MALAWI CCDR

Transport Sector Background Note: Road Transport Criticality and Resilience

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Abbreviations and Acronyms

GDP Gross Domestic Product  
HDM4 Highway Development and Management Model (version 4)  
Km kilometer  
MW2063 Malawi Vision 2063  
NTMP Malawi National Transport Master Plan  
RAI Rural Access Index  
RONET Road Network Evaluation Tools  
SATCC Southern Africa Transport and Communications Commission

All dollar amounts are US dollars unless otherwise indicated.
Climate Vulnerability: An Economic Risk Assessment of Malawi’s Road Transport Infrastructure

Executive Summary

Climate models indicate that Malawi is confronted with the significant likelihood of increased frequency and intensity of extreme climatic events, such as flood, droughts, and landslides. Over the past decade, Malawi has experienced several catastrophic floods that have damaged or destroyed road and bridge assets, in addition to causing widespread economic disruptions impacting agriculture, water, irrigation, and infrastructure. Evidence provided in Malawi Road Authority’s initial damage assessment conducted after Tropical Storm Ana in January 2022, which records more than US$67 million in damages to more than 2,500 km of roads, as well as dozens of bridges, culverts and other drainage structures, with recovery needs likely to exceed US$160 million.

This transport sector technical note presents a high-level road network criticality analysis to complement the Malawi Country and Climate Development Report (2022). A summary of its main findings includes the following:

- The road network is exposed to a significant climate change risk in Malawi. Approximately 4,350 km of the country’s classified road network (of about 15,551 km) is potentially affected by 1 in 50-year fluvial flooding, of which 3,600 km (34 percent) of the network is likely to be disrupted. About 1,400 km is assessed to be in poor condition and thus considered as highly susceptible to heavy rain and flood.

- A main north-south corridor, National Road M1 remains the most critical road corridor, essentially serving as the core to Malawi’s road network. Other primary north-south connectors and regional corridors (M3 and M5, particularly) are also of high criticality. Without these roads, the total trip duration to connect the major cities would increase by up to 27 percent. Key secondary and tertiary routes are also considered vital to reducing economic risks by ensuring network resilience within the Northern (S100, T303), Central (S125, T358), and Southern (S129, S137, S152, T423) regions. For agricultural growth and food security purposes, the climate resilience of these roads is vital for ensuring sustainable access.

- The total economic risk of climate events to the road network is estimated at US$163 million per year, which is equivalent to about 1.3 percent of the country’s GDP. The estimated potential annual damage to infrastructure is about US$4.3 million (extreme events not withstanding), while the potential disruption costs amount to approximately US$158 million per year.

- Malawi’s total investment needs for adaptation and resilience (through 2037) is estimated to be between US$437 million and US$1.75 billion, with a potential cost-benefit ratio of between 1.7 and 2.7 based on investment scenarios and selected discount rate for respective projects.

Key interventions that Malawi can pursue to improve road network resilience and adaptation include:

- **Introducing a statutory mandate to conduct integrated Climate Risk and Vulnerability Assessments for all transport infrastructure projects.** If Malawi is to reduce its long-run costs related to reconstruction or asset recovery, resilience planning and adaptation measures must be identified, considered in the economic and financial appraisal process, and addressed through either structural or non-structural interventions, especially for the county’s road and bridge network. Such a mandate would codify the stated objectives of the National Transport Policy (2019), which is to integrate resilience and adaptation into construction of public infrastructure assets.

- **Development of contemporary road asset management system and prioritization framework.** A geo-referenced database of road assets and conditions is essential to enabling more robust
assessments of the core network’s climate vulnerability and exposure risks. Such tools are critically important to ensuring investment efficiency, where annual road work programs are prioritized through multi-criteria analysis capable of evaluating network criticality, climate vulnerability, incidence of poverty in adjacent areas, and proximity to potential agriculture clusters and agri-businesses. Road assets, as well as other transport assets, must also be captured as part of a national database of critical public infrastructure.

- **Undertaking a comprehensive assessment of Malawi’s road and bridge infrastructure inventory and condition.** Data and analysis of aging and risk-exposed structures would then form a basis to develop a prioritized Bridge Replacement and Maintenance Plan, with identified interventions based on network criticality. Cross-ministerial collaboration will also be vital in accessing current meteorology data and revising hydrology standards, as the Malawi "Guidelines for peak flood estimation for design of culverts and bridges and design of spillways of dams" (1987) are exceedingly outdated.

