A FRAMEWORK TO PRIORITIZE CRITICAL ROAD SEGMENTS FOR CLIMATE-RESILIENCE INVESTMENTS

P. Sohouenou, D. Soto, C. Vignote & K. Selouane
Resallience (by Sixense), Nanterre, France
philippe.sohouenou@resallience.com

SUMMARY

With climate change, the impacts of natural hazards (such as floods, snow events and landslides) on road networks and mobility could worsen. Hence, strengthening the resilience of road infrastructures to natural hazards is more critical than ever before. To reach this objective, the design, operation and maintenance of road infrastructures should be informed by climate, transport, infrastructure and land-use data and models. In particular, transport operators and public authorities need to analyze such data and models to identify critical roads (i.e. roads whose unavailability would result in the highest impacts on the transport system and surrounding territory), which should be given priority for resilience strengthening investments. The present paper introduces a framework for identifying critical road segments in a road network using climate hazard data, infrastructure data, transport data and land-use data. The data is analyzed and combined to obtain a composite criticality index that integrates three aspects of road segment's criticality: (i) the vulnerability of the road infrastructure, (ii) the resilience of the road infrastructure, and (iii) the criticality of the territorial services supported by the road infrastructure. Hence, the proposed framework provides a comprehensive method to identify the road segments that should be given top priority for climate resilience investments. Two case studies are used to illustrate the proposed framework.

1. INTRODUCTION

Natural hazards, such as floods, snow events and landslides can damage and obstruct road infrastructures, leading to repair costs and service disruptions impacting society and the economy. The UK Department for Transport [1] estimated that the July 2007 flood in London led to almost 10,000 people being stranded while the repair costs were estimated at £40 to 60 million. Similarly, damage to transport infrastructure in Ouagadougou (Burkina Faso) during the September 2009 floods was estimated at 4.9 billion CFA francs (7.5 million €) by the World Bank [2]. The damage also resulted in several neighborhoods being stranded for days (and weeks in some cases). In addition, the impacts of climate hazards on road networks and mobility could worsen in many parts of the world with climate change [3].

To reduce the impacts of such disruptions on society, transport operators and public authorities need to identify critical roads (i.e. roads whose unavailability would result in the highest impacts on the transport system and surrounding territory), which should be given priority for resilience strengthening investments. The present paper introduces a framework for identifying critical road segments in a road network using three criteria: (i) the road infrastructure's vulnerability i.e. the propensity of the infrastructure to experience harm due to a hazard, (ii) the resilience of the road infrastructure i.e. the ability of the infrastructure to sustain and recover from disruptions, and (iii) the criticality of the territorial services supported by the road infrastructure. Although, methodologies addressing these different criteria have been proposed in the literature ([4–9]), they rarely consider these three concepts inside the same approach. This could be explained by two reasons. Firstly, the application of the resilience concept to road infrastructures is relatively new. Secondly, the consideration of these three concepts requires a diverse set of skills (climate hazard modelling, transport system analysis, urban analysis, risk and resilience analysis) and data (climate hazard data, infrastructure data, transport data and land-use data). Still, the integration of the vulnerability, resilience and territorial criticality of the road infrastructure into one methodology is crucial to support transport operators and public authorities in optimizing budget allocation for climate resilience investments.

The present paper is structure as follows. The methodology is presented in Section 2 and applied to two case studies–a highway network in France and an urban network in Ouagadougou–in section 3. Finally, the discussion and conclusions are presented in Section 4.

2. FRAMEWORK FOR PRIORITIZING CRITICAL ROAD SEGMENTS

2.1. Road network division into road segments

Road networks are composed of infrastructures (bridges, intersections, dead-ends, street segments, etc.) that interact together to provide mobility services, i.e. allow road users to reach their chosen destination using different transport options (private car, public transport, etc). The present framework requires the division of the network to be analysed into road segments (or sections). This division can be done according to several criteria depending on the network characteristics and stakeholder's objectives. As an indication, urban road networks can typically be divided into functional elements, using intersections and dead-ends to divide the network into segments. Highway networks can be divided into functional elements using the exits, entry and interchanges to divide the networks into segments. The present framework then aims to identify the most critical road segments among those segments.

2.2. Criticality components

To evaluate the criticality of the different road segments of a given road network, the proposed framework considers three elements: the vulnerability of the road infrastructure, the resilience of the road infrastructure, and the criticality of the territorial services supported by the road infrastructure.

Vulnerability of the road infrastructure

The vulnerability of the road infrastructure measures the degree to which the infrastructure is likely to experience harm due to exposure to a hazard. The infrastructure vulnerability is the combination of its exposure (i.e. nature and degree to which a system is exposed to significant climatic variations) and sensitivity (i.e. amplitude of potential damages that could be caused by a given climate hazard).

