Journal of Transport and Supply Chain Management
ISSN: (Online) 1995-5235, (Print) 2310-8789

Technology foresight for the South African road transport sector by 2035

Authors:
Frederik C. Rust[1]
Leslie R. Sampson[2]
Adriana A. Cachia[3]
Benoit M.J.A. Verhaeghe[4]
Helena S. Fourie[5]
Michelle A. Smit[4]
Alwyn Hoffman[6]
Wynand J.v.d.M. Steyn[7]
Karien Venter[4]
Samuel Lefophane[8]

Affiliations:
[1]Pavement Engineering Research Consultancy (Pty) Ltd, Hermanus, South Africa

[2]Sampson Consulting, Pretoria, South Africa

[3]Adelle Cachia Consulting, Hermanus, South Africa

[4]Smart Mobility Cluster, Council for Scientific and Industrial Research, Pretoria, South Africa

[5]SANRAL, Pretoria, South Africa

[6]Department of Electronic Engineering, Faculty of Engineering, North-West University, Potchefstroom, South Africa

[7]Department of Built Environment and Information Technology, Faculty of Engineering, University of Pretoria, Pretoria, South Africa

[8]Council for Scientific and Industrial Research, Johannesburg, South Africa

Corresponding author:
Frederik Rust,
chris@perc.co.za

Dates:
Received: 26 Jan. 2024
Accepted: 23 July 2024
Published: 30 Aug. 2024

Background: Foresight can be used to define futuristic orientated research and development (R&D) that is required to position the road transport sector for a challenging future.

Objectives: To develop a set of futuristic R&D projects that could be added to a balanced SANRAL R&D portfolio to position SANRAL and the transport sector for the future on a 15-year horizon.

Method: Inputs into and ranking of the drivers, trends and technologies that will impact the transport sector were obtained from interviews with eminent thinkers, participants in workshops and a survey leading to five potential future scenarios. Qualitative and quantitative data analysis yielded several key solutions (KSs) and key interventions (KIs) to position the sector. This was complemented with the novel use of technology trees to analyse the linkages between new and existing knowledge and to identify gaps in knowledge and subsequently the identification of key R&D opportunities.

Results: Through backcasting from the desired future scenario as well as using 412 stakeholder inputs, 12 KSs and 61 KIs were defined and ranked. The top 30, most futuristic KIs were analysed using 18 hierarchical technology trees to define R&D opportunities.

Conclusion: The analysis emphasised the importance of new technologies such as data science, machine learning, smart transport and advanced materials to position the sector.

Contribution: The use of a novel, structured technology foresight approach that utilises scenario development combined with hierarchical technology trees was demonstrated. To position the road transport sector for a challenging future, 12 new thematic KSs and 61 KIs were developed.

Keywords: technology foresight; futures study; R&D; transport sector; technology tree.

Introduction

Research and development (R&D) is essential for technological innovation that, in turn, stimulates socio-economic development (Bessant et al. 2014:1; Link 1993:2; Link & Scott 2013:15), provided that vital aspects such as funding and talent are well managed (Sarpong et al. 2023). Continued socio-economic development and job creation rely on competitive industries and companies that benefit from well-directed R&D. Social good such as improved roads and transport is often derived from the public-funded R&D. However, public funds are limited particularly in developing countries, which emphasises the need for the optimisation of R&D expenditure (Bessant et al. 2014:1; DSI 2023; Lazarotti, Manzini & Mari 2011:212). Foresight is a structured approach to develop R&D and technology development themes that will impact industry growth and development (Georghiou 1996:360). It can provide a sound foundation for planning and optimising an R&D programme that is both impactful and relevant to the future, as illustrated in this article.

Infrastructure investment into roads, harbours, railway lines and airports drives socio-economic growth (Cigu, Agheorghiesei & Toader 2019:1–22; Magoutas et al. 2023:780; Zhang 2013:24) through effective transport of freight and passengers (Ng et al. 2018:292). This, in turn, effects job creation, poverty alleviation and the reduction of inequality (World Bank 2014). Thus, relevant and well-planned R&D into roads and transport that yields relevant solutions to current and future challenges can have a major impact on socio-economic development.

How to cite this article: Rust, F.C., Sampson, L.R., Cachia, A.A., Verhaeghe, B.M.J.A., Fourie, H.S., Smit, M.A. et al., 2024, 'Technology foresight for the South African road transport sector by 2035', *Journal of Transport and Supply Chain Management* 18(0), a1012. https://doi.org/10.4102/jtscm.v18i0.1012

The South African National Roads Agency SOC Ltd (SANRAL), a state-owned entity, initiated a new R&D programme in 2019 (Rust et al. 2023:958). The agency identified technology foresight as vital to ensure that the R&D programme positions the transport sector for the future. It therefore commissioned a technology foresight study to provide a futuristic input into the R&D programme.

Technology and knowledge that emanate from R&D in roads and transport vary from new materials and products, new road and bridge design methods and traffic engineering solutions to road safety solutions (Rust 2010:87). This underlines the variability and complexity of R&D in roads and transport. In addition, there are local and global drivers that impact the transport sector currently and will shape its future such as the Fourth Industrial Revolution (4IR) (Rust et al. 2023:958).

Although R&D in the South African road transport sector has historically focussed on solving short-term problems (Rust & Koen 2011:3), there are significant drivers of change and challenges coming to bear (Rust et al. 2023:958). These include *inter alia* significant traffic load increases, climate change, urbanisation, as well as significant advances in technology through, for example, the 4IR (Schwab 2017). This is exacerbated by a current loss of skills in the sector, systemic problems such as corruption, need for improved road safety and security and a scarcity of good quality road building materials. This requires R&D to be focussed on positioning the road transport sector for a challenging future.

This article describes the use of technology foresight to position the road transport sector for the future. The process, for the first time to the knowledge of the authors, uses technology trees as a tool. It initially defines the current state and reality of the transport sector and then develops the future scenarios from which utilising a backcasting approach, the key solutions (KSs) and key interventions (KIs) required to move the roads transport sector from its current reality towards an ideal future were determined. In a novel approach, technology trees were used to assess the interrelationships of the KSs as well as their relationships to existing knowledge.

Research problem

Initial activities by SANRAL in 2019 to structure an R&D portfolio led to a set of research projects that were mainly focussed on current problems and not aimed at positioning the transport sector for the future. The agency identified technology foresight as vital to ensure that the R&D portfolio is balanced and includes a significant number of projects that are aimed at positioning of the transport sector within the study timeframe of 15 years and hence commissioned the technology foresight study. The research problem was to identify the drivers and trends that will impact the future transport system in South Africa as well as the emerging technologies that will impact the transport sector. Furthermore, the challenge was to use this as a foundation for analysis, using innovative tools such as technology trees, to determine the potential R&D focus areas required to position the sector for the future and deliver solutions for future challenges.

Objectives and purpose of the study

The purpose of the study was to develop future scenarios for the South African road transport sector in a 15-year time scale and to use this to recommend the R&D focus areas that SANRAL should consider to position the transport sector for the future. Technology foresight focusses on a medium to long-term view of the future, with time frames between 5 and 30 years. The project team, in co-operation with stakeholders, chose a 15-year horizon deeming 5 years to be too short for the transport sector where technology development moves relatively slowly and 30 years to be too long to provide a meaningful strategy to SANRAL. The objective of this study was to use a structured technology foresight process to:

- determine and rate the future drivers, trends and technologies that will impact the road transport sector;
- based on stakeholder inputs and an international scan of new technologies, develop an understanding of the KSs and KIs required to position the sector for the future;
- use a novel technology foresight approach in applying technology trees to analyse the relationships between the KIs and existing knowledge and to identify potential gaps in knowledge required to position the sector for future challenges.

The results were used by SANRAL to formulate its future R&D programme.

Research questions

The following research questions were defined for the study:

- **Question 1:** What drivers, trends and technologies will influence the South African transport sector currently and in the future?
- **Question 2:** What technologies or technological fields should be researched now to position the transport sector for the future?

Literature review and conceptual framework

Nature of technology foresight

The uncertainty of the future necessitates the use of tools such as technology foresight to inform strategic planning and even create the future (Ejdys et al. 2015:378). Foresight provides an understanding of the drivers and trends that shape the long-term future thus improving decision-making. As a strategic, forward-looking technology analysis, based on expert input and participation (Mauksch, Von der Gracht & Gordon 2020), it helps to develop and prioritise R&D. Foresight is associated with future studies, technology forecasting and technology assessment (Andersen & Andersen 2014:278). In particular, technology foresight is a structured approach that will impact industry growth and development (Georghiou 1996:360) and can be conducted at a global or sectoral level such as for the road transport sector.

Technology foresight does not attempt to forecast specific outcomes at a particular point in time but rather focusses on the development of various scenarios that leads to an understanding of a variety of situations under different circumstances for the target sector. This includes the identification of unprecedented events and wildcards (Ejdys et al. 2015:379). Technology foresight often utilises tools such as scenarios and road maps to develop strategy and to reach consensus among participants (Marinković et al. 2022). It is an ongoing learning process to provide different future scenarios for strategic planning (Gold et al. 2024).

Foresight can be used for several purposes, including to forecast developments and changes in the areas of society, environment, economy, technology and science; to define key areas of science and technology that are vital for economic development and improve quality of life; to identify new market opportunities; to initiate public-private collaborative programmes and to link different interest groups (European Union 2005:22). Foresight has also been used to facilitate Open Innovation and information sharing (Sanabria et al. 2024), to enhance Business Model Innovation (Moqaddamerad & Ali 2024) and for city region visioning associated with resilience and climate change adaptation (Dixon et al. 2023). Technology foresight has also been used specifically in the transport sector to improve goal setting and planning in Spain (Navarro-Ligero & Valenzuela-Montes 2022) and in participatory foresight studies to assess the impact of autonomous vehicles (AVs) (Lyons 2022). Foresight and Delphi processes were used by Meyer, Von der Gracht and Hartmann (2022) to assess the timeframe for 14 major technologies to be implemented in the transport sector. These included electric trucks, alternative fuels, truck platooning, autonomous trucks, use of pipelines and drones to alleviate truck traffic, digitisation of the transport sector, internet of things (IoT) and smart transport logistics.

A number of methods and tools are used in technology foresight. These include (Rust & 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 and
- economic analysis.

Other methods identified include:

- Horizon scanning (Pouru-Mikkola et al. 2023);
- Predictive analytics (Olaniyi et al. 2023); and
- Interactive backcasting (Szathmári, Köves & Gáspár 2024).

Each foresight study is unique and may use one or a combination of the above methods.