- **Adapting technical and design standards to Malawi’s specific geographic, environmental, and operational context.** The Southern Africa Transport and Communications Commission (SATCC) road standards, which are still in draft form, were intended to be used on the regional trunk road network and do not provide for local variations in climate and materials that might affect the design of lower traffic road networks nor cover requirements for hydrology, drainage design, or road maintenance. Bringing the Malawi Road Authority, Malawi Bureau of Standards, Central Materials Laboratory, National Construction Industry Council and University programs together to collaborate on sector research and development to improve enforcement of codes and standards is crucially important to the adaptation agenda.

- **Crisis Response mechanisms that provide immediate emergency recovery support following an eligible crisis or emergency are needed.** Rapid recovery and reconstruction require that Malawi’s Road Authority and Road Finance Administration have in place adequate contingency plans, which should include both financial arrangements, such as credit lines or insurance products, as well as measures that facilitate road network restoration through prearranged contracts for civil works and emergency services.
Background

1. A small, landlocked, and largely agrarian country, Malawi is considered one of the most vulnerable countries to climate change. The lack of reliable transport infrastructure and services is emerging as one of the most pressing constraints to Malawi’s economic growth prospects. Agriculture contributes to about 26 percent of gross domestic product (GDP) and 72 percent of employment, with the vast majority in small-scale farming with low returns. Trade accounts for 65.3 percent of GDP, and 80 percent of export earnings are in agriculture. Tobacco is the most important commodity, making up more than half of exports. The country’s economic performance remains subdued and fluctuating due to slow diversification and vulnerability to external shocks, including extreme climate events.

2. While Malawi has rail, air, and water transport, its landlocked status creates an over-reliance on road transport, accounting for 99 percent of passenger services, 70 percent of domestic freight, and 90 percent of international freight. International transport costs have an influence across the economy, and the high cost of internal freight transport has a major impact on agricultural commercialization given the low value of mostly unprocessed agricultural products. Imports to Malawi primarily come through four ports: Beira in Mozambique, Durban in South Africa, Dar es Salaam in Tanzania, and Nacala in Mozambique. Most cargo, even bulk freight, is transported by road despite long distances to seaports (for example, over 600 km between Blantyre and Beira). In 2020, most of Malawi’s import and export cargo was handled at the Ports of Beira and Durban and transported entirely by road through both Dedza and Mwanza border crossings on Malawi’s western border with Mozambique. An overreliance on a road transport network in poor condition, lack of competition due to cabotage rules favoring vested interests in a small haulage industry, as well as high landed fuel costs all combine to significantly reduce the overall competitiveness of Malawi’s exports and increase the price of key imports.

3. Malawi’s Road Network. In functional terms, the main, secondary, and tertiary roads effectively make up the country’s primary network, with district, urban and other undesignated roads acting as a feeder system to the primary network. Detailed road condition data on Malawi’s total classified road network of approximately 15,551 km is limited; the main road network is mostly paved and reasonably well-maintained, but the overall quality has deteriorated over recent years. The secondary and tertiary roads, which accounts for nearly 75 percent of the total network, are largely unpaved and remain in poor condition because of a lack of proper maintenance and insufficient funding. It is estimated that only 23.1 percent (2016) of the rural population has access to an all-season road, leaving about 11 million people unconnected. While the Rural Access Index (RAI) is relatively high around large cities such as Blantyre, Lilongwe and Karonga, the index tends to be generally low in remote, hilly or hinterland areas.

4. Strategic Climate Change Adaptation Action Plan. The National Transport Master Plan (2017-2037) outlines a Strategic Climate Change Adaptation Action Plan as a framework for advancing climate change management and disaster risk reduction objectives specific to Malawi’s transport sector. Climate sensitivity and exposure analyses for Malawi’s roads, tunnels, and bridges reflect the high vulnerability risk that the dual threats of heavy rainfall and flooding, as well as ground subsidence, present to the country’s road network. Though higher temperatures and increased solar radiation will reduce the lifecycle of paved road surfaces, the more dangerous threat to the road network is the level of damage to bridges, culverts, embankments and other drainage structures, due to more intense rainfall and run-off. During the rainy season numerous sections become impassable, limiting access to markets and services.