The assessment of the infrastructure vulnerability (*V*) requires data about the climate hazard (location, intensity, frequency and duration) as well as the infrastructure location and sensitivity to a given hazard (which depends on the physical characteristics of the infrastructure e.g. elevation of the road compared to the terrain).

Resilience of the road infrastructure

The resilience of the road infrastructure measures the ability of the infrastructure to continue to deliver or rapidly recover its functionality (i.e. allow road users to pass) when damaged or disturbed. Assessments of road infrastructure's resilience require data about the expected evolution of the infrastructure vulnerability (amplitude of physical and operational damages) through a recovery process. For example, the evolution of the floodwater level following heavy precipitation provides an indication of the infrastructure ability to absorb and treat excess water. Resilience assessment can also consider the ability and rapidity of transport operators to repair and clear road infrastructure following climate hazards (e.g. snowing).

In other words, the resilience index (*R*) should be an extension of the vulnerability index over time. For example, in the case study presented below, the vulnerability index measures flood water depth while the resilience index considers the evolution of this water depth through time.

Criticality of the territorial services supported by the road infrastructure

In a road network, certain road segments are more important than others depending on the mobility services that they support (e.g. access to residential areas vs access to healthcare facilities). In practice, the relative importance of the road segments is related to the functioning of the territory ([10]). The present framework considers and quantifies this relative importance using a territorial criticality index (*TCr*), which considerers several criteria such as the traffic and the land use around the road infrastructure.

2.3. Quantification and combination of the criticality components

To support decision-makers in selecting the most critical road sections in a network for climate-resilience investments, the three elements mentioned above should all be considered. To this end, a composite road segment criticality index (*CCr*) can be computed using indices that quantify the vulnerability, resilience and territorial criticality associated to the road segments. The mathematical formula used to combine the three indices should be adapted to the case study to obtain a good dispersion of scores and reflect stakeholders' preference for the vulnerability, resilience or territorial criticality criterion. Figure 1 provides a summary of the workflow and data required to apply the framework. It is worth noting that considering the spatial aspect of climate and territorial data, geographic information systems (GIS) are natural mean to implement the framework.

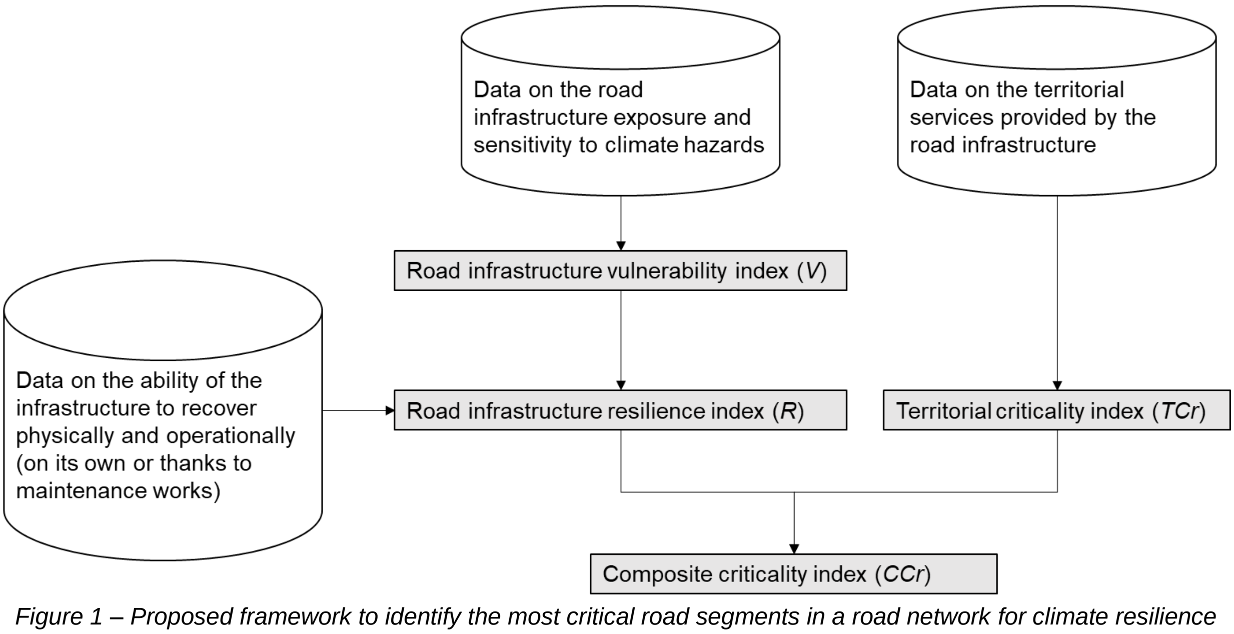

Figure 1 – Proposed framework to identify the most critical road segments in a road network for climate resilience investments

3. CASE STUDIES

3.1. The Cofiroute highway network (France)

This case study focuses on the part of the French highway network managed by the company Cofiroute (VINCI Autoroutes). This network includes 1 212 km of road in central-western France (A10, A11, A19, A28, A71, A81, A85, A86 Duplex). This network is shown in the Figure 2.

