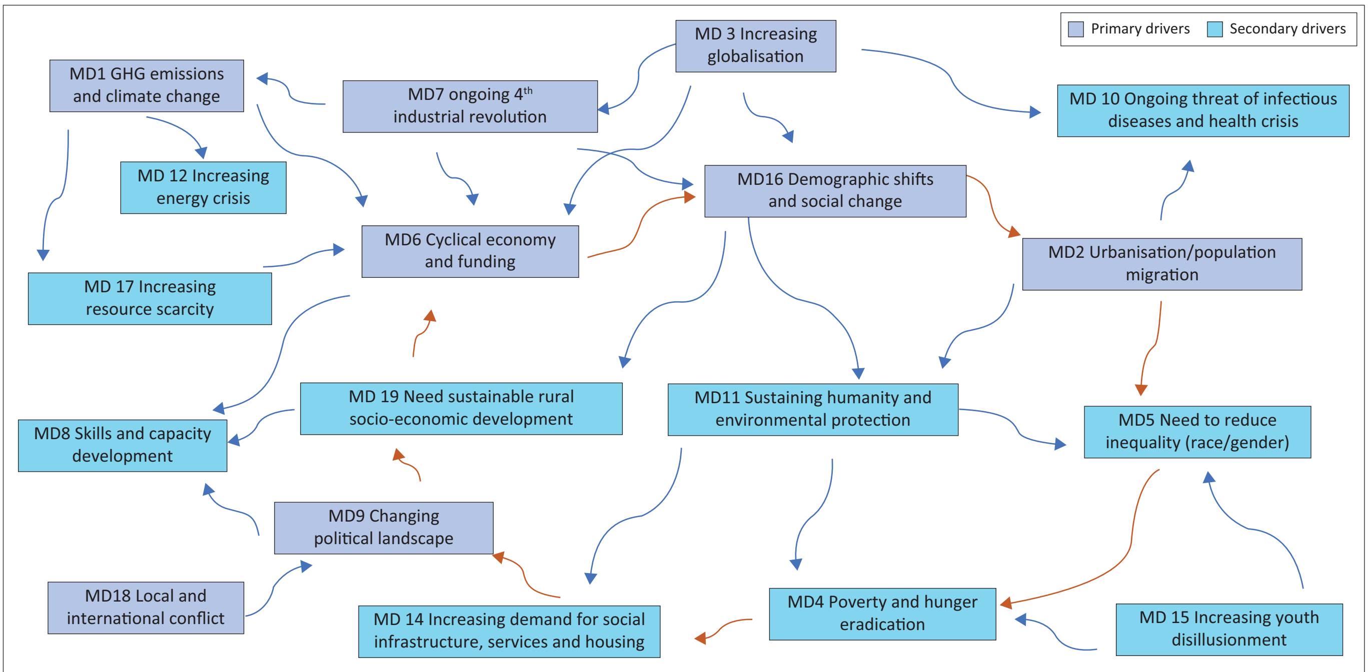


FIGURE 3: High-level causal loop diagram of drivers and trends.

Economy cluster causal loop diagram

For the SANRAL R&D programme, the most pertinent mega-drivers, industry-level drivers and trends were used to compile a CLD relevant to the cyclical economy and lack of funding, as shown in Figure 4. The diagram depicts two loops, indicated by the brown arrows:

- a reinforcing loop around urbanisation and traffic growth
- a reinforcing loop that relates to loss of skills and capacity.

In the reinforcing loop at the bottom, the following flow can be noted:

- The cyclical economy (MD6) and lack of funding lead to urbanisation and population migration (MD2) as people move to cities in search of jobs and services.
- This leads to changes in the nature and demand for mobility (ID15), particularly in cities and inter-urban links.
- The increased demand leads to increased traffic volume (TR49) and congestion, with the consequent overloading of roads.
- This then leads to growth in highway networks (and other roads) (TR13), which requires investment in construction and increases the maintenance cost of the road network.
- The loop is closed with even less funding available because of increased costs.