5. Past extreme events - the January 2015 Shire Valley flooding and Cyclone Idai in March 2019 - highlight the high exposure risk and resultant damage or asset losses in the road sector. Wide swaths of the road network were affected and transport connectivity disrupted. Damage to roads
accounted for nearly half of the total estimated US$370.5 million recovery and reconstruction costs related to these two events. Most recently, Tropical Storm Ana, which struck Malawi and Mozambique in late January 2022, caused catastrophic flooding and washouts across several central and southern Malawi districts, impacting agriculture, water, irrigation, and infrastructure, including disruption to major roads and bridges, impairing emergency response, leaving people in need of humanitarian assistance and delaying recovery efforts. The initial assessment suggests more than US$67 million in damages to more than 2,500 km of roads, as well as dozens of bridges, culverts and other drainage structures, with recovery needs likely to exceed US$160 million.
A high-level road transport network criticality analysis

6. Assigning a level of criticality to transport links and nodes to determine the loss of network functionality (including travel time and cost) can support selectivity by targeting adaptation measures on the network’s most important linkages, specifically those that would create the greatest disruption when functionality is lost. “A highly resilient transport network can lose many assets (such as road segments) without losing much functionality”. Criticality analyses can therefore identify investments in stronger bridges, higher capacity culverts or improved slope protection that can ultimately lower the expected annual costs for road users, due to flood disruptions, by increasing the resilience of a network and generating positive economic returns.

7. The analysis is conducted by: (i) developing a simple but practical tool to assess climate exposure and vulnerability to potential ruptures in the road transport network; (ii) applying Malawi’s terrestrial and climate data to identify prospective priority areas to target for road upgrading and maintenance that improves the resilience of the network; and (iii) estimating the potential economic impact of climate-related losses to road transport infrastructure and the broader economy. The analysis can, therefore, inform several policy and planning initiatives necessary to ensure that measures to improve climate resiliency in the road sector contribute to Malawi’s development agenda.

8. Although there are different definitions and views, an overall framework to assess “resilience” of transport infrastructure (or services) is essentially dependent on four factors: (i) climate exposure, (ii) resilience of infrastructure, (iii) resilience as a network, and (iv) economic exposure or valuation. Applying this methodology assists in understanding the potential benefits of various climate adaptation measures and targeted actions.

Figure 1: Framework for Assessing Resilience
9. **Climate risk exposure.** The climate risk to infrastructure is generally determined by the degree of exposure to and resilience of transport assets to extreme events. While precipitation causes road conditions to deteriorate over time in the absence of proper maintenance, its more immediate effects are to vehicle stability and road traffic, where disruptions generally occur with more than 250 mm flood height. Malawi has sizable areas that are prone to flooding, especially in the south. For transport infrastructure, “resilience”, which is formally defined by the adaptive response of a system to stress, is generally determined by two factors: resilience of the infrastructure asset, and resilience as a network through system redundancies.

![Figure 2: Change in road conditions by rainfall per month](image)

![Figure 3: Vehicle speed and extreme rainfall](image)

![Figure 4: Length of roads in flood prone areas](image)

10. **Resilience of infrastructure.** From an engineering perspective, infrastructure resilience refers to the ability of a system to prepare for, absorb, recover from, and adapt to disturbances. In general, roads with adequate drainage structures, such as culverts and swales, are more resilient than those without them. Poorly maintained and/or unpaved roads are generally vulnerable to climate events. Since the road conditions are inversely related to the structural number, it is assumed that the resilience is the inverse of the observed roughness. When applying a standard damage
factor for transport infrastructure, it is further assumed that the loss of road asset value would be proportionally dependent on the depth of flood.

**Figure 5: Standard roughness scale by surface type**

![Roughness Scale Diagram](image1)

Source: Sayers et al. (1986).

**Figure 6: Standard damage factor of transport infrastructure**

![Damage Factor Diagram](image2)


11. Poorly maintained and/or unpaved roads are generally more vulnerable to climate events. In Malawi, about 28 percent of the classified road network is paved. There are 4,312 km of paved and 11,139 km of unpaved roads. In addition, 9,478 km of undesignated and undesigned community roads complement Malawi’s classified road network. Though detailed road network
condition data is unavailable in Malawi, a road condition survey conducted in 2016 using a mobile phone-based application indicates that about one-third of paved roads are in good condition, while nearly half of unpaved roads are in poor condition. This analysis estimates that approximately 4,350 km of Malawi’s classified road network is potentially affected by 1 in 50-year fluvial flooding, of which 3,600 km (34 percent) of the classified network are likely to be disrupted. Among the roads that are located to flood prone areas, about 1,400 km are in poor condition. These roads are highly susceptible to heavy rainfall and flooding.