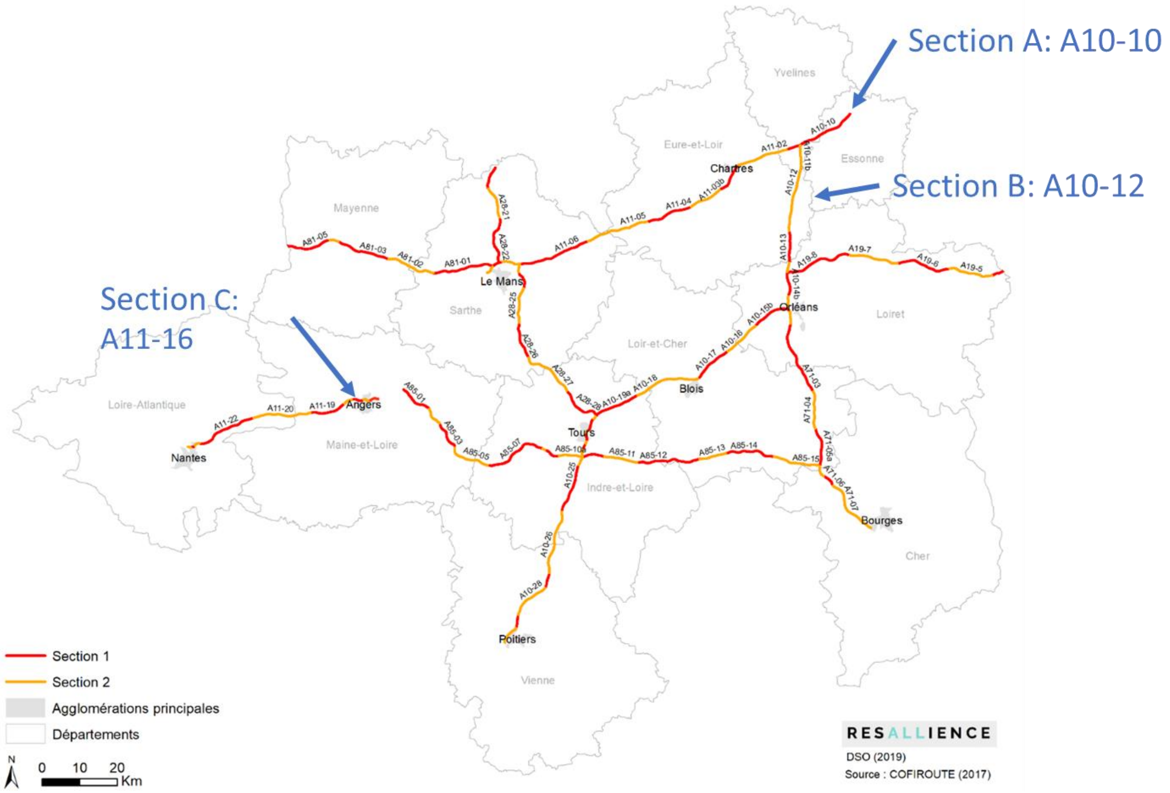

Figure 2 - Situation map of the Cofiroute highway network (© RESALLIENCE, 2021)

The proposed framework was used to select a set of highway segments that should be analysed in detail for future climate-resilience investments. The Cofiroute highway network was divided into sections using the freeway entrances/exits, in accordance with the highway manager policies. The present paper focuses on three highway segments (A, B and C) for brevity, shown in Figure 2. The three sections were arbitrarily chosen to showcase how the consideration of the different criticality elements (infrastructure vulnerability, infrastructure resilience and criticality of the territorial services provided) can help discriminate between sections. In this case study, the resilience component (the ability of the road infrastructure to recover its functionality) was not considered due to data unavailability.