The reinforcing loop at the top shows the following flow:

- The cyclical economy (MD6) and lack of funding cause a cyclical flow of funding and a lack of funding available for infrastructure development and maintenance (including roads) (ID2).
- This implies that the most important aspect then becomes the attempt to sustain the condition of the infrastructure network (ID12) without major improvements (which, in the case of roads, is made more difficult by resource scarcity [MD17] and, for example, oil and bitumen shortages and price increases [TR18]).
- This leads to the trend of decreasing spending on infrastructure (TR8), which, combined with the cyclical nature of the funding, places large construction companies at risk (as has been observed in the recent past) (TR16). If unchecked, this has the side effect of a decline in the condition of infrastructure (TR1) and particularly the neglect of rural infrastructure (TR37).
- The consequence is a loss of skills and capacity, which also spills over to government sectors (ID4).
- This leads to a need to build a capable state (ID1) in which SANRAL can play a major role in the road transport sector (ID9).
- The system is made more complex with the imperative to transform the industry, with particular emphasis on job creation and support to small, medium and micro-enterprises (SMMEs) (ID6).
- Skills in the planning and execution of work in government departments will also be lost, which exacerbates the cyclical nature of the funding (due to slow or reduced allocation of funding for projects) and forms a negative reinforcing loop.

Levers in the CLD to turn around the negative loops could be identified and relevant interventions designed to change the situation. A powerful lever is developing the relevant skills and the associated building of a capable state. This will improve efficiency and cause less severe cycles in funding levels.