The nature of the road transport sector in South Africa

Any transport system comprises many elements and players, which makes it a complex system combining road, rail, ports, pipelines, air transport, maritime transport, conveyor belts and cables, non-motorised transport (NMT) and minibus taxis (Ittmann et al. 2016). Transport and transport infrastructure are vital drivers of socio-economic development and growth. Ittmann (2018) reported that pre-coronavirus disease 2019 (COVID-19), the South African transport sector was still performing reasonably well although the Logistics Performance Index (LPI) had decreased from 3.67 in 2012 to 3.28 in 2018, and the world ranking had dropped from 23 in 2012 to 33 in 2018. The LPI increased to 3.7 in 2022 (World Bank 2022). The World Bank indicated a marked decrease in the world ranking of South African transport infrastructure from 19th in 2012 to 38th in 2018 (Ittmann 2018). Over a similar period, the railway system in South Africa also performed less than adequately, and large quantities of freight were still moved over long distances by road (Ittmann et al. 2016). The transport sector was severely impacted by COVID-19 (Teuteberg & Aina 2021). Biznews (2023) reported that the South African transport sector is still in dire straits. Train service utilisation has dropped by as much as 97% between 2008 and 2022. Freight rail infrastructure and ports are inefficient and challenges are exacerbated by rising fuel costs. The freight logistics chain has recently been disrupted with bottlenecks at ports causing significant losses to the economy. The ports of Cape Town and Durban are now rated among the world's worst performing (Hellenic Shipping News 2023).

The National Road Agency (SANRAL Ltd SOC) manages the South African national road network, which consists of 22 197 km of highways (SANRAL 2023a). The provincial road network and the metro and municipal road networks of non-urban and rural roads and urban roads are managed by provincial and municipal road authorities, respectively. This includes 136 721 km of paved and 459 957 km of unpaved roads. In addition, there are also an estimated 140 000 km of un-proclaimed gravel roads.

SANRAL spent R8.49 bn on new projects and road maintenance in 2022/2023 (SANRAL 2023b:46). A significant amount of this is for road maintenance, and thus the national network is in good condition with only 12.4% in a poor to very poor state (SANRAL 2023b:46). The agency created jobs for 1928 small contractors during 2019/2020 with 80.2% of this work going to black-owned enterprises. SANRAL values road safety; the educational projects on road safety have reached 587 800 learners and 2247 parents (SANRAL 2023b:186). Of equal importance is mobility and traffic management with the Freeway Management System and associated Traffic Management Centres being emphasised. The smart roads initiative of SANRAL focusses on traffic management and safety improvement.

Apart from the national road network, the *South African Institution of Civil Engineering* (SAICE) Infrastructure Report Card (IRC) of 2022 rated the condition of South African road infrastructure as well below adequate (SAICE 2022). Provincial and metropolitan roads were rated at a level of D, where A is world class and E is unfit for purpose.

Rust et al. (2023:958) identified a number of pertinent characteristics of the transport sector. Most importantly, although roads are essential in stimulating the economy, the provincial and municipal networks are, in most cases, in poor condition and are deteriorating fast. This is mainly because of a backlog of road maintenance exacerbated by scarce and costly road-building materials. The quality of public transport and challenges with road safety are of major concern. Furthermore, limitations on funding and skills in both the public and private sectors, as well as systemic challenges such as corruption, are hampering road infrastructure provision and maintenance, placing emphasis on the need for a capable state and effective governance. This is of particular importance in view of increasing urbanisation, increasing loading of infrastructure and congestion impacting on public transport, traffic management, transport planning and road safety. The transport sector is a major contributor to green house gas (GHG) emissions, and its reduction will become a significant challenge in the near future. These challenges necessitate effective innovation in a generally developing country and limited economy, utilising *inter alia* technologies from the 4IR such as electric vehicles (EVs), autonomous vehicles (AVs), new age materials and artificial intelligence (AI)/machine learning (ML) to position the sector for the future.

Transport sector R&D programmes

Historically, government and private sector had funded R&D, for example the Department of Transport, the South African National Roads Agency Ltd SOC (SANRAL) and the South African Bitumen Association. However, most of these research programmes were designed to address immediate issues of the day and did not have a futuristic view (Rust 2009:87). In 2019, SANRAL, in line with its Horizon 2030 strategy (SANRAL 2017:3), initiated a new R&D programme that covers several roads and transport focus areas:

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

Methods

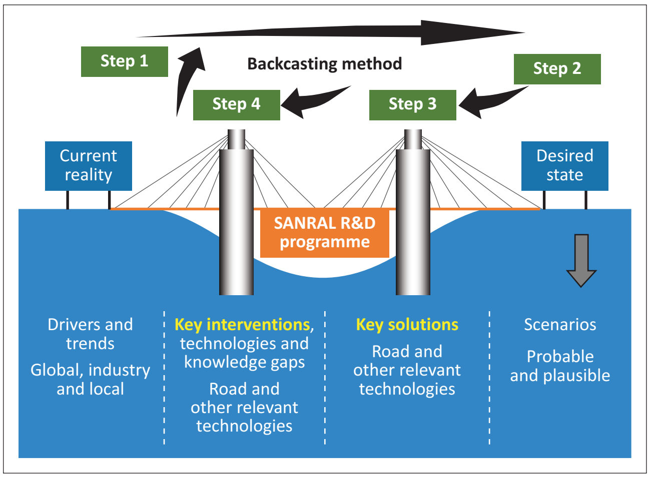
The project followed a modified approach for foresight analysis specific to the needs of the South African road transport sector (modified from Rust & Koen 2011:3) This consisted of:

- defining the current reality and challenges faced by the road transport sector;
- developing a set of future scenarios and a desired future scenario and
- backcasting to determine the network of R&D activities and interventions (particularly KSs and KIs) required for the road transport sector to progress from the current reality towards the desired future using technology trees to assess the relationship of newly envisaged technologies to existing knowledge and to identify gaps in knowledge.

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

The current reality analysis (see Figure 1) was conducted, based on the characteristics, drivers, trends, challenges and opportunities of the road transport sector (Rust et al. 2023:958). This work was based on a desktop study, interviews, stakeholder inputs and a survey. Causal maps were used to analyse the interrelationship between the drivers, trends and technologies to inform interdependencies and identify the main causal loops that describe the state of the road transport sector (Rust et al. 2023:958).

The drivers, trends, technologies as well as challenges and opportunities for the road transport sector were used to develop five potential scenarios for the roads transport sector on a 15-year horizon. This then allowed for the development of a description of the desired, probable future state of the road transport sector (scenario five) through qualitative analysis of the data from the desktop study, inputs from the interviews and data from



Source: Adapted from 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), 3

FIGURE 1: Phased approach to technology foresight study.

stakeholder workshops. This was done by using a classical foresight approach where extreme scenarios are developed based on two intersecting major drivers, in this case socio-economic development and sector capability.

Backcasting from the desired future state, 12 thematic KSs were developed that would take the road transport sector towards the desired future state. Then, 61 KIs were developed (of which 30 are futuristic) that would be required to bridge the gap between the current reality and the desired future within the thematic KSs. This was done by analysing all data and information collected using *inter alia*:

- casual loop diagrams (Rust et al. 2023:958);
- inputs derived from stakeholder groups through interviews, online workshops and a survey;
- consolidating the data into 12 thematic KSs, and
- evaluation and rating of the KIs and outcomes by stakeholders.

In a novel approach, technology trees were used to position the 30 futuristic KIs in relation to existing fields of knowledge to indicate knowledge gaps and potential R&D focus areas. The 30 futuristic KIs were then analysed in terms of their applicability in the five scenarios as well as their relevance to the SANRAL Horizon 2030 strategy.

Data sources

The data gathering processes included (Rust et al. 2023:958):

- A desk top study completed in July 2021 that identified drivers, trends and technologies that will influence the road transport sector;
- Six webinars with eminent speakers in May 2022 attended by 219 participants (researchers, stakeholders and government officials);
- Detailed interviews with seven technical experts in the transport sector.
- Six stakeholder workshops in July and August 2022 attended by 111 participants (researchers, stakeholders and government officials) and
- A questionnaire with 26 respondents.

The purpose of the workshops was for participants to:

- Augment the list of drivers, trends and technologies identified in the desktop study;
- List the challenges and opportunities facing the transport sector and
- Rate the drivers, trends, technologies, challenges and opportunities using a real-time online tool with a six-point Likert scale for importance and relevance.

The project therefore included qualitative and quantitative research methods used in a mixed model. The qualitative data were synthesised through data reduction to yield specific technology focus areas. Statistical analysis was conducted on the qualitative data.

This article describes the development of the five scenarios, the 12 thematic KSs and 30 futuristic KIs as well as their position and relationship in a set of 18 technology trees. The 30 required KIs to position the transport sector for the future have been taken up by SANRAL for consideration as projects in their R&D programme.

Scenario development

Scenario planning is an excellent tool to ensure that future strategies flowing from foresight work are robust and can stand up to various futures (Ringland 2010). Scenarios assist in the understanding of complex systems by providing a structure for making sense of market intelligence against the backdrop of information from horizon scanning and forecasting and thus provide a platform for debating various aspects of potential futures and provide input into the strategic decision-making process. A set of scenarios can be used as a benchmark for future plans and allow for new options to be explored (Ringland 2010).

The main axes of the 4-block scenario matrix were selected from the most important drivers and trends emanating from the study. Scenarios were developed using a matrix analysis of the drivers and trends in relation to the positive and negative ends of the scenario axes. This led to detailed descriptions of five scenarios that are discussed in detail further on.

Thematic key solution and key intervention development

The data from the stakeholder interactions, particularly the challenges and opportunities, were analysed qualitatively using matrices to identify thematic KSs and more detailed KIs. This was based on an analysis of the most important challenges identified and the potential solutions based on the identified opportunities, trends and future technologies.

Technology trees

Technology trees can be used to map R&D programmes structured around platforms supported by capabilities (applied technologies), base technologies and research infrastructure (Rust 2009:237). In this regard, 'technology' is used in its broadest sense and includes knowledge-based methods and solutions. The platform is the logical grouping and utilisation of a set of core capabilities (Meyer & Utterback 1993). A technology platform has a distinctive, inherent set of technologies that provide a competitive advantage. Technology platforms can be used to understand the level of innovation and renewal and can be used as a foundation on which to build new solutions effectively. Platforms can be used to cost-effectively develop several KIs through the sharing of base technologies and capabilities.

Firstly, to construct the technology trees, the key needs and opportunities in a specific focus area were identified. Secondly, the end products required to address these needs with their available delivery systems for implementation were determined. The end products can be developed more cost-effectively from a platform where the capabilities and base technologies are integrated to support the development of the solution to a key problem. Thus, the top structures of the technology trees were grouped around a set of technology platforms. The supporting structure of the technology trees consists of capabilities, base technologies and infrastructure that will be used to develop the end products through the technology platform. This is discussed in more detail further on.

The process is summarised in Figure 2.