Road infrastructure vulnerability

The vulnerability of the road network was assessed using flood maps from the French government regulatory framework ([11,12]) summarised in Figure 3, which quantify the exposure and intensity of the hazard according to a scale between 1 (low intensity) and 7 (high intensity). However, the latter does not consider all the watercourses that could affect the road infrastructure. Figure 4 shows the hydrographic network of the study area, which presents a number of minor and major watercourses that border or intersect the highways. These watercourses are potential threats to the operation of the highway network, particularly where the elevation difference between the natural terrain and the infrastructure is small and considering that climate change could lead to an increased frequency of extreme precipitation events. Hence, these watercourses were also considered.

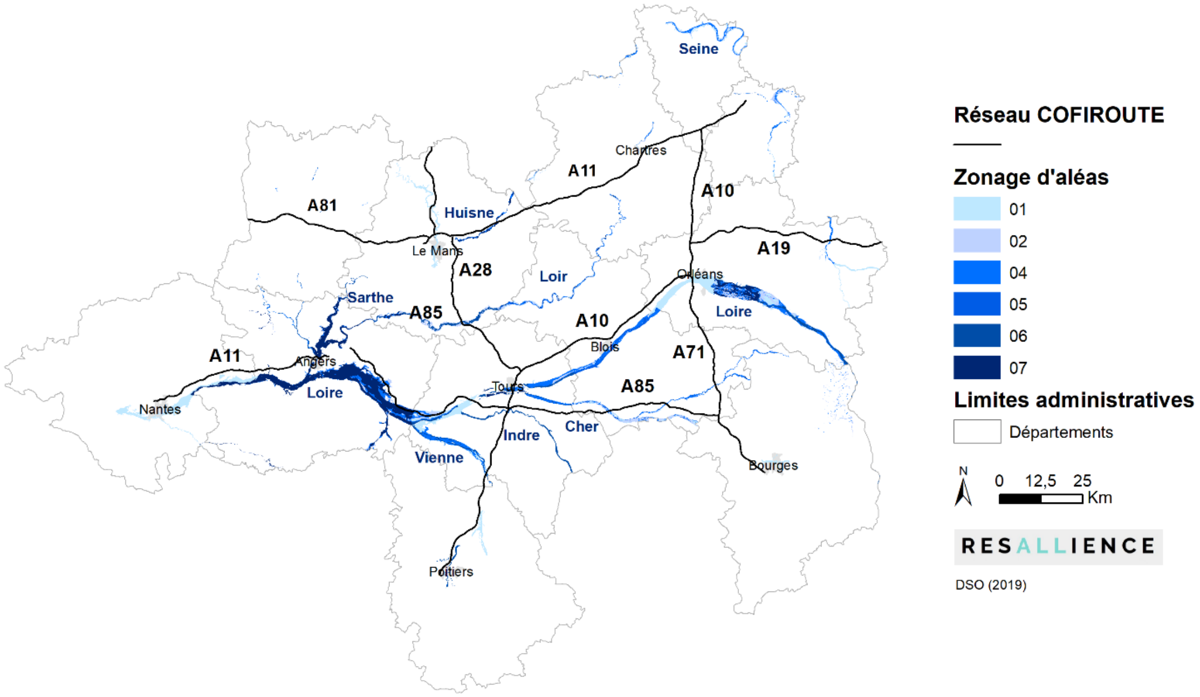

Figure 3 - Flood hazard zones near the COFIROUTE motorway network, rated on a scale from 1 (low intensity) to 7 (high intensity) (© RESALLIENCE, 2019)