12. **Resilience as a network.** As transport infrastructure functions as a network, resilience is also achieved through system redundancies. Also referred to as robustness, redundancy, and criticality, a network is more resilient when it comprises alternative routes and/or alternative transport options. Several studies involving hydraulic simulations and traffic forecasts examine the impact of road closure. Using spatial data and software, the impact of road closure is estimated as a proxy of climate vulnerability by measuring the additional time required to take a detour.

13. The criticality of road link $k$ is defined by:

$$criticality_k = \frac{\sum_i \sum_j t_{ij}^k}{\sum_i \sum_j t_{ij}^*}$$

$I$ and $J$ represents the origin node and the destination node, respectively. $t^*$ is the shortest travel time between node $i$ and $j$. This is the baseline case. On the other hand, $t^k$ represents the shortest travel time between node $i$ and $j$ when road link $k$ is closed. In this case, the assigned route could be suboptimal, adding to more travel time, because a certain detour may have to be taken. To capture the whole network, $I$ and $J$ are defined by a set of all existing intersections of roads given a road network data.

14. The measured criticality shows how each road link is critical in the network. In general, the measurement decreases if there are an abundance of alternative routes. If there are few alternative routes, the criticality increases because travelers are forced to take a long detour. Of note, the constructed index is influenced by both the relative quality or connectivity of road in question as well as in relation to asset conditions in the surrounding area. If only one road is in particularly good condition in a certain area, thereby allowing higher speeds and wider access, than that road is of higher criticality. Alternatively, if a road is in good condition but other roads are also in good condition, then the measured criticality may not be as high.

15. **Road network criticality analysis.** The analysis draws on 2016 road condition data (and is determined based on network engineering parameters, without consideration of actual mobility or travel demand for freight and passenger movements). The twenty largest enclaves are considered, of which the total population is about two million, or 60 percent of the country’s urban population. Not surprisingly, the key north-south roads, such as M1, M3, and M5 have the highest criticality. The primary trunk of the North-South corridor is considered particularly critical. Without these roads, the total trip duration to connect the major cities would increase substantially by up to 27 percent.
16. **Economic criticality.** To gain a more complete picture of overall road network criticality, the analysis must consider the relative economic importance of each road segment or corridor, reflecting the enabling role that road networks provide in connecting productive regions to markets. Ideally, this is captured through detailed traffic counts representing the volume (or value) of traffic generated among all possible pairs of origins and destinations. By integrating traffic $g_{ij}$ in the above criticality analysis as weights, the economic criticality is calculated by:

$$
economic \, criticality_k = \frac{\sum_i \sum_j g_{ij} t_{ij}^k}{\sum_i \sum_j g_{ij} t_{ij}^*}$$

where $g_{ij}$ represents the trip demand between origin $i$ and destination $j$. Thus, the expected delay caused by road closure at link $k$ is amplified by the traffic volume between each OD pair. As origin-destination matrices are not readily available, it is estimated by using a gravity model, which is the simplest common procedure of trip distribution:

$$g_{ij} = A o_i d_j f(t_{ij})$$

where $A$ is a constant term, and the economic significance of origin and destination, often called by the trip production and the trip attraction, is denoted by $o_i$ and $d_i$, respectively. $f(\bullet)$ is a deterrence function between the two locations, which is assumed to be $f(t_{ij})=e^{-t_{ij}}$. Thus, the trip demand is proportional to the economic significance at the origin and destination node and negatively weighted with the deterrence between them, which is determined by travel time $t$ between nodes $i$ and $j$. The economic significance differs depending on context. (See Annex 1).

17. Two key factors are considered in analyzing the economic criticality of Malawi’s road network. The first is focused on rapidly urbanizing areas and the primary movements among them. The 20 largest enclaves are treated as both origins and destinations. This is expected to represent the overall inter-city traffic patterns. The second estimate is focused on agricultural growth. While 256 traditional/local administration areas are considered as origins, the 20 largest cities are assumed to be their destinations. Thus, the predicted traffic generation is expected to capture the transport demand for moving agricultural produce to major consumption areas. With the inter-city traffic estimates, the distribution of economic criticality is likely to be more skewed towards the major roads connecting larger and more dense cities in the center and south of the country.