Ethical considerations

The project entailed literature review and data analysis. The CSIR ethics committee exempted the project form ethics clearance 1002/58600/2018/P1.4.

Results

Drivers, trends and technologies in the transport sector

The analysis of the data and information collected led to the definition of the mega-drivers, sector-level drivers, trends and technologies for the road transport sector (Rust et al. 2023:958). For the sake of brevity, only the top 10 ranked items in each of the groups are repeated here (Table 1, Table 2 and Table 3).

From the preceding, it is evident that the skills gap in the roads transport sector that impacts on the capability of the state and governance is a very important driver. In addition, socio-economic development that leads to urbanisation, increasing power usage, increasing GHG emissions, scarcity of resources and traffic congestion on the one hand and impacts on economic growth, eradication of poverty and inequality, the employment of the youth and improved services, on the other hand, is equally important.

Technology development is often the response to challenges and opportunities in a sector and is informed

TABLE 1: Top 10 of 16 mega-drivers ranked by importance rating.

Mega-driver	Importance (%)	Relevance (%)
Skills and capacity development particularly among the youth and in technical/engineering fields with emphasis on 4IR skills (relating to skills required to deploy 4IR technologies)	90.8	88.2
Increasing energy crisis that impacts on the economy and social development	88.6	87.7
Urbanisation and population migration. Increasing population particularly in urban areas places pressure on housing, transport and utility infrastructure	85.5	89.5
Increasing resource scarcity other than energy such as water and food	82.5	81.1
GHG emissions and climate change. The emission of GHGs that lead to climate change and impacts on global warming and weather change	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	81.1	80.3
Changing political landscape (power shifts from west to east) and South African political fluidity and challenges	79.4	82.0
4IR and an innovation economy including autonomous vehicles, 3-D printing, advanced robotics, advanced materials, the IoT, sensors, blockchain technology and synthetic biology	78.9	80.7
Poverty, hunger and inequality based on race and gender – legacy of exclusion. Including access to mobility	77.6	75.0
Cyclical nature of the economy; long-term fluctuations of economic activity and therefore ability to fund infrastructure	76.3	82.0

4IR, Fourth Industrial Revolution; GHG, greenhouse gas; IoT, Internet of Things.

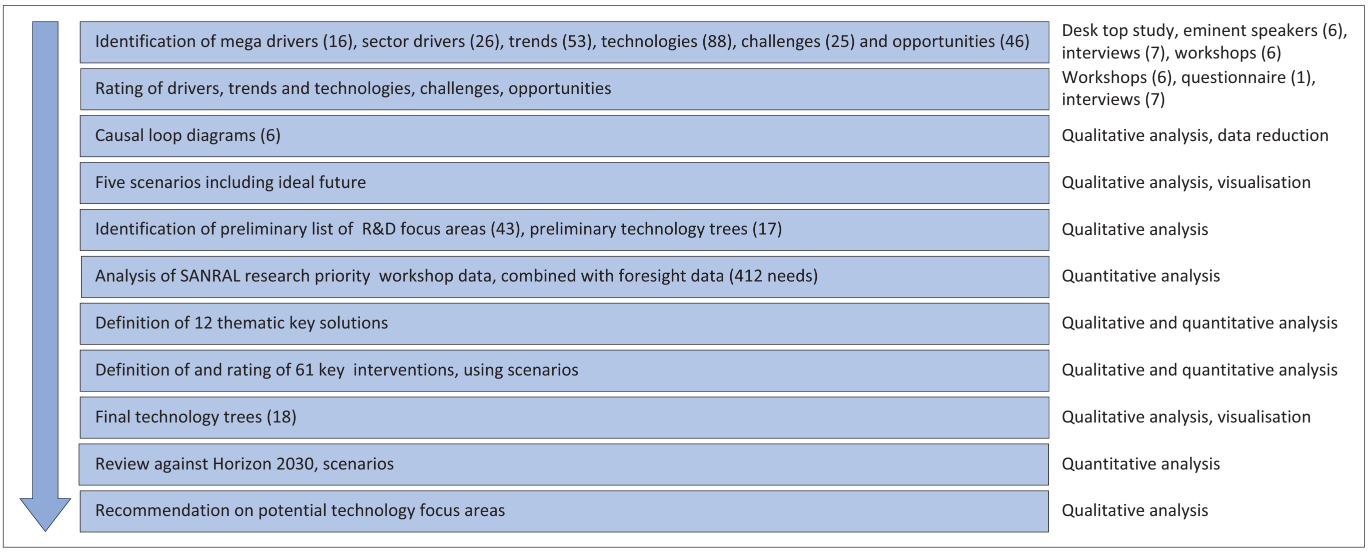


FIGURE 2: Summary of methodology.

TABLE 2: Top 10 of 26 sector-level drivers.

Industry-level driver	Importance (%)
Need to build a capable state	95.0
Public sector governance	91.0
Sustaining road condition	91.0
Need for safe, secure and reliable public transport	88.0
Loss of skills and need for human capital development	85.0
Integrated logistics planning	84.0
Need for improved road safety	84.0
Oil and bitumen shortage and price increase	82.0
Safety and security in general	81.0
Cyclical funding with impact on industry capability	80.0

TABLE 3: Top 10 of 53 trend groups ranked by importance.

Trend group	Importance (%)	Impact (%)
Transport infrastructure condition and growth	96.0	95.0
Increasingly weakening South African economy	93.0	92.0
Need for increase in road infrastructure investment	87.0	86.0
Young population unequal and unemployed	83.0	78.0
Increasing traffic congestion	80.0	84.0
Advances in road safety, for example safe system approach	77.0	76.0
Transport sector change and transformation	77.0	80.0
Skills development for 4IR technologies	76.0	75.0
Impact of climate change, for example adverse weather events	76.0	75.0
Dissatisfaction with public transport	75.0	79.0

4IR, Fourth Industrial Revolution.

by drivers and trends. A total of 79 key technologies and knowledge packages were identified that will impact the transport sector (SANRAL 2021:254). To facilitate analysis, the technologies were grouped into 20 categories and then rated by stakeholders. The top 15 technology groups are indicated in Table 4.

As evident from Table 4, new technologies to address road safety; a bitumen replacement; new modelling techniques that include self-learning models based on ML techniques; asset management and preservation, smart materials and smart transport technologies were highly ranked.

Scenarios

Analysis of the drivers, trends, challenges and opportunities led to the identification of two future key uncertainties that are relevant and important to the transport sector (SANRAL 2022):

- Socio-economic development and
- Sector capability (public and private sectors).

These axes then lead to the definition of five scenarios (Figure 3):

- Positive economic development, strong sector: 'Free Flow scenario', which is a Utopian scenario with all aspects being positive.
- Negative economic development, weak sector: 'Gridlock scenario', which is akin to a failed country.

TABLE 4: Top 15 of 20 technology groupings ranked by importance.

Technology group	Importance (%)
Road safety technologies and methods: Safe System Approach; Road safety data management techniques	89.0
Bitumen replacements (green bio-binders);	76.0
Modelling and software: BIM, ML prediction models, Big data; Digital twinning;	76.0
Asset management technologies: Smart asset management through advanced sensor technologies.	76.0
Smart materials: Low water usage technologies, self-healing roads and embedded sensors in materials;	75.0
Sensors in vehicles: Sensors and IoT; vehicle-to-vehicle and vehicle-to-road communication;	75.0
Waste materials: Plastic roads and recycled waste materials;	74.0
Smart transport technologies: MAAS; AI for traffic light control; blockchain; smart mobility	74.0
Robots and drones: Monitoring of traffic flow and events, infrastructure inspection	73.0
Modified materials: for example, nano-modified materials, bio-based stabilisation and bio enzyme stabilisation, green materials	72.0
Mobile phone technologies: use of cell phone sensors for example accelerometers to determine road conditions and traffic flow	72.0
Smart vehicle technologies: Electrical vehicles; Advanced battery technologies; Wireless inductive charging; Autonomous vehicles; alternative fuels	72.0
AI and ML	70.0
Smart roads and sensors: In-road sensors; self-sensing and self-adapting pavements	69.0
Advanced construction technologies: 3-D printing; intelligent compaction and off-site manufacturing;	69.0

BIM, Building Information Modelling; ML, Machine Learning; AI, artificial intelligence; MAAS, mobility as a service; IoT, Internet of Things.

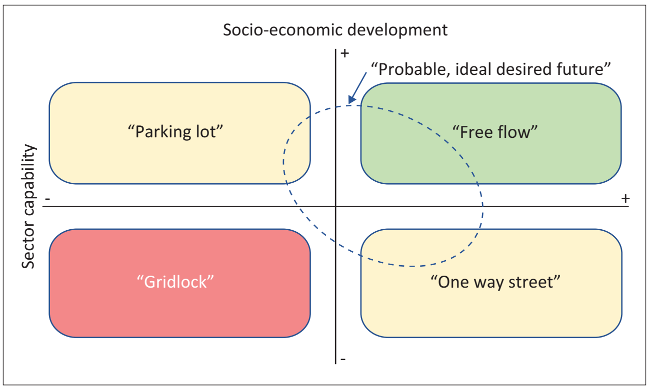


FIGURE 3: Five scenarios based on socio-economic development and sector capability.

- Positive economy, weak sector: 'Parking Lot scenario', which indicates that, in spite of significant economic growth and investment, the sector is weak, with low skills levels and cannot get traction.
- Negative economic development, strong sector: 'One-Way Street scenario', during which a strong, capable private sector takes its skills off-shore to survive.
- A most probable, slightly positive future scenario or ***Desired Future*** for the transport sector.

It is important to note that scenario planning does not attempt to predict which scenario will take place but rather use the scenarios to describe actions that will position the sector ideally for the set of scenarios. The probable scenario is selected to be moderately positive so as to create a positive vision for the transport sector to strive for. The ultimate goal of the study is to determine the optimum technological pathway that the sector can take through the SANRAL R&D programme to strive for this probable desired future.

Detailed descriptions of the scenarios are given in the SANRAL Foresight Final Report (SANRAL 2023b). Brief detail of the moderately positive Probable Desired Future scenario is given in Table 5.

Key challenges and opportunities

The interactions with stakeholders through workshops, interviews and a survey identified 25 key challenges and opportunities (SANRAL 2023b). The following were indicated as potential areas of research or capacity building:

- Training of practitioners to improve general skills but also specifically in new age technologies, thus ensuring localisation of new technologies.
- In-house training programmes for road authorities in both technical as well as operational and managerial aspects.
- Technologies to reduce the maintenance backlog that could include 4IR materials that are superior in performance and cost-effectiveness.
- Application of data mining to existing SANRAL data to assess performance of existing systems and methods (e.g. overload control, unsafe road behaviour and illegal road usage) and recommend improved operational practices.
- Technologies to continuously monitor road infrastructure and road users and to convert the collected data into intelligence that will increase the expected lifetime of roads, reduce congestion and improve road safety.
- Improvement of road safety statistics by augmenting the current road safety research with an investigation of technologies that can improve road safety.
- Methods for integrated transport planning across modes.
- Materials and design that can deal with increased loading, particularly 4IR materials that are superior in performance, durability and cost-effectiveness.
- Sustainable, cost-effective, climate-resilient maintenance rehabilitation and construction methods developed and implemented as standard practices.
- Legislation and policies that facilitates the implementation of new technologies and a well-funded relevant research programme that addresses the whole road network and not only national roads (in conjunction with the national Department of Transport [DOT]).