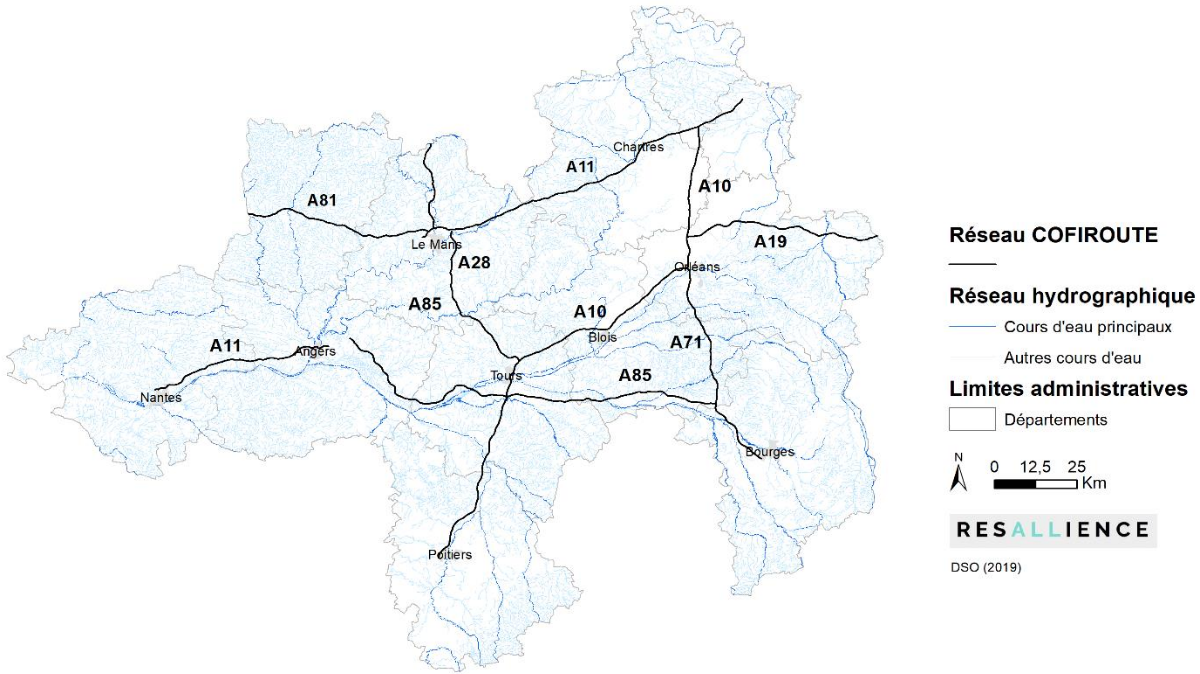

Figure 4 – Hydrographic network around the COFIROUTE motorway network (© RESALLIENCE, 2019)

To quantify the vulnerability of the road infrastructure, the exposure and sensitivity of the infrastructure to flooding were both considered and combined. The exposure was assessed using the following scale:

- Value 0: no watercourse along or intersecting a section of highway
- Value 1: presence of at least one watercourse which borders or intersects a section of highway

- Value 2: presence of a watercourse subject to a regulatory system and whose hazard intensity is low (regulatory hazard values between 1 and 3)
- Value 3: presence of a watercourse subject to a regulatory system and whose hazard intensity is average (regulatory hazard values between 4 and 5)
- Value 4: presence of a watercourse subject to a regulatory system and whose hazard intensity is strong (regulatory hazard values between 6 and 7)

The road infrastructure may be subject to flooding by overflow or runoff depending on the elevation differential with the surrounding natural terrain (i.e. sensitivity). The threshold of 2m was chosen to determine whether an infrastructure was sensitive to floods. This value is considered, in France, as the upper limit of the water height reached during a 100-year flood in case of a strong hazard scenario. It is also used as a threshold value for the application of the water law. Using data on the elevation of the infrastructure and terrain from IGN ([13]), the sensitivity of the highway sections to flood was assessed.

Finally, the vulnerability of the road segments to floods was computed by multiplying the exposure and sensitivity scores. Table 1 shows the exposure, sensitivity and vulnerability scores associated with the three highway segments considered.

Table 1 – Exposure, sensitivity and vulnerability of three road segments in the Cofiroute highway network

Section ID	**Section name**	**Exposure of the road segment (from 0 to 5)**	**Sensitivity of the road segment (0 or 1)**	**Vulnerability of the road segment (from 0 to 4)**
A	A10-10	1	0	0
B	A10-12	0	1	0
C	A11-16	4	1	4

Territorial and composite criticality indicators

The present case study focuses on a highway network, which typically provides a fast connection between cities and remote areas. Therefore, the territorial criticality indicator used in this case study considers the major territorial issues related to the highways. The indicator adopted considers several criteria:

- Population density near a motorway section (I_{pop})
- Number of establishments open to the public near a motorway section (I_{ERP})
- Number of economic activity buildings near a motorway section (I_{Eco})
- Number of Critical Infrastructures (CI) near a motorway section (I_{CI})
- Average annual daily traffic on each motorway section ($I_{Traffic}$)

These indicators were combined into a single territorial criticality indicator (TCr) as follows:

$$TCr = I_{pop} + I_{ERP} + I_{ECO} + I_{CI} + I_{Traffic} \quad (1)$$

The threshold of 4km around the highway section was considered to assess the number of inhabitants, establishments open to the public, economic activity buildings and critical Infrastructures near a given section. Each sub indicator was given a score scaled from 1 to 5, as shown in Table 2. The latter is adapted from [14]. Hence the Territorial criticality indicator is a score scaled between 5 and 25.