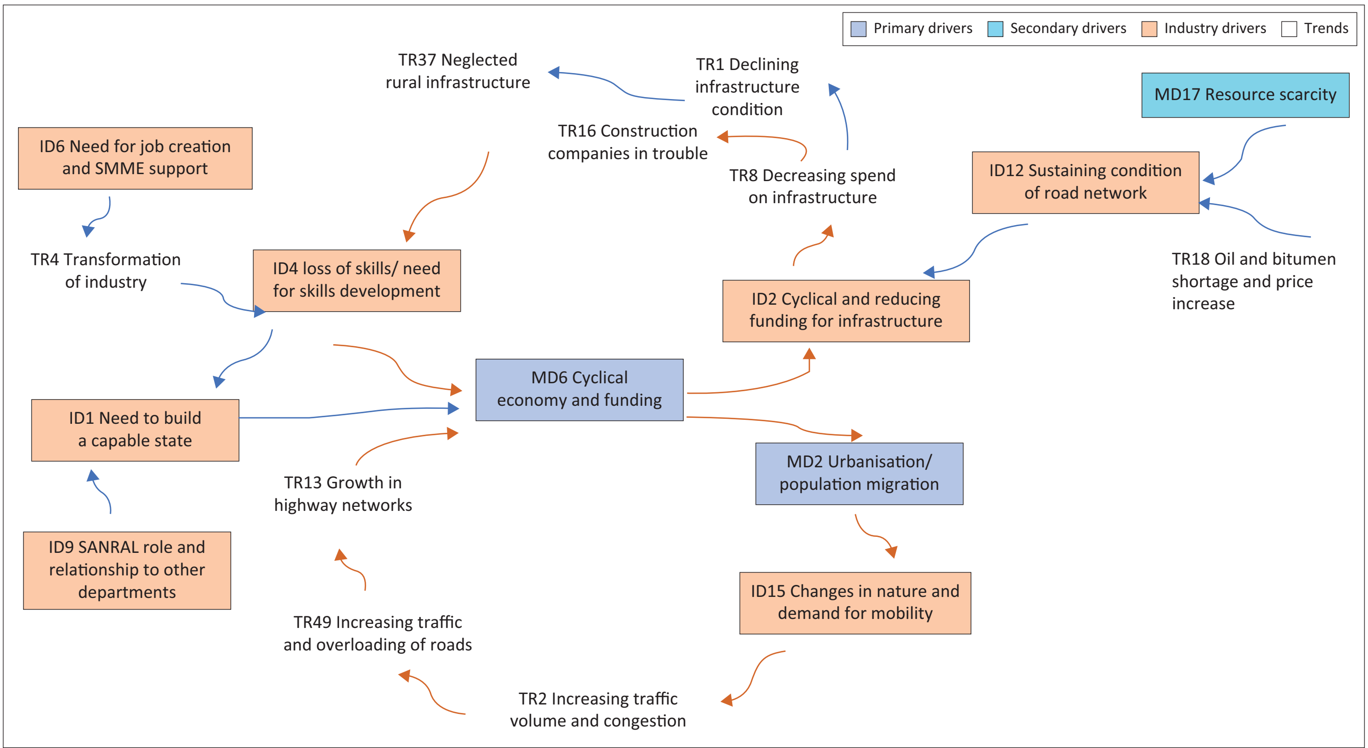


FIGURE 4: The economy causal loop diagram.

The technology causal loop diagram

Similar to the economic cluster, the items relevant to the Fourth Industrial Revolution driver were used to compile a CLD. This is depicted in Figure 5. The diagram has two reinforcing loops:

- a smart materials loop
- a smart mobility and smart roads loop.

Note that the analysis of the drivers and trends in the CLD led to the identification of a previously not-identified trend, namely 'Localisation of technologies'. In this way, the analysis of the CLDs assisted the research team in validating the completeness of the driver and trend sets.

The flow in the materials reinforcing loop at the top is as follows:

- The 4th Industrial Revolution (MD7) has given rise to new, advanced materials (TR11) – based on, for example, nanotechnology and biotechnology, often with embedded sensors that render them smart, self-healing materials.
- In a side loop, there is also an increased emphasis on the use of waste materials (TR19) due to a focus on resource efficiency and resource scarcity and the need to use green materials (TR9) because of the environmental challenge.
- The advent and use of these materials have led to the need for new design and construction methods (TR20).
- These new methods can lead to the challenges of implementing the advanced technologies in a developing-world environment (TR27).
- This emphasises the need to localise the new technologies to become relevant and useful in a developing-world environment (TR51). This trend was not originally picked up from the literature review and was added as the CLD was analysed (hence the orange colour).
- Finally, this affects the 4th Industrial Revolution (MD7) through the development of new, appropriate technology based on the original advanced technologies.

Using advanced materials that are green and incorporate waste can be a powerful lever to improve the overall performance and whole-life cost of road infrastructure.

Potential future research and development focus areas

Analysis of the outputs from the study yielded potential focus areas for R&D which are addressed next.

Smart roads and the Internet of Things

The use of sensors in self-aware road infrastructure to collect real time data on road and traffic flow performance can be combined with big data analysis techniques and artificial intelligence techniques such as machine learning. This can produce self-learning prediction models for road pavement performance and traffic flow performance that will improve in accuracy as they assimilate data and thus improve designs. These systems can be powered by energy generation from road infrastructure using photovoltaics and heat generation.

Advanced materials technologies

In view of the additional demands placed on roads by growing traffic loading and climate change effects, there should be a focus on high strength, durable, all-weather materials that are at the same time environmentally friendly. On the back of the 4th industrial revolution (4IR) and developments in new materials this activity should focus on self-healing materials, cement and bitumen replacements that are green, and high-performance materials that can withstand increased loading. A typical example is the use of bio-stabilisation from bacteria to replace cement-treated materials.