Similarly, an analysis of the list of opportunities in relation to the Causal Loop Diagrams (CLDs) indicates that the following are important focus areas:

- Methods and content for road user education and training programmes.
- Frameworks for improved planning and collaboration between the modes of transportation to allow better forward thinking and planning.
- Implementation plan for the application of the safe systems approach.

TABLE 5: Description of probable, desired future scenario.

Aspect	Characteristic
Economy	Growth of 3.0% of GDP ahead of population growth of 1.7%; modest but steady per person income improvement; investment funding of 20.0%; Fiscus well funded; public sector investment one third of gross domestic fixed investment; Rand stable and inflation at 3.0% to 6.0%; strong support for SMMEs
Competitiveness	Moderate but meaningful improvement in industrial competitiveness; export sector moves from commodity based to more industrially based; rising economic competitiveness; growing share of world exports
Employment, equality. Social development	Reduction in unemployment to 20.0% and Gini co-efficient improves from 0.65 to 0.5 (in line with emerging economies); focus on social development through job creation (including labour-enhanced construction); increased investment into social infrastructure
Sector capability	Sufficient capability to ensure continuous improvement; skills in government and public sector rebuilt
Governance and service delivery	Institutional integrity sound; significantly improved service delivery; backlogs to infrastructure significantly reduced; effective disbursement of funds at all levels of government
Skills	Focus on general upskilling of workforce (also to deal with new technologies) through well-funded sustainable skills development programmes
Transport sector	Responds to urbanisation with innovative solutions; increased investment into transport infrastructure; greater demand for optimum management and performance of the transport system
Road safety and traffic management	Public sector invests significantly in road safety improvement through new technologies such as driver behaviour modelling using ML as well as improved governance; advanced methods for traffic flow prediction required to deal with urbanisation MAAS methods deployed
Public transport	Significantly improved public transport using new technologies to improve safety, scheduling, commuter communication and service delivery using solutions such as MAAS
Geospatial	South Africa is regionally integrated; urbanisation increases but balanced with rural growth and rural infrastructure; increasing pressure on infrastructure because of urbanisation
Technology	New technologies embraced and related skills levels improved; weather-resistant technologies employed
Materials	Bitumen scarcity because of lower oil refining and more electrical vehicles; scarcity of good quality road building materials
Resources	Focus on resource optimisation; use of waste materials; Re-use and recycling of materials; modification of low-quality materials to meet specifications through nano-technology and biotechnology
Road condition	In general, urban and rural road conditions are improved through well-funded quality maintenance that is coordinated between all levels of government; improved planning for adverse weather events; reduction in vehicle operating costs
Climate change	50.0% electrification of the transport sector by 2037; hydrogen-based vehicles increased; reduction of GHGs; focus on environmentally friendly materials and processes for example low-water compaction and use of marginal materials; leads to bitumen scarcity and cost increases; climate change adaptation methods and strategies in place

GDP, gross domestic product; SMMEs, small, medium and micro enterprises; ML, machine learning; MAAS, Mobility as a Service; GHGs, greenhouse gases.

- The development of sustainable funding models for transport infrastructure provision and maintenance.
- Advanced traffic control with intelligent transport systems.
- Improved road performance prediction models using ML and big data analysis of Long-Term Pavement Performance (LTPP) and Accelerated Pavement Testing (APT) data.
- Integrated policy framework for adaptation of technologies.
- Use of AI during data collection and data mining in support of transport risk modelling.

- Implementation of a national electrification strategy with renewables to support the transition to EVs and fuel cell electric vehicles (FCEVs).
- Introduction of advanced technologies for crash prevention.
- Improved analysis of driver behaviour using ML techniques.
- Pre-manufactured road slabs that carry other services.
- Electricity generation through roads.
- Introduction of advanced technologies for accident prevention and road safety.
- Ongoing development of contractors especially for maintenance using labour-enhanced methods.

Thematic key solutions and key interventions

The analysis of 412 inputs from stakeholders in respect of challenges, opportunities and project ideas was used to compile a list of 12 high-level Thematic KSs:

1. Development of alternative materials for design, construction and maintenance of roads and bridges.
2. Incorporation and customisation of the latest automation, data processing and robotics practice.
3. Capacity building programmes in line with latest best practice.
4. Improved transport planning, traffic management and provision of transport services.
5. Improved road safety and security.
6. Improved road and bridge design construction, rehabilitation and maintenance practice.
7. Increased attention to environmental sustainability.
8. Monitoring, evaluation and testing methods in line with latest best practice.
9. Transformation, community participation and ongoing small, medium and micro enterprise (SMME) development.
10. Improved asset management through sustainable and stable financial and procurement practices supported by good governance and appropriate management systems.
11. Up-to-date knowledge, information and communication management systems.
12. Development and updating of relevant best practice documentation and specifications for roads and transport.

Using the backcasting approach, 61 KIs that will bridge the gap between the thematic KSs and the current reality of the transport sector were determined. The KIs were rated according to their importance to SANRAL; how well they address the Desired Future Scenario; their potential impact in the Desired Future Scenario; the required research intensity to develop them and the ease of developing these solutions. The top 30 KIs were then added to the SANRAL portfolio of potential future projects. In addition, 18 technology platforms were identified from which the KIs can be developed:

- P1: Smart transport and mobility
- P2: Smart transport infrastructure
- P3: Transport planning
- P4: Effective R&D programme
- P5: Capacity/capability development
- P6: Pavement materials technology and testing
- P7: Pavement design and analysis
- P8: Pavement testing and performance
- P9: Construction and maintenance
- P10: Asset management
- P11: Traffic management
- P12: Road safety design and management
- P13: Road safety engineering and technology
- P14: Structures (bridges)
- P15: Geotechnical engineering
- P16: Hydraulics and drainage
- P17: Environment
- P18: Data Sciences Applications in Transport

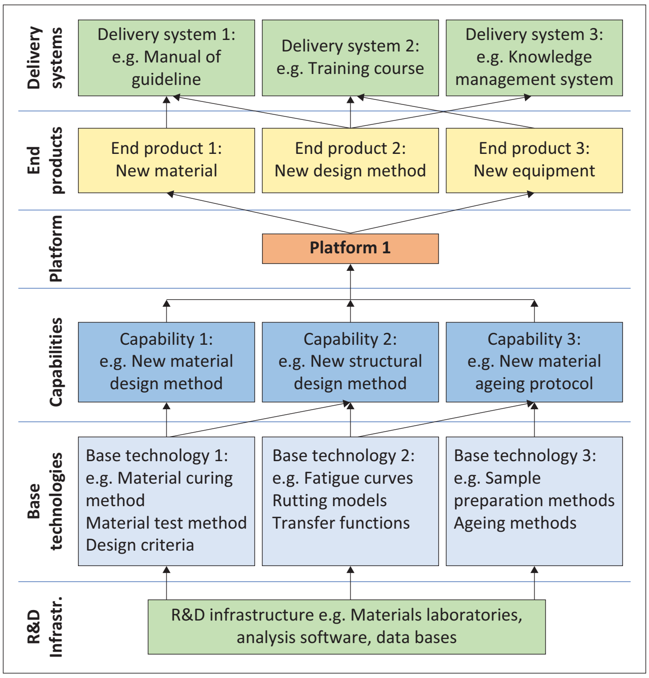
The KIs and their associated thematic KSs and platforms are presented in Table 6.

Technology trees

Figure 4 shows a schematic of a technology tree.

Technology trees can be used at the strategic level for a research programme or at a specific focus area level with more technical detail. Projects can be plotted at the appropriate level, that is implementation projects are plotted high in the tree, development projects near the middle and basic R&D projects at the bottom.

Linkages between the projects and their supporting base or applied technologies can then be explored and their execution planned accordingly. The balance of the R&D project portfolio in terms of the type of project (implementation, development



Source: Adapted from Rust, F.C., 2009, 'A systems approach to managing R&D in the road infrastructure sector in South Africa', p. 237, PhD thesis, University of the Witwatersrand
R&D Infrastr., Research and development infrastructure.

FIGURE 4: Schematic of a technology tree.

TABLE 6: Thirty futuristic key interventions.

Thematic key solution	Platform	Key intervention	Score (%)
KS2	P18	1. Develop an AI and ML core capability (platform) for ML-based pavement performance prediction, traffic modelling and safety analysis	89.7
KS8	P8	2. AI/ ML-based pavement performance prediction	89.7
KS2	P2	3. Smart, self-aware infrastructure with embedded sensors and communication technologies IoT enabling real-time pavement damage modelling	88.0
KS2	P18	4. Appropriate utilisation of big data, AI and ML for improved management and analysis of roads, bridge and transport data	87.0
KS1	P6	5. Bitumen replacement and non-bituminous binders	86.3
KS4	P3	6. Advanced transport planning, MAAS and modelling, including ML use	85.3
KS5	P13	7. Technologies for improving road safety and security (including modelling using ML)	84.7
KS1	P6	8. Innovative re-used and recycled materials in pavements	84.3
KS8	P8	9. Advanced core competence in LTPP and APT with associated instrumentation, testing devices, data bases, analysis methods such as AI/ML modelling for performance prediction	82.7
KS1	P16	10. Updated, sustainable, climate-resilient drainage/hydraulic design and management methods for roads and bridges	82.7
KS1	P6	11. Heavy duty materials, materials and design that can deal with overloading, particularly 4IR materials that are superior in performance, durability and cost-effectiveness	82.7
KS1	P6	12. Innovative use of waste in pavements	82.2
KS1	P6	13. Development and use of alternative greener materials in design, construction and maintenance	81.7
KS7	P17	14. Climate change mitigation techniques and solutions	80.7
KS7	P17	15. Climate change impact and adaptation of transport infrastructure, modelling and risk assessment, flood estimation	80.3
KS4	P3	16. BIM systems for transport infrastructure. Modelling and optimising projects by planning, designing, building and operating BIM models	79.0
KS1	P16	17. Advanced methods and techniques for rainfall and flood estimation, risk analysis and mitigation responses	79.0
KS1	P6	18. Innovative stabilisation methods for improved performance of granular/marginal materials (chemical and mechanical) using for example nano-technology	79.0
KS1	P6	19. Performance-based materials testing, design and quality management	79.0
KS6	P9	20. Water-efficient construction related to dry compaction methods, low water usage materials and compaction methods including water quality	78.7
KS7	P17	21. Sustainable, cost-effective, climate-resilient design, construction, rehabilitation and maintenance methods developed and implemented as standard practices	78.7
KS11	P10	22. Enabling Asset Management Systems, including climate resilience through vulnerability assessment/mapping and embedment in asset management both engineering and non-engineering adaptation of asset management	78.3
KS1	P6	23. Smart materials for roads and bridges (e.g. embedded sensors, self-aware, self-healing)	78.3
KS1	P6	24. Innovative, alternative, multi-purpose surfacings that can carry services and generate energy	78.3
KS2	P2	25. Investigation of alternative energy sources and energy savings from road infrastructure (construction and operations)	78.0
KS6	P9	26. Smart construction methods and construction methods for new, green, smart materials	78.0
KS4	P11	27. Advanced traffic management, use of ML for prediction of traffic state, dynamic traffic control, V2V and V2R communication technologies to assist with traffic management	77.7
KS2	P2	28. EVs, FCEVs and AVs – infrastructure enablement and operations	77.7
KS1	P15	29. Advanced geotechnical design, slope stability and site investigation to counter extreme weather events	77.7
KS1	P6	30. Advanced concrete mix design, green concrete	77.3