Table 2 – Criteria used for computing the territorial criticality indicator in the Cofiroute case study

	Score				
Indicator	**1 pt**	**2 pts**	**3 pts**	**4 pts**	**5 pts**
Pop (Habitants)	Pop<16374	16 375< Pop <33590	33591<Pop<66137	66138<Pop<119905	Pop >119906
ERP (Number)	ERP<50	51<ERP < 104	105<ERP<176	177<ERP<296	ERP>297
Eco (Number)	Eco<580	581<Eco<1066	1067<Eco<1512	1513<Eco<2211	Eco>2212
CI (Number)	IC<36	37<IC<56	57<IC<77	78<IC<127	IC>128
Traffic (Vehicules)	Traffic<16500	16501<Traffic< 29100	29101<Traffic <39000	39001<Traffic< 55000	Traffic>55 001

Finally, the composite criticality index was obtained by multiplying the infrastructure vulnerability and the territorial criticality indicators associated to each section, as shown in Table 3. The results show that section C is highly critical (CCr=80/100) while the two other sections are not critical (CCr=0) as they are not vulnerable to flooding. However, section A would be slightly more critical than section B based on the territorial criticality score (Table 3).

Table 3 – Infrastructure vulnerability, Territorial criticality and Composite criticality indicators associated to three road segments in the Cofiroute network

ID	**Section name**	**Infrastructure vulnerability score (from 0 to 4)**	**Territorial criticality score (from 5 to 25)**	**Composite Criticality score (from 0 to 100)**
A	A10-10	0	20	0
B	A10-12	0	14	0
C	A11-16	4	20	80

3.2. The future Bus rapid Transit network of Ouagadougou (Burkina Faso)

This case study focuses on the road infrastructure supporting the planned Bus rapid Transit (BRT) network of Ouagadougou in Burkina Faso. This BRT system includes nine lines of high capacity buses that will act as the primary network of a multimodal transport system. Figure 5 shows the layout of the planned BRT system.

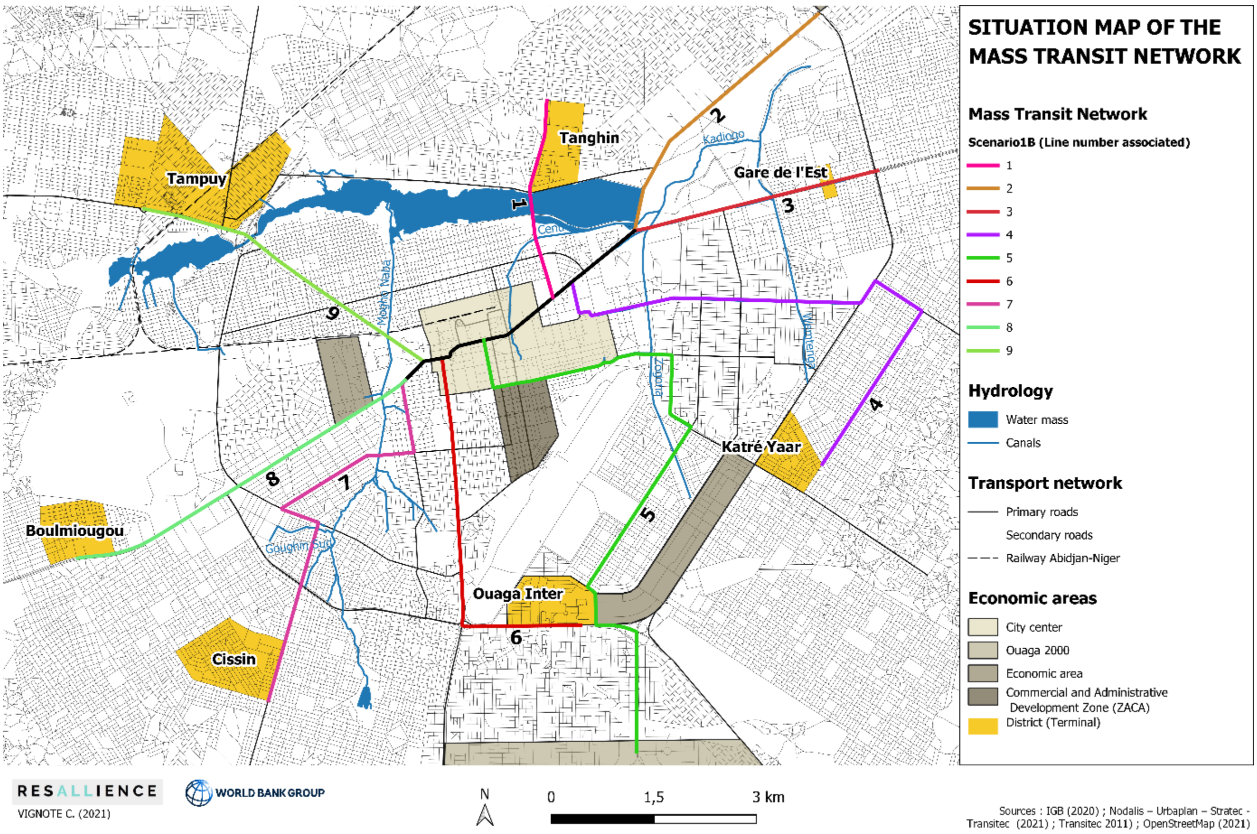

Figure 5 – Situation map of the planned mass transit system network in Ouagadougou, Burkina Faso (© RESALLIENCE, 2021)