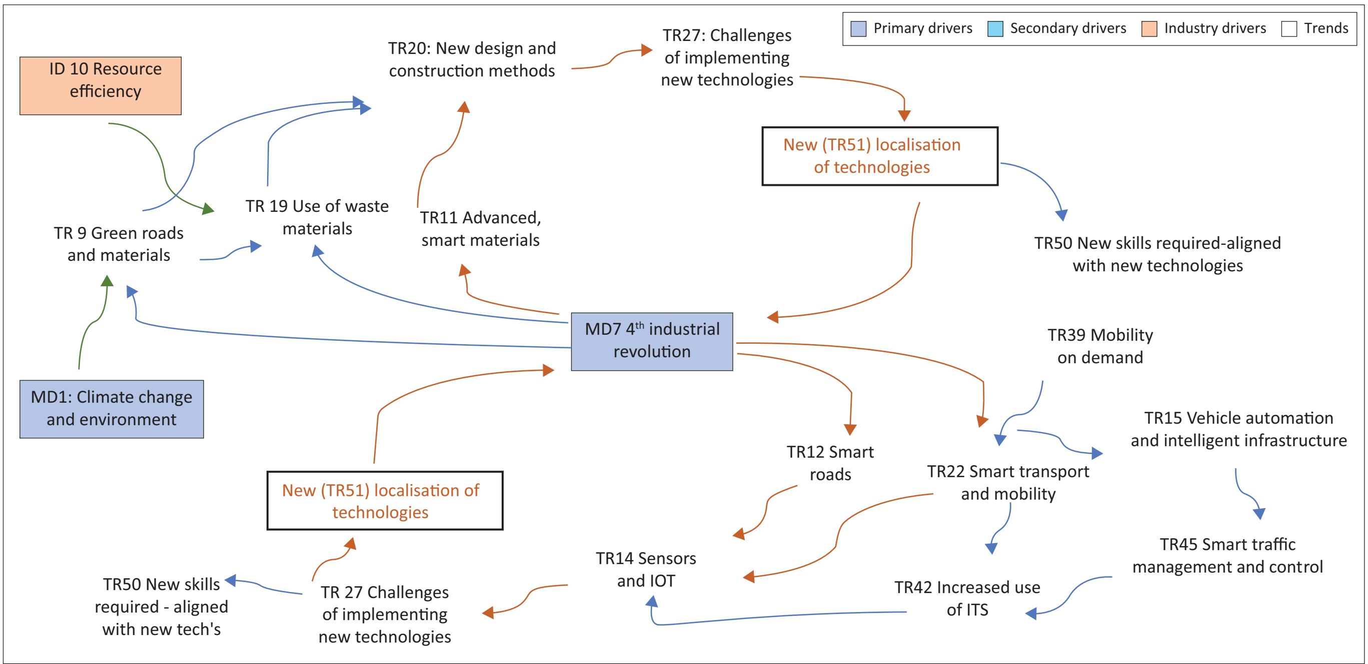


FIGURE 5: The technology causal loop diagram.

Beneficiation of waste and marginal materials

The use of 4th Industrial Revolution technologies such as nano-modification of materials can be used to beneficiate waste and marginal road building materials to acceptable standard. This is important in view of the scarcity of high-quality, non-renewable crushed aggregates and natural gravels experienced in the road building industry in association with the increasing cost of bitumen and cement.

Infrastructure that accommodates advanced vehicle modes

The advent of EVs and AVs will require special infrastructure that provides charging stations or 'on-the-go' charging of EVs and AVs as well as the required sensors and Internet of Things (IOT) infrastructure to manage and control such vehicles.

Advanced transport technologies

This area should focus on the deployment of alternative modes of transport (such as the Hyperloop), as well as their feasibility and applicability in South African conditions in order to improve traffic operations and road safety.

Conclusion and way forward

The drivers, trends and technologies that will impact the future of the transport sector were successfully defined and rated for their importance and relevance. Systems diagrams and CLDs were used in a novel process to portray the drivers and trends visually and show their interdependence and interaction. They were also used to validate the driver, trend and technology sets and identify potential gaps in knowledge for future R&D, thus meeting the major objective of the study.

The end goal of the study is to develop a set of future scenarios and define a 'desired future' for the transport sector. Through back-casting from the desired future, the key solutions required will be determined, and the new technologies and knowledge gaps to move, in this case, the South African transport sector from its current reality to the desired future will be identified.

This process can be used by decision-makers in R&D to assist their strategic R&D planning processes.

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The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Authors' contributions

F.C.R., L.R.S., A.A.C., B.M.V., H.S.F. and M.A.S. contributed to the conceptual development, methodology, data analysis and writing of the article.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Disclaimer

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