AI, Artificial Intelligence; ML, Machine Learning; IoT, Internet of Things; MAAS, Mobility as a Service; LTPP, Long-Term Pavement Performance; APT, Accelerated Pavement Testing; BIM, Building Information Modelling; V2V, vehicle-to-vehicle; V2R, vehicle-to-road; EVs, electrical vehicles; FCEVs, Fuel Cell Electric Vehicles; AVs, Autonomous Vehicles; 4IR, Fourth Industrial Revolution.

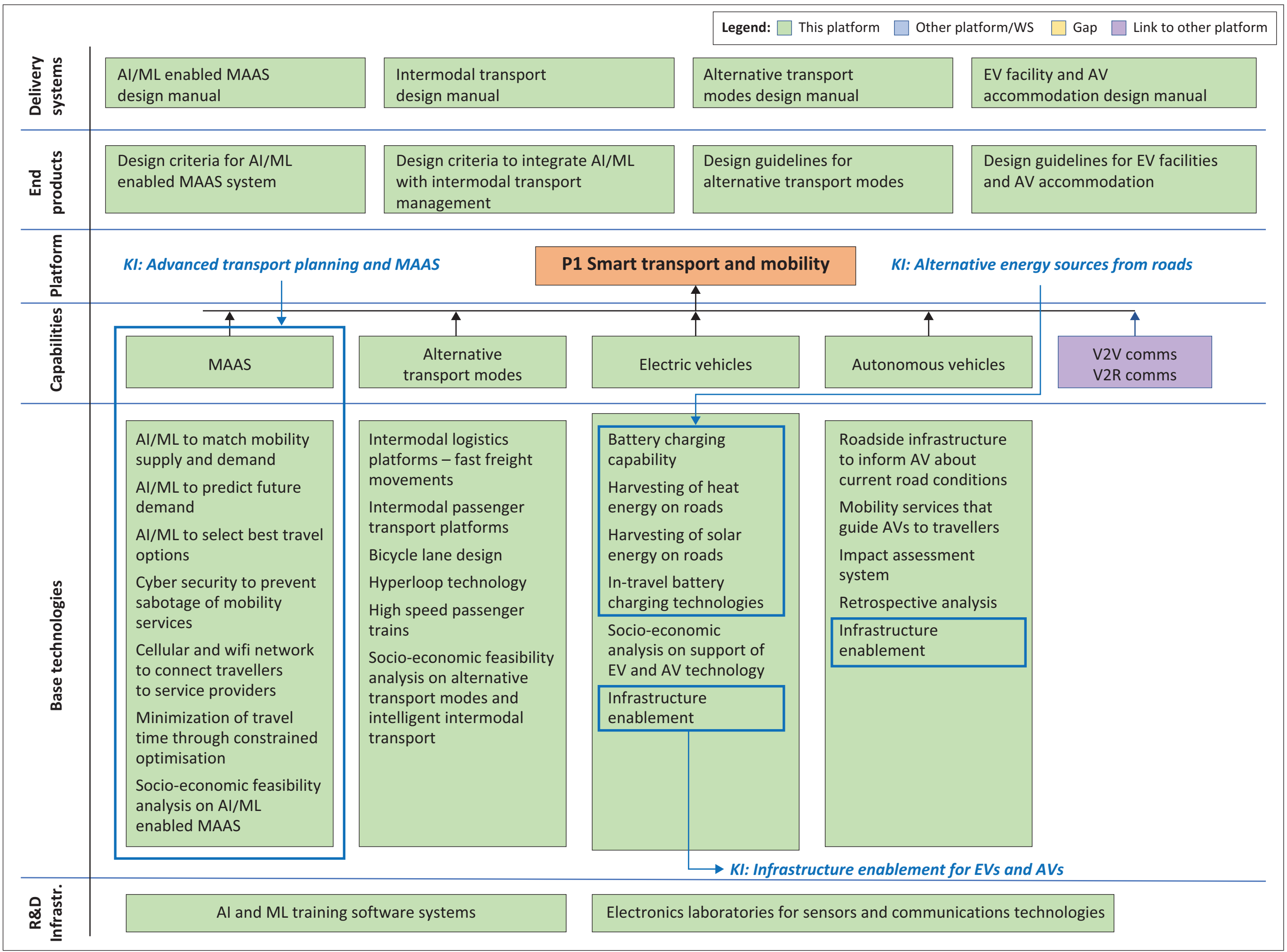
or R&D) can then be assessed and corrected to fit the programme's strategic objectives. These diagrams also provide a powerful way of depicting how the objectives of a research programme link to specific projects and are useful in communicating with researchers, stakeholders and funders.

In all 18 technology trees for the 18 platforms, listed earlier, were developed and used to assess the potential gaps in knowledge based on the list of 30 futuristic KIs. The KIs were developed to provide an indication of what capabilities and base technologies would be required to develop the KSs. This analysis highlighted the importance of Data Sciences and ML, and led to the development of the 18th platform and technology tree on data sciences. The analysis also identified a number of supporting KIs that are required to operate and implement the results of the SANRAL R&D programme:

- Technical and managerial training courses;
- Systems for an optimised R&D programme including a research impact assessment system;
- Effective and relevant stakeholder communication systems and
- Transformation and participation of communities to identify needs.

As examples the technology trees and their associated Key Interventions for the following platforms are shown:

- P1: Smart transport and mobility (see Figure 5);
- P2: Smart transport infrastructure (see Figure 6);
- P6: Pavement materials technology and testing (see Figure 7);
- P8: Pavement testing and performance (see Figure 8);
- P13: Road safety engineering and technology (see Figure 9) and



AI, Artificial Intelligence; ML, Machine Learning; MAAS, Mobility as a Service; V2V, vehicle-to-vehicle; V2R, vehicle-to-road; EV, Electrical Vehicles; AV, Autonomous Vehicles; KI, Key Interventions; R&D Infrastr., Research and development infrastructure; WS, Workshop.

FIGURE 5: Technology tree for smart transport and mobility.

- P18: Data Sciences Applications in Transport (see Figure 10).

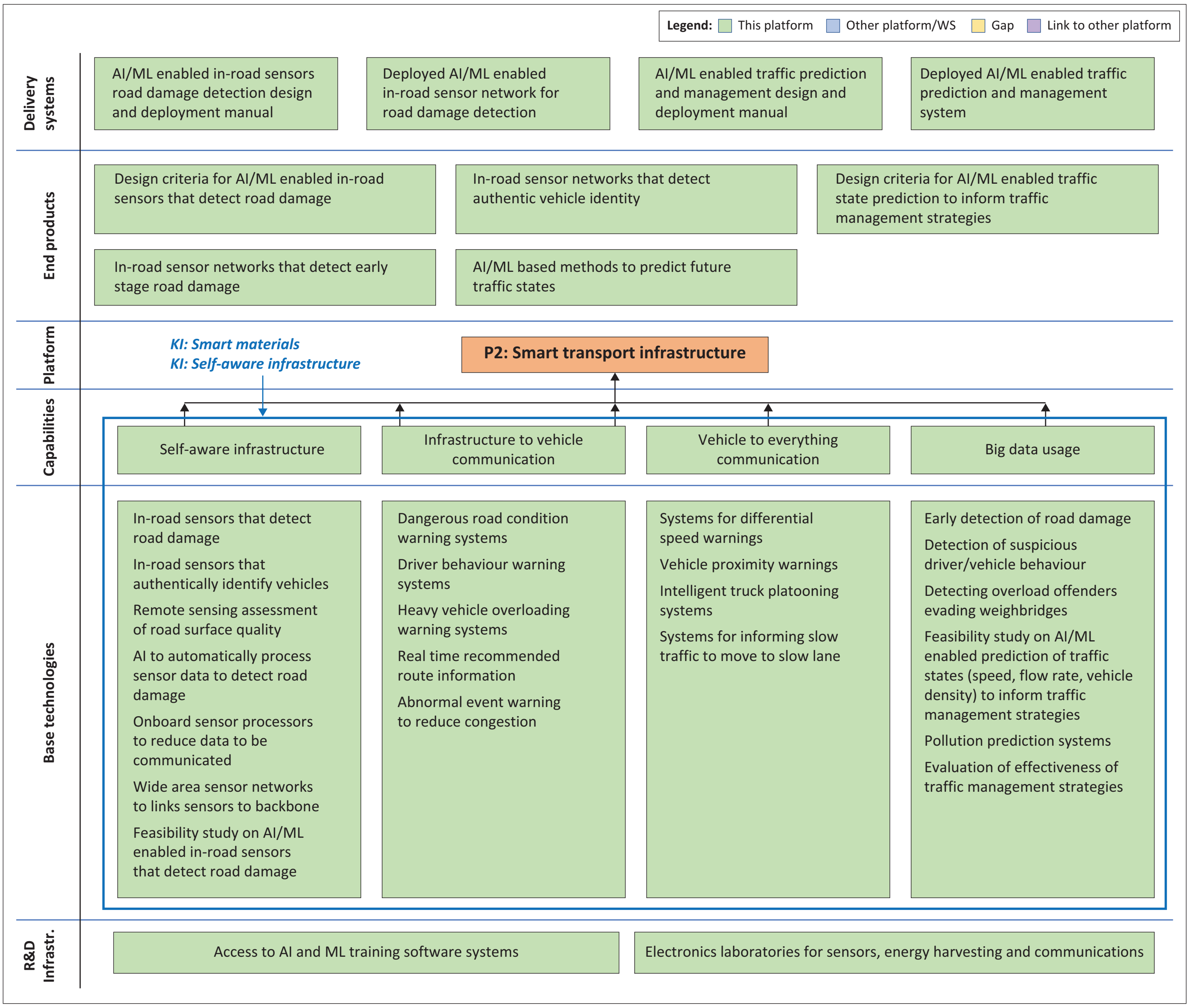
The KIs relating to a specific technology platform are shown in blue boxes. The elements inside a blue box will form the main basis for developing an R&D project plan to address the particular KI. As an example, in Figure 5, the project plan for the KI: Alternative energy sources from roads should consider:

- Battery charging capability;
- Harvesting of heat energy on roads;
- Harvesting of solar energy on roads and
- In-travel battery charging technologies.