18. National Road M1 remains the most critical road corridor, essential serving as a core lifeline to Malawi’s road network. With crop production data, agricultural criticality is still concentrated along major cities, but has a more radial quality, as many agricultural areas surrounding the major cities contribute substantially to agricultural gravity. Because these agricultural areas are
geographically dispersed, there are several critical secondary and tertiary road segments leading to the two major economic poles of Blantyre and Lilongwe. Secondary and Tertiary routes are also considered vital to reducing economic risks by ensuring network resilience within the Northern (S100, T303), Central (S125, T358), and Southern (S129, S137, S152, T423) regions. For agricultural growth and food security purposes, increasing the climate resilience of these roads is vital for ensuring sustainable access.

19. **Economic risk of transport infrastructure vulnerability.** The potential impact of climate events on road transport infrastructure is determined through two additional lenses: (i) damage to infrastructure, and (ii) disruption to mobility. The damage to specific road assets is primarily dependent on the level of potential climate exposure and the degree of resilience of each infrastructure asset. The disruption to mobility is determined by climate exposure and to transport assets and their resilience as a network.

\[
\begin{align*}
\text{Potential economic impact} &= \text{Damage of infrastructure} + \text{Disruption cost} \\
\text{Damage of infrastructure} &= \text{Climate exposure} \times \text{Resilience of infrastructure} \times \text{Asset value} \\
\text{Disruption cost} &= \text{Climate exposure} \times \text{Resilience as a network} \times \text{Value of time}
\end{align*}
\]

The following additional assumptions are made, variables for which can be modified depending on country or local context:

- **Origin and destination.** Potential mobility between agricultural production areas (districts) and major cities is considered.
- **Climate hazard:** 1-in-50-year fluvial flood.
- **Damage factor:** Proportional to flood depth (up to five meters).
- **Resilience of infrastructure:** Inversely related to the observed road conditions observed in the 2016 data. The assumed damage mitigation varies from 10 to 40 percent, depending on the road conditions.
- **Asset values:** US$600,000 per km for paved road, US$100,000 per km for unpaved road. This analysis uses recent road reconstruction unit costs.\(^1\) Ideally, this should be defined by the asset value of the existing road network, which can be calculated by standard road management software, such as HDM4 or RONET model.
- **Potential traffic disruption:** A road is disrupted when flood depth exceeds 25 cm.
- **Duration of road closure:** 10 days.
- **Value of time:** Average delay costs of passengers and freights is estimated at US$2.47 per vehicle-hour, based on GDP per capita and average shipment value in Malawi services. (See Annex 2).

20. The total economic risk of climate events to the road network is estimated at US$163 million per year, which is equivalent to about 1.3 percent of the country’s GDP. Potential economic losses caused by road disruption can often be far greater than possible infrastructure damages. The estimated potential annual damage to infrastructure is about US$4.3 million (extreme
events not withstanding), while the potential disruption costs amount to approximately US$158 million per year. These results need to be understood with caution because they are highly sensitive (almost proportional) to the above assumed parameters. The asset value is likely to be underestimated because the true value of the infrastructure asset is greater than simple replacement costs. On the other hand, the disruption costs may be overestimated because expected deterrence is simply accumulated; there may exist a better route to avoid all affected roads.

21. In the end, more resilient infrastructure will generally cost more than current infrastructure designs. Not taking account of the climate adaptation inherently incorporated into major transport capital works programs, Malawi’s total investment needs for adaptation and resilience (through 2037) is estimated to be between US$437 million and US$1.75 billion, with a potential cost-benefit ratio of between 1.7 and 2.7, based on respective investment scenarios and selected discount rate.\textsuperscript{12} Regardless of climate change as a factor, the Malawi Government spends about US$100 million annually on the road sector. It is estimated that resilient roads cost 3 to 23 percent more than “normal” roads.\textsuperscript{13} Expected benefits from resilience are therefore likely to outweigh the potential additional costs required.
Resilience and Adaptation: Recommendations for Malawi’s Road Sector

22. Investment priorities that future-proof Malawi’s road transportation systems against climate shocks will be essential to network connectivity and resilience. The Malawi’s Vision 2063 (MW2063) Five-Year quick win intervention areas for the road sector are also laudable, although they face a range of policy and funding bottlenecks:

- **Increase the overall length of paved roads to above 50 percent by 2030, with a special focus on rural roads offering tourism and mining potential.** Ambitious and well intentioned, the nearly US$900 million in road upgrading investments envisaged in MW2063 present acute fiscal risks and industry capacity challenges. Related targets would place pressure on the road industry to provide 180-210 km of new or upgraded sealed roads annually, for a cumulative total of more than 2,300 km by 2030. In recent years, the average annual budget for both paved and unpaved road works was approximately MK74.1 billion (US$95 million), with a total of 287 kilometers of new road constructed between 2015-2020 (against a target of 490 kilometers), thereby achieving an equivalent turnover of nearly 60 km per annum at an investment cost of roughly US$600,000 per km. Construction sector outputs would therefore need to rise four-fold to achieve the MW2063 objectives.

- **Undertaking systematic maintenance and rehabilitation of road infrastructure, including in rural areas - largely constrained by the absence of a robust road asset management system capable of prioritizing and sequencing investments based on criticality and climate resilience across all levels of the road network.** Though Roads Authority's primary HDM4 tool used for paved road network management performs standard economic analyses, a more comprehensive and prioritized road infrastructure investment plan requires additional criteria, as well as consistent and reliable data collection.

- **Decentralizing road maintenance by emulating aspects of District Infrastructure Roads Maintenance Programme** - which first requires a focus on identifying a consistent prioritization framework to rationalize annual programming, as well as allocation of adequate financial resources. Developing a comprehensive Rural Road Maintenance Strategy or Master Plan to identify, prioritize and invest in rural connectivity would facilitate the success of the decentralization agenda.

- **Setting and enforcing high technical standards for better infrastructure quality** - which invariably requires institutionalizing the recently updated construction standards and specifications for civil and building works. Greater emphasis and expectation must be placed on quality assurance systems, reliable material selection and testing, and ensuring that specifications for bitumen and asphalt designs are appropriately adjusted to site specific dynamics.

23. The National Transport Master Plan (2017-2037) urges Malawi to institute a statutory requirement for conducting an integrated Climate Risk and Vulnerability Assessment for all transport infrastructure projects. Furthermore, a National Transport Policy (2019) outlines national expectations to integrate resilience planning and measures in construction of public infrastructure assets. Evaluating the robustness of designs as well as relevant construction and maintenance specifications, in a manner that holistically examines how climate (change) risks have been identified, considered in the economic and financial appraisal process, and addressed through either structural or non-structural interventions is fundamental to the adaptation and mitigation agenda. This is especially crucial for new, large-scale strategic transport infrastructure investments (across all modes) by analyzing the wider sustainability implications if Malawi is to reduce long-run costs related to reconstruction or asset recovery.

24. A new spatial planning framework that evaluates network criticality, climate vulnerability, incidence of poverty in adjacent areas, and proximity to potential agriculture clusters and agri-businesses is necessary for road prioritization. Malawi Roads Authority currently lacks a
geo-referenced database of its road assets and ancillary infrastructure capable of assessing the core network’s climate vulnerability and exposure risks as part of a national database of critical public infrastructure. Recent World Bank analyses on evaluation frameworks that support road agency decisions on whether “to pave or not to pave”\textsuperscript{16} rural roads recognizes that traditional economic (cost-benefit) analysis is not sufficiently robust and warrants additional parameters that take account of climate adaptation, among other considerations. Grant funding provided by the Quality Infrastructure Investment Partnership is expected to facilitate development of a road asset management strategy that embeds updated prioritization criteria and road condition data management protocols. The strategy, to be developed by 2023, will look to optimize the country’s limited resources, embed systematic processes, and sequence investments through three-year rolling plans at both the National and District levels across the country.

25. **Undertake a comprehensive assessment of Malawi’s road and bridge infrastructure inventory and condition as a critical priority.** Development of a cogent methodology to forecast the likelihood and exposure risk of roads and bridges to natural hazards (flood, wind and temperature) during preparation of hydrological and geotechnical studies, which must then support updated technical specifications and guidance material for bridge, culvert and drainage design life. Data and analysis of aging and risk-exposed structures would then form a basis to develop a prioritized Bridge Replacement and Maintenance Plan, with identified interventions based on network criticality. Cross-ministerial collaboration will be vital, as updates to the Malawi “Guidelines for peak flood estimation for design of culverts and bridges and design of spillways of dams” (1987) are considered as fundamental if transport networks are to capably forecast and model risk exposure, with responsibility for updating meteorology data and hydrology standards under the Ministry of Forestry. Malawi would also benefit from developing country-specific Guidelines for Structures like Drifts and Irish Bridges, emphasizing asset performance under flood loading to increase the resilience and connectivity of low volume crossings.