The proposed framework was applied to identify the critical road sections on the layout of the BRT system that should be prioritised for flood resilience and adaptation investments. The present paper focuses on the application of the framework to Line 7 for brevity instead of analysing the whole BRT network layout. Three flood-prone sections along the itinerary of Line 7 are analysed to showcase how the consideration of the different criticality elements (road infrastructure vulnerability, resilience and criticality of the territorial services provided) can help discriminate between sections. These sections are shown in the Figure below. Zone A corresponds to the roundabout de la Bataille du Rail, where the itineraries of Line 7 and 8 separate (Figure 5). Zone B is along Ave Oumarou Kanazoe, where Line 7 passes (Figure 5). Zone C corresponds to the Nation Unies roundabout and Avenue Nelson Mandela in the city centre, where most BRT lines pass (black line in Figure 5).

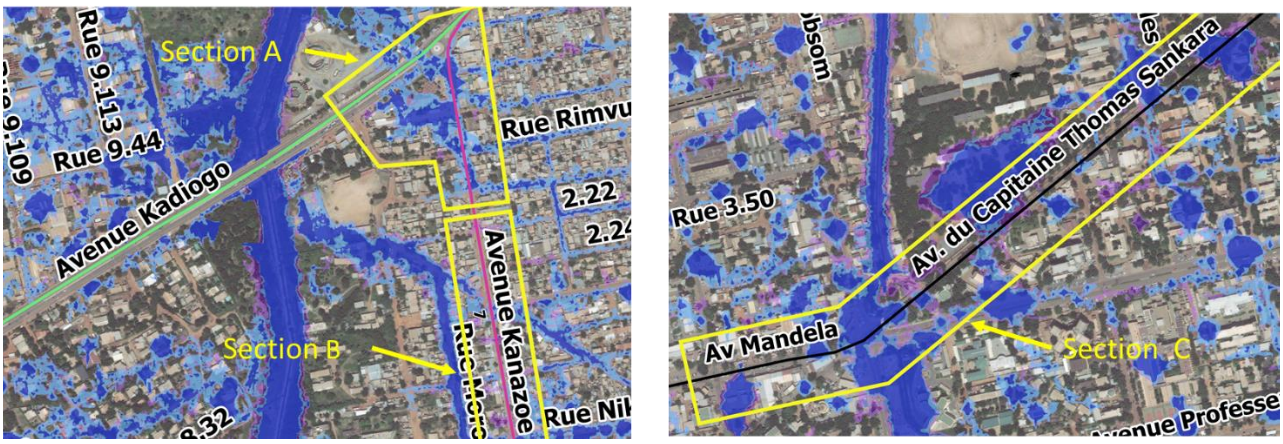

Figure 6 – Maps of the three flood-prone areas analyzed. Light and dark blue areas are flooded by the 2-year return period rain with a water height below 15 cm and above 15 cm, respectively (© RESALLIENCE, 2021).

Road infrastructure vulnerability

The vulnerability of the road network to flooding was directly assessed using the results of a hydraulic model of the city—developed by SEPIA Conseils [15]. The model considered a 2-year return period rain event and an average water level in the downstream dams.

The hydraulic model provided peak flows and heights that were used to assess the vulnerability of the road segments to flooding using a continuous scale based on the impacts on the traffic on the road segments. The affected road segments were categorised as unimpacted, flooded with slowed traffic (water height below 15 cm) and flooded with blocked traffic (water height above 15 cm). This classification is based on experts' judgement and the study of Pregnolato et al. [16], which relates floating depth and speed reductions. The water in the three zones considered surpassed 15 cm. Hence, the three zones were classified as flooded with blocked traffic (water height above 15 cm). This classification can be translated into infrastructure vulnerability values as follows:

- Value 0: no impacts
- Value 1: flooded with slowed traffic (water height below 15 cm)
- Value 2: flooded with blocked traffic (water height above 15 cm).