In the process of project plan development and through initial desktop studies, additional aspects will be added.

From the technology trees, the following can be noted:

- The KIs plot in the lower half of the technology trees because of their technical, basic and applied R&D nature.
- However, they should be linked to the relevant end products and delivery systems during project proposal development to ensure eventual uptake.
- Some of the initial trees needed to be revised to emphasise elements of the KI explicitly and further revisions are likely as projects progress and technology develops.
- A number of the KIs appear in more than one technology tree and this should be considered during project proposal development.
- The technology trees form a hierarchy of their own with some trees supporting others. Examples are: 'Data Sciences' supporting 'Pavement testing and performance'; 'Material testing and technology' supporting 'Pavement structural design'; 'Pavement testing and performance' supporting 'Pavement structural design' and 'Data Sciences applications' supporting 'Transport planning' and 'Traffic management'.
- This implies that, for some projects, more than one technology tree should be consulted to ensure synergy and coordination between research teams.
- During project proposal development all levels of the technology trees should be taken into consideration to ensure that the full innovation value chain is addressed from R&D to implementation.



AI, Artificial Intelligence; ML, Machine Learning; KI, Key Interventions; R&D Infrastr., Research and development infrastructure; WS, Workshop.

FIGURE 6: Technology tree for smart transport infrastructure.

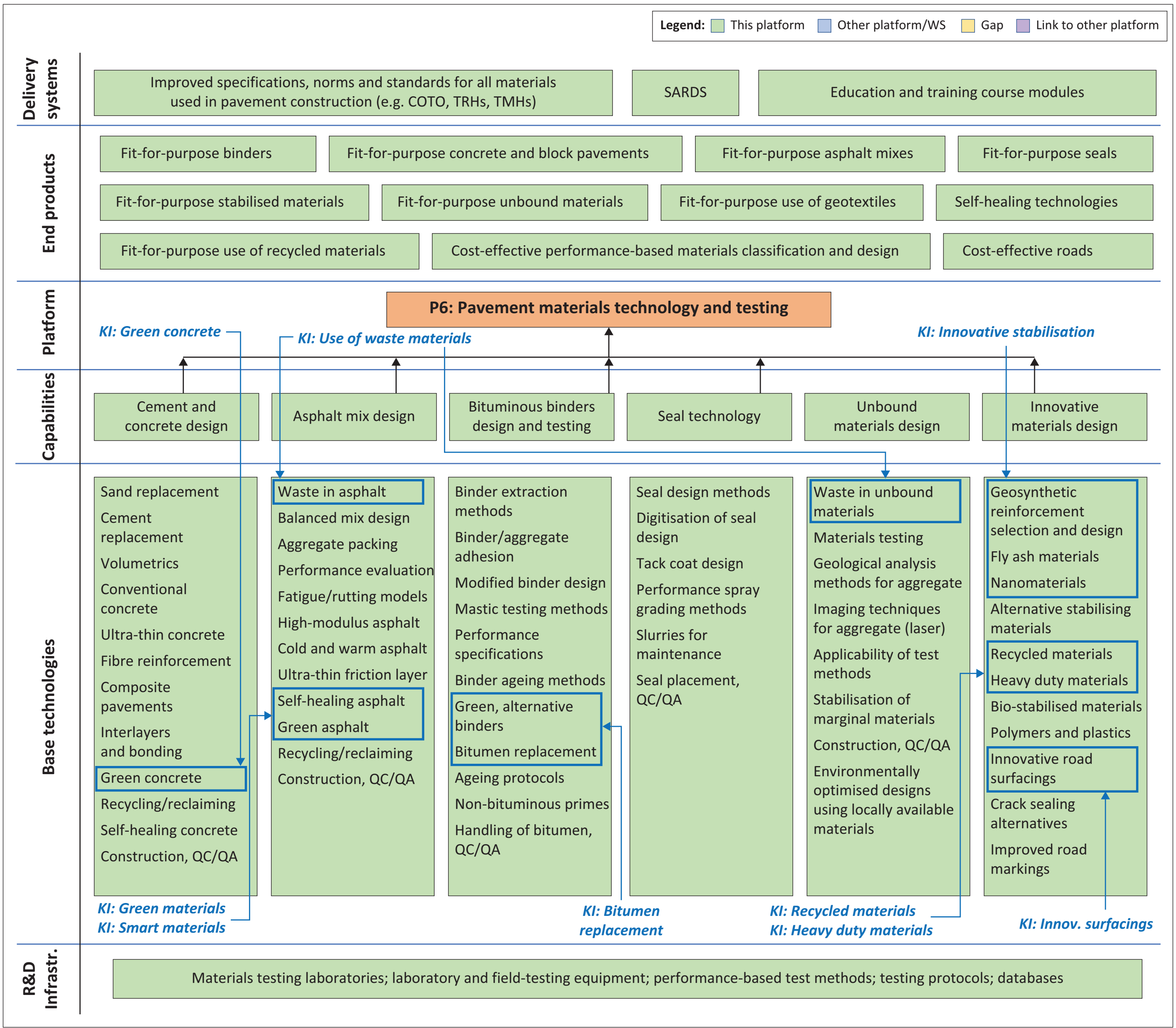
Discussion and conclusion

This study utilised a novel technique in Technology Foresight through the use of technology trees to develop a holistic picture of the R&D focus areas that the South African transport sector should be focussing on to position for the future. Techniques such as driver and trend analysis and scenario development have been used for Foresight both in South Africa and abroad. Several of the long-term drivers such as urbanisation and climate change have been defined before in Foresight studies. However, this study focussed very specifically on the role of new, emerging technologies such as AI, ML, sensor technology and smart materials technologies in positioning the transport sector for the future. The findings and results have taken international aspects and emerging technologies into account but also have a uniquely South African viewpoint and as such is most applicable to the South African transport sector.

The drivers, technologies and trends were used to develop five scenarios for the transport sector 15 years hence. Based on the analysis of interviews, stakeholder inputs and a literature review 12 thematic KSs and 30 futuristic KIs were defined that can shape the future of the transport sector and move it towards the Desired Future scenario. The relationship of the KIs to current knowledge was analysed using 18 hierarchical technology trees. Specific gaps in knowledge were identified and the technology trees were adjusted accordingly.

This analysis emphasised the following:

- Significant effort should be placed on the development of a technology platform that supports the application of data sciences technologies such as big data management and ML technologies to harness the utilisation of AI principles to improve the performance of the transport sector.
- The use of ML techniques to predict road pavement performance, traffic flow and traffic safety events need to form a critical part of future technologies;

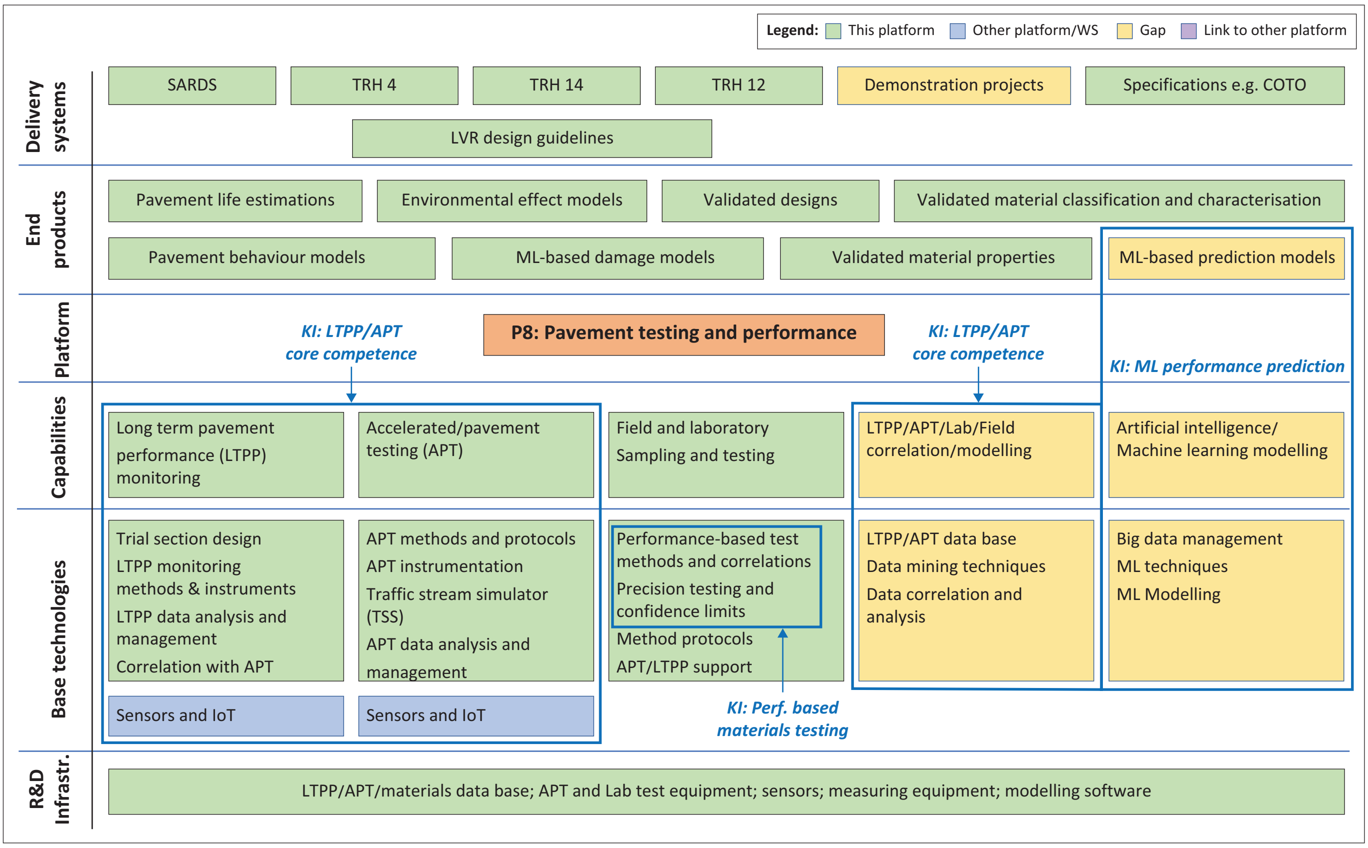


KI, Key Interventions; R&D Infrastr., Research and Development Infrastructure; COTO, Committee of Transport Officials; TRHs, Technical Recommendations for Highways; TMHs, Technical Methods for Highways; WS, Workshop; QC/QA, Quality control/Quality assurance; SARDS, South African Road Design System.