26. **Adapting technical and design standards to Malawi’s specific geographic, environmental, and operational context is increasingly paramount.** The Southern Africa Transport and Communications Commission (SATCC) road standards, which are still in draft form, were intended to be used on the regional trunk road network and do not provide for local variations in climate and materials that might affect the design of lower traffic road networks nor cover requirements for hydrology, drainage design, or road maintenance. Bringing the Road Authority, Malawi Bureau of Standards, Central Materials Laboratory, National Construction Industry Council and University programs together to collaborate on sector research and development to improve enforcement of codes and standards is crucially important to the adaptation agenda.

27. **Crisis Response mechanisms that provide immediate emergency recovery support following an eligible crisis or emergency are needed.** Rapid recovery and reconstruction require that Malawi’s Road Authority and Road Finance Administration have in place adequate contingency plans, which should include both financial arrangements, such as credit lines or insurance products, as well as measures that facilitate road network restoration through prearranged contracts for civil works and emergency services.

28. **Nature-based solutions may ultimately provide the most cost-effective approach to road network resilience in flood and drought prone regions.** Applying a Green Roads for Water\textsuperscript{17} concept to Malawi’s geographies and climates would entail an emphasis on: (i) designing road alignments and cross drainage in mountainous terrains in a manner that diverts water to recharge aquifers in semiarid climates, while also acknowledging the need to provide low-cost and effective slope stabilization; (ii) managing flooding and boosting agricultural productivity in wet lowlands, where roads can effectively double as protective embankments and serve as evacuation routes and flood shelters; (iii) serving local communities by using roads to harvest water in arid and semiarid areas; (iv) water runoff can also be directed to create buffers to curtail encroachment by livestock keepers or farmers; and, (v) supporting wildlife areas using water catchments as part of wildlife management and regreening of designated parks areas.
Annex 1. Criticality Analysis

Different criticality measurements

1. Mathematically, criticality is defined by:

\[ \text{criticality}_k = \frac{\sum_i \sum_j t_{ij}^k}{\sum_i \sum_j t_{ij}} \]

where the term in the denominator represents the time it takes to get from node \( i \) to node \( j \) in the unperturbed network. The term in the numerator represents the corresponding time when link \( k \) is not passable. Thus, the criticality is essentially measured by how many more times would be required because of this closed road.

2. While the concept is the same, there are different methods to compute this criticality. First, strict criticality can be considered by removing a particular link \( k \). Unfortunately, strict criticality is undefined when a road is the only link between two disjoint sets of nodes in the road network, like a bridge. In such a case, criticality cannot be computed, though it can be interpreted intuitively to mean that criticality is significant.

3. For computational purposes, two other methods are considered: criticality (1) and criticality (2) wherein the assumption that link \( k \) is removed is relaxed. In the first case, rather than deleting links outright, the duration of traversing the link in question is increased to the longest duration link in the network (for example, 2.36 hours in our Malawi case). In the second case, rather than deleting links outright, the speed of traversing the links in question is reduced significantly to 1 km per hour, which is practically impassable even by walk, adding the duration of the link changes appropriately.

4. There are pros and cons. For the strict criticality, there are many undefined criticality segments in grey. The results from criticality (1) and (2) are broadly consistent, indicating that the spinal roads going from the north to the south generally have high criticality. By criticality (2), certain
additional roads are identified as critical. By construction, this criticality measurement is affected by road length in data. There is a tendency that the measured criticality is higher when a road has no alternative and is longer. In the analysis, therefore, criticality (1) is used as a default measurement.

**Traffic estimates**

5. To evaluate the economic risk of transport infrastructure, it is needed to know the volume of traffic between all possible pairs of origins and destinations. Unfortunately, however, such a traffic matrix is often not available, particularly in developing countries.