Road infrastructure resilience

The resilience of the road infrastructure was assessed based on the flood cause, depth and duration. The flood cause and duration were evaluated using the flood maps and hydrographs—i.e. graphs showing the rate of flow (discharge) versus time past a specific point—from the hydraulic model as well as the digital-terrain and surface models used to build the model [15]. The flood maps, digital terrain models and digital surface models allowed the identification of the probable cause of the flood (overflow of the canal closed to the area considered, low points, etc.). The hydrographs allowed to assess whether the drainage system was able to rapidly absorb excess water.

For example, Zone C is located on the United Nations roundabout, which is crossed by most bus lines. There is a 130m-long section of the canal central buried a few meters east of the roundabout. The entire area undergoes flooding caused by the 2-year return period storms. The hydrograph (Figure 7) confirms that the flooding in this zone is caused by an overflow of the canal as floods (orange curve in Figure 7) appear almost one hour after the peak of rainfall intensities (blue bars in Figure 7). This duration is in the order of magnitude of the watershed's concentration time. The hydrograph shows a sudden rise in water level, corresponding to the moment when the canal overflows to the neighbouring areas, and then a slow decrease (more than four hours to return to normal conditions).

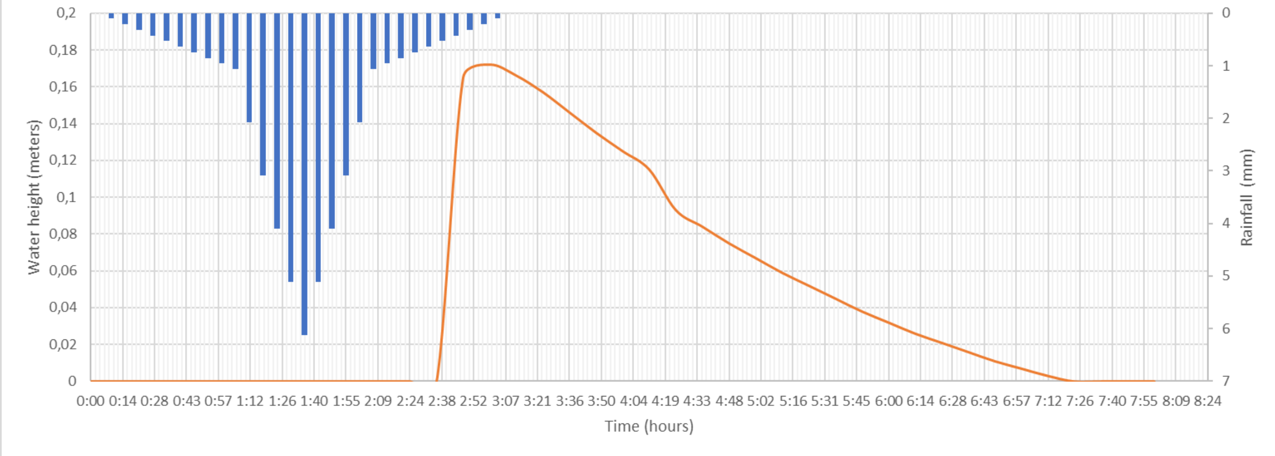

Figure 7 – Hydrograph (water height) in Zone C under the 2-year return period storm, blue bars = rainfall (mm), orange curve = water height (m) (©SEPIA Conseils, 2021)

The flooded road sections of the BRT system were assigned a flood resilience score (from 1 to 4) depending on the flood depth and duration using exerts' judgement. The sections flooded for the longest period with the highest depth of water were given the maximum score (4) while the sections flooded with the lowest water height and limited time compared to the other sections were assigned a score of 1.

- Value 0: no impacts
- Value 1: flooded with slowed traffic and rapid recovery
- Value 2: flooded with slowed traffic and slow recovery
- Value 3: flooded with blocked traffic and rapid recovery
- Value 4: flooded with blocked traffic and slow recovery

Table 4 provides a summary of the flood vulnerability and resilience assessment of the three areas.

Table 4 – Infrastructure vulnerability and resilience indicator values associated to three flood-prone sections of the planned BRT system in Ouagadougou

Section ID	**Bus line(s) affected**	**Road/intersection affected (Ave = Avenue)**	**Description of the flood**	**Infrastructure vulnerability score (from 0 to 2)**	**Infrastructure resilience score (from 0 to 4)**
A	Line 7 & Line 8	Ave Oumarou Kanazoe & Ave Kadiogo	Flood due to surface run-off coming from the streets to the east. There is no clear path for water arriving to Ave Kanazoe to the Mogho Naaba canal, which increases floods on the avenue, and thus on the roundabout (place de la bataille du rail). The flood depth reaches 30cm.