FIGURE 7: Technology tree for pavement materials testing and technology.

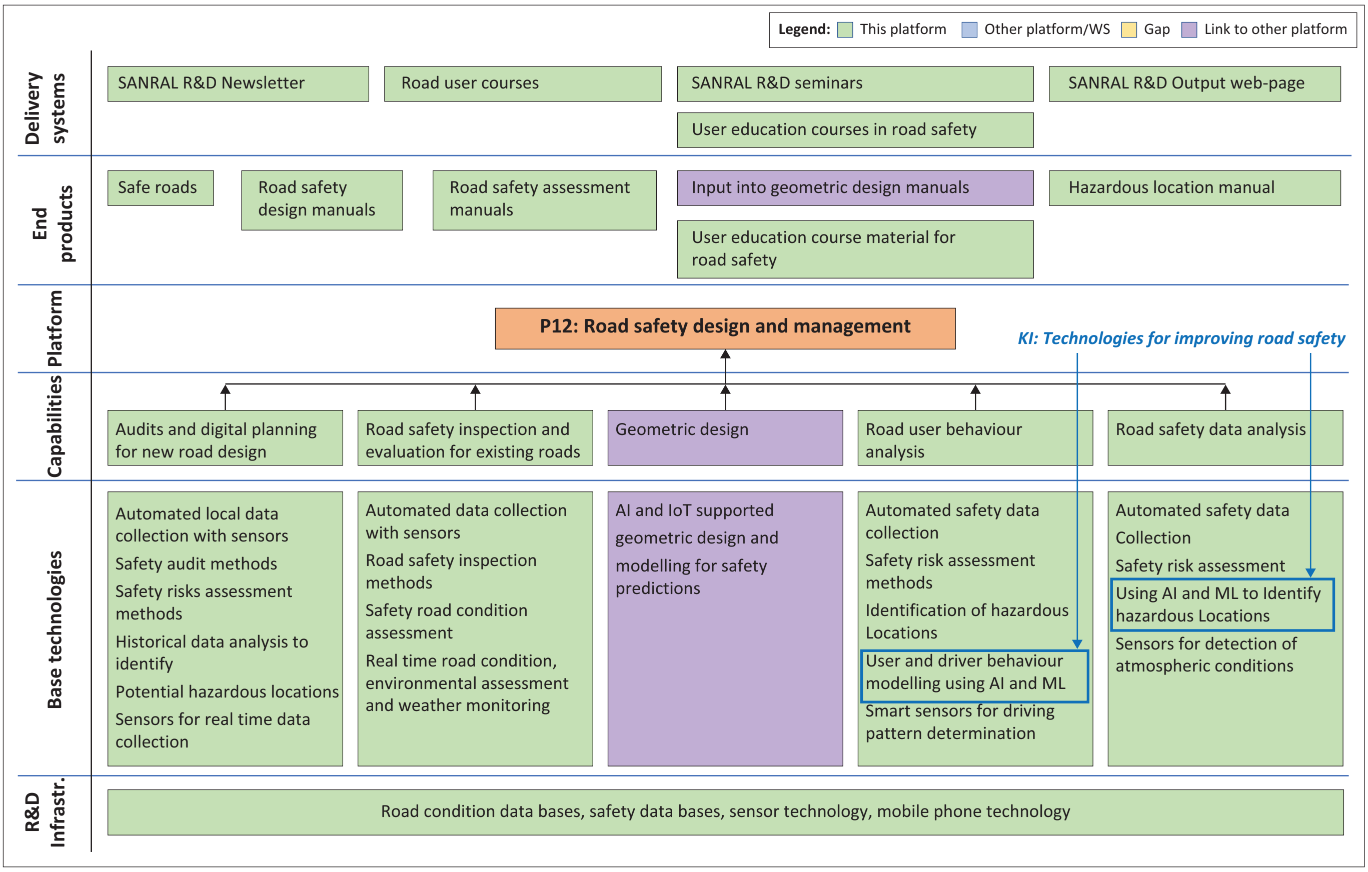
- Smart, self-aware transport and infrastructure utilising technologies such as embedded sensors, V2V and V2R technologies and the IoT will be required to position the transport sector for future EVs and AVs;
- In view of scarcity of good quality materials, new materials technologies focussing on a replacement for bitumen and the upgrading of low-quality materials using for example nano-technology will be required;
- Improved modelling of road pavement performance using data from LTPP and APT evaluations as input into self-learning, ML prediction models will be required to maximise road pavement performance in view of increased traffic loading;
- Designs, technologies, asset management systems and prediction technologies to address climate change impacts will need to be developed. This will include climate mitigation aspects such as green concrete as well as climate resilient designs and materials to prevent premature failures caused by extreme weather events such as flooding and high temperatures and
- In view of increased urbanisation and traffic volumes and loading, advanced traffic management systems and improved traffic safety technologies based on, *inter alia* ML techniques will be required.

Research question 1 pertaining to the identification of drivers and trends that will impact the transport sector was comprehensively addressed in the study through the identification of 42 drivers and 53 trends based on broad-based input from local and international participants. Research question 2 pertaining to the development of potential R&D focus areas that will position the transport sector was comprehensively addressed through the development of 30 futuristic KIs and their relationship with each other and existing knowledge as depicted in the 18 technology trees. The use of scenario development combined with the analysis



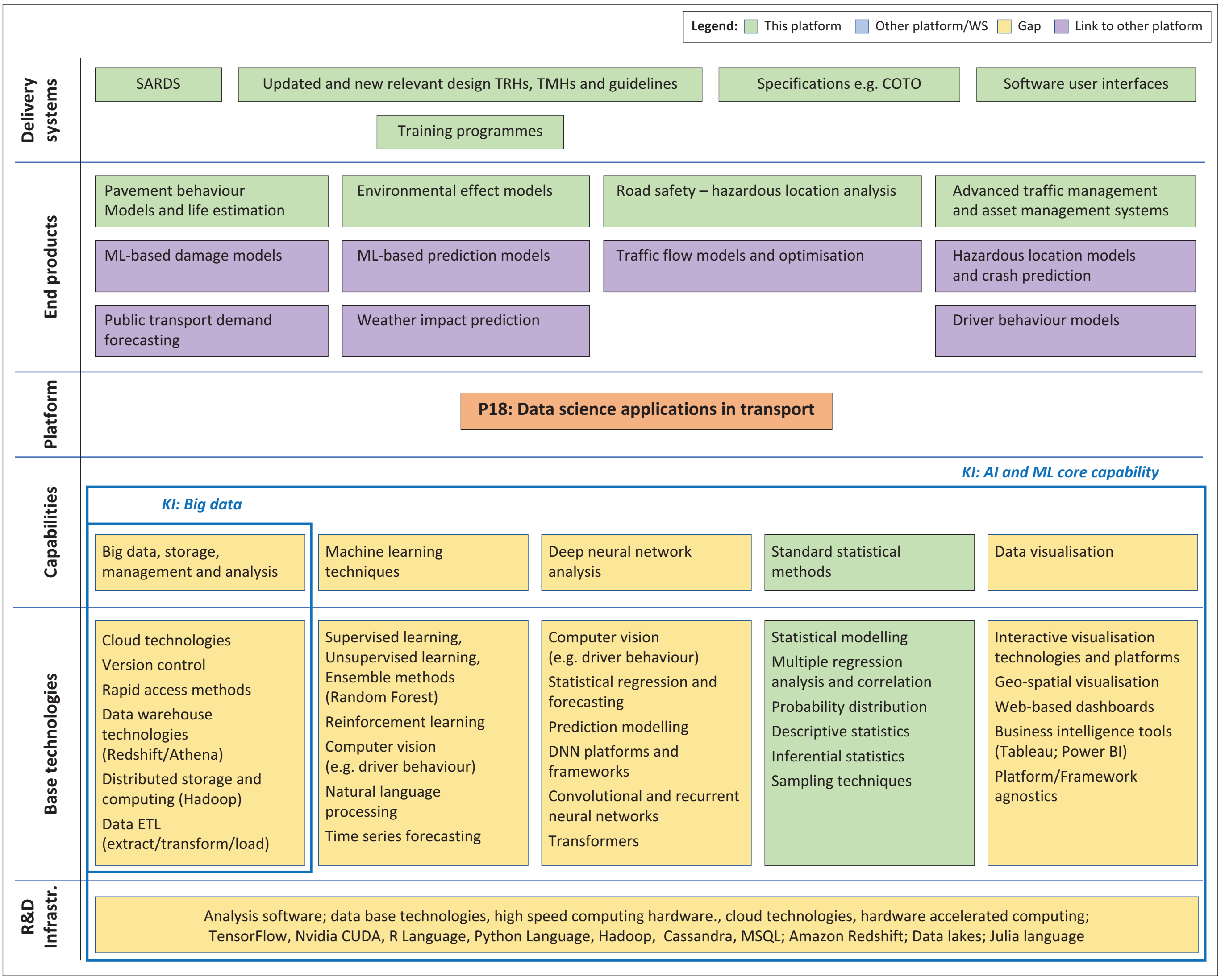
AI, Artificial Intelligence; ML, Machine Learning; LTPP, Long-Term Pavement Performance; APT, Accelerated Pavement Testing; BIM, Building Information Modelling; IoT, Internet of Things; KI, Key Interventions; R&D Infrastr., Research and Development Infrastructure; COTO, Committee of Transport Officials; TRH, Technical Recommendations for Highways; WS, Workshop; SARDS, South African Road Design System; LVR, Low Volume Roads.

FIGURE 8: Technology tree for pavement testing and performance.



AI, Artificial Intelligence; ML, Machine Learning; IoT, Internet of Things; KI, Key Interventions; R&D Infrastr., Research and development infrastructure; WS, Workshop.

FIGURE 9: Technology tree for road safety design and management.



AI, Artificial Intelligence; ML, Machine Learning; KI, Key Interventions; R&D Infrastr., Research and development infrastructure; COTO, Committee of Transport Officials; DNN, Deep Neural Network; TRHs, Technical Recommendations for Highways; TMHs, Technical Methods for Highways; WS, Workshop; SARDS, South African Road Design System.

FIGURE 10: Technology tree for data science applications in transport.

of the drivers and trends in the transport sector was effectively combined with technology tree analysis for the first time and will continue to be used as the SANRAL R&D programme progresses into the future. SANRAL has added these recommendations to their list of potential future research and innovation projects for further evaluation and approval.