6. Using the minimum available data, the OD matrix is estimated by using a gravity model, which is the simplest common procedure of trip distribution (Lindstrom and Persson, 2018). The simplest formulation is:

\[
g_{ij} = A o_i d_j f(t_{ij})
\]

which is determined by the economic significance of origin \(o_i\) and destination \(d_i\), normally called by the trip production and the trip attraction, respectively. While \(f(*)\) is a deterrence function between the two locations, \(A\) is a constant term (simply set to 1). The trip demand is normally proportional to the economic significance at the origin and destination node. It is negatively weighted with the deterrence function, of which a commonly used form is the negative exponential deterrence function of travel time \(t\) between nodes \(i\) and \(j\):

\[
f(t_{ij}) = e^{-\pi t_{ij}}
\]

\(\pi\) is a parameter that is often set to 2, following the Newton’s Law of Gravity.

7. Two scenarios are considered: The first examines the city-to-city mobility. The second aims at estimating the mobility between agricultural production areas to major cities. By accumulating the estimated gravity, the total gravity on each road link is calculated. This can be interpreted as the estimated total traffic flow on each road.

8. Note that the measured traffic indicates the significance of the traffic in relative terms. The absolute values may not be meaningful, especially when the economic significance is measured by other variables than population. To interpret the results economically, certain normalization is needed. In the Malawi case, the measured gravity is normalized using an average daily traffic of 1,268 vehicles along paved roads based on the national transport master plan.
Annex 2. Value of Time

1. To evaluate the potential economic loss of disrupted traffic, the average value of time for the general traffic, including both passengers and cargos, is estimated. According to the Government data, about 60 percent of the total vehicle fleet in Malawi is light passenger cars. Trucks account for about 30 percent. While Malawi’s GDP per capita is US$636 per year, the average cargo value is US$2,681 per ton according to the shipment data. In the literature, it is estimated that each day in transit is equivalent to an ad-valorem tariff of 0.6 to 2.1 percent (Hummerls and Schaur 2013). In this analysis, it is assumed that 0.6 percent of the shipping value would be lost per day. That is equivalent to US$0.67 per ton-hour.

2. Assuming the normal vehicle occupancy for passenger cars and the standard freight capacity for trucks, the value of time is estimated at US$0.25 to US$11 per fleet, depending on type of vehicle. The weighted average with the fleet shares is US$2.47 per vehicle-hour.

<table>
<thead>
<tr>
<th>Vehicle Category</th>
<th>Registered vehicles (number)</th>
<th>(%)</th>
<th>Transport capacity</th>
<th>Value of time lost (US$/vehicle-hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>14,720</td>
<td>5.1</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>Light Passengers</td>
<td>181,006</td>
<td>62.0</td>
<td>2</td>
<td>0.50</td>
</tr>
<tr>
<td>Medium Passengers</td>
<td>2,130</td>
<td>0.7</td>
<td>10</td>
<td>2.49</td>
</tr>
<tr>
<td>Heavy Passengers</td>
<td>9,287</td>
<td>3.2</td>
<td>40</td>
<td>9.96</td>
</tr>
<tr>
<td>Light Goods</td>
<td>43,732</td>
<td>15.0</td>
<td>1</td>
<td>2.93</td>
</tr>
<tr>
<td>Medium Goods</td>
<td>9,315</td>
<td>3.2</td>
<td>1</td>
<td>7.62</td>
</tr>
<tr>
<td>Heavy Goods</td>
<td>28,003</td>
<td>9.7</td>
<td>1</td>
<td>11.64</td>
</tr>
<tr>
<td>Special</td>
<td>1,661</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total / Weighted average</td>
<td>289,854</td>
<td>100.0</td>
<td></td>
<td>2.47</td>
</tr>
</tbody>
</table>
Notes

1 Malawi ranks 161 out of 181 in the ND-Global Adaptation Initiative Index.
9 The classification of the undesignated road network is expected to be included in an update to the Public Road Act, currently under review by Ministry of Transport and Public Works and the Ministry of Justice, which is tentatively scheduled for Parliamentary debate in November 2022. The additional road network will put further pressure on unconstrained investment demand.
11 Estimates derived from the Road Finance Administration Strategic Plan using an average between the cost per kilometer of rehabilitation (US$300,000) and reconstruction (US$900,000).
15 The National Transport Policy (2019) is a key policy outcome of the Malawi Disaster Risk Management Development Policy Financing with Catastrophe Deferred Drawdown Operation (P165056).
References