Acknowledgements

Mr Imraan Akhalwa was a student member of the team and contributed to the early literature review.

Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

F.C.R. was the principal investigator and project leader. He contributed to all aspects of the article including conceptualisation, analysis, writing and editing of the article. L.R.S., A.A.C. and B.V. contributed to conceptualisation, analysis, writing and editing of the article. H.F., K.V. and S.L contributed to writing and editing of the article. M.S. and A.H. contributed to analysis and writing of the article. W.S. contributed to conceptualisation, writing and editing of the article.

Funding information

This research was funded by SANRAL SOC LTD. Project Number 1002/58600/2018/P1.4.

Data availability

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

Disclaimer

The views and opinions expressed in this article are those of the authors and are the product of professional research.

References

Andersen, A.D. & Andersen, P.D., 2014, 'Innovation system foresight', *Technological Forecasting & Social Change* 88, 276–286. https://doi.org/10.1016/j.techfore.2014.06.016

Bessant, J., Ramalingam, B., Rush, H., Marshall, N., Hoffman, K. & Gray, B., 2014, *Innovation Management, Innovation Ecosystems and Humanitarian Innovation*, Project report, UK Department of International Development, London.

Biznews, 2023, *SA transport woes: CRA macro review reveals economy struggles (biznews.com)*, viewed 14 November 2023, from https://www.biznews.com/sarenewal/2023/11/12/south-africas-transport-woes-cra-macro-review.

Cigu, E., Agheorghiesei, D.T. & Toader, E., 2019, 'Transport infrastructure development, public performance and long-run economic growth: A case study for the EU-28 countries', *Sustainability* 11(1), 1–22. https://doi.org/10.3390/su11010067

Dixon, T.J., Karuri-Sebina, G., Ravetz, J. & Tewdwr-Jones, M., 2023, 'Re-imagining the future: City-region foresight and visioning in an era of fragmented governance', *Regional Studies* 57(4), 609–616. https://doi.org/10.1080/00343404.2022.2076825

DSI, 2023, Survey shows that high proportion of R&D funding comes from government, Department of Science and Innovation, viewed 08 November 2023, from https://www.dst.gov.za/index.php/media-room/latest-news/3857-survey-shows-that-high-proportion-of-r-d-funding-comes-from-government.

Ejdys, J., Nazarko, J., Nazarko, L. & Halicka, K., 2015, 'Foresight application for transport sector', in M. Fiorini, & J.-C. Lin (eds.). *Clean mobility and intelligent transport systems*, pp. 378–400, Institution of Engineering and Technology, London.

European Union, 2005, Foresight for transport: A foresight exercise to help forward thinking in transport and sectoral integration, Final Report, EU contract number: GMA2/2000/32057 SI2.322291, European Union, Brussels.

Georghiou, L., 1996, 'The UK technology foresight programme', *Futures* 28(4), 359–377. https://doi.org/10.1016/0016-3287(96)00013-4

Gold, J., Jolliffe, P., Stewart, J., Glaister, C. & Halliday, S., 2024, Futures and foresight learning in HRD', *European Journal of Training and Development* 48(1/2), 133–148. https://doi.org/10.1108/EJTD-05-2022-0059

Hellenic Shipping News, 2023, *South Africa's ports and rail system facing imminent 'collapse'*, viewed 25 January 2024, from https://www.hellenicshippingnews.com/south-africas-ports-and-rail-system-facing-imminent-collapse/.

Ittmann, H.W., 2018, 'Logistics performance in South Africa', *Journal of Transport and Supply Chain Management* 12, 422. https://doi.org/10.4102/jtscm.v12i0.422

Ittmann, H.W., Mashoko, L., Nkuna, S., Petros, U. & Schnetler, M., 2016, *Transport sector analysis – National view*, CSIR Report, CSIR, Pretoria.

Lazarotti, V., Manzini, R. & Mari, L., 2011, 'A model for R&D performance measurement', *International Journal of Production Economics* 134, 212–223. https://doi.org/10.1016/j.ijpe.2011.06.018

Link, A.N., 1993, 'Methods for evaluating the return on R&D investments', in B. Bozeman & J. Melkers (eds.), *Evaluating R&D impacts: Methods and practice*, p. 2, Kluwer Academic Publishers, New York, NY.

Link, A.N. & Scott, J.T., 2013, 'The theory and practice of public-sector R&D economic impact analysis', in A.N. Link & N.S. Vonortas (eds.), *Handbook on the theory and practice of program evaluation*, pp. 15–55, Edward Elgar Publishing, Cheltenham.

Lyons, G., 2022, 'The driverless cars emulsion: Using participatory foresight and constructive conflict to address transport's wicked problems', *Futures* 136(2022), 102889. https://doi.org/10.1016/j.futures.2021.102889

Magoutas, A., Manolopoulos, D., Tsoulfas, G.T. & Koudeli, M., 2023, 'Economic impact of road transportation infrastructure projects: The case of Egnatia Odos Motorway', *European Planning Studies* 31(4), 780–801. https://doi.org/10.1080/09654313.2022.2082243

Marinković, M., Al-Tabbaa, O., Khan, Z. & Wu, J., 2022, 'Corporate foresight: A systematic literature review and future research trajectories', *Journal of Business Research* 144, 289–231. https://doi.org/10.1016/j.jbusres.2022.01.097

Mauksch, S., Von der Gracht, H.A. & Gordon, J.J., 2020, 'Who is an expert for foresight? A review of identification methods', *Technological Forecasting and Social Change* 154, 119982.https://doi.org/10.1016/j.techfore.2020.119982

Meyer, M.H. & Utterback, J.M., 1993, 'The product family and the dynamics of core capability', *Sloan Management Review* 34, 29–47.

Meyer, T., Von der Gracht, H.A. & Hartmann, E., 2022, 'Technology foresight for sustainable road freight transportation: Insights from a global real time Delphi study', *Futures & Foresight Science* 4, e202. https://doi.org/10.1002/ffo2.101

Moqaddamerad, S. & Ali, M., 2024, 'Strategic foresight and business model innovation: The sequential mediating role of sensemaking and learning', *Technological Forecasting and Social Change* 200, 123095. https://doi.org/10.1016/j.techfore.2023.123095

Navarro-Ligero, N.L. & Valenzuela-Montes, L.M., 2022, 'Scenario archetypes in urban transport planning: Insights from the implementation of LRT systems', *Transport Policy* 118(2022), 152–164. https://doi.org/10.1016/j.tranpol.2022.02.002

Ng, C.P., Law, T.H., Jakarni, F.M. & Kulanthayan, S., 2018, 'Relative improvements in road mobility as compared to improvements in road accessibility and urban growth: A panel data analysis', *Transportation Research Part A. Policy and Practice* 117, 292–301. https://doi.org/10.1016/j.tra.2018.08.032

Olaniyi, F.G., Olaniyi, O.O., Adigwe, C.S., Abalaka, A. & Shah, N.H., 2023, 'Harnessing predictive analytics for strategic foresight: A comprehensive review of techniques and applications in transforming raw data to actionable insights', *Asian Journal of Economics, Business and Accounting* 23(22), 441–459. https://doi.org/10.9734/ajeba/2023/v23i221164

Pouru-Mikkola, L., Minkkinen, M., Malho, M. & Neuvonen, A., 2023, 'Exploring knowledge creation, capabilities, and relations in a distributed policy foresight system: Case iFinland', *Technological Forecasting and Social Change* 186(Part B), 3–4. https://doi.org/10.1016/j.techfore.2022.122190

Ringland, G., 2010, 'The role of scenarios in strategic foresight', *Technological Forecasting & Social Change* 77(9), 1493–1498. https://doi.org/10.1016/j.techfore.2010.06.010

Rust, F.C., 2009, 'A systems approach to managing R&D in the road infrastructure sector in South Africa', PhD thesis, University of the Witwatersrand.

Rust, F.C., 2010, 'Critical requirements for a systems-based R&D management process', in *CSIR biennial conference: 'Science real and relevant'*, 31 August–01 September 2010, CSIR, Pretoria.

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.

Rust, F.C., Sampson, L.R., Cachia, A.A., Verhaeghe, B.M., Fourie, H.S. & Smit, M.A., 2023, 'Use of causal loop diagrams to assess future drivers and trends in the South African road transport sector', *Journal of Transport and Supply Chain Management* 17, a958. https://doi.org/10.4102/jtscm.v17i0.958

Rust, F.C., Sono, P., Van Dijk, G., Fourie, H.S. & Smit, M.A., 2021, 'Conceptualising a benefit assessment framework for the South African National Roads Agency Ltd SOC Research and Development Programme', *Administratio Publica* 29(3), 19–43.

SAICE, 2022, *SAICE 2022 infrastructure report card for South Africa*, South African Institution of Civil Engineering, Midrand.

SANRAL, 2017, *SANRAL strategy: Horizon 2030*, The South African National Roads Agency, Pretoria.

SANRAL, 2021, South African Transport Technology Foresight Study 2035: Foresight report and input into SANRAL R&D portfolio, South African National Roads Agency SOC Ltd, SANRAL, Pretoria.

SANRAL, 2022, Technology foresight study: Report on scenarios and technologies, SANRAL Project report, SANRAL, Pretoria.

SANRAL, 2023a, Integrated report 2022/23, vol. 1, SANRAL, Pretoria.

SANRAL, 2023b, Technology foresight study: Final report, SANRAL, Pretoria.

Sarpong, D., Boakye, D., Ofosu, G. & Botchie, D., 2023, 'The three pointers of research and development (R&D) for growth-boosting sustainable innovation system', *Technovation* 122(2023), 102581. https://doi.org/10.1016/j.technovation.2022.102581

Schwab, K., 2017, *The fourth industrial revolution*, Crown Publishing Group, Division of Random House Inc, Penguin Random House, London.

Szathmári, A., Köves, A. & Gáspár, J., 2024, 'Human-centred decision support for the common good: A combination of participatory foresight methods', *Journal of Decision Systems* 1–15. https://doi.org/10.1080/12460125.2024.2345946

Teuteberg, S. & Aina, I., 2021, *Transport sector report*, Labour, Research Service, Cape Town.

The World Bank, 2014, *Transport: Sector results profile*, viewed 12 December 2019, from http://www.worldbank.org/en/results/2013/04/14/transport-results-profile.

The World Bank, 2022, *Logistics performance index: Overall (1=low to 5=high) - South Africa,* viewed 20 May 2024, from https://data.worldbank.org/indicator/LP.LPI.OVRL.XQ?locations=ZA.

Zhang, X., 2013, 'Has transport infrastructure promoted regional economic growth? – With an analysis of the spatial spillover effects of transport infrastructure', *Social Sciences in China* 34(2), 24–47. https://doi.org/10.1080/02529203.2013.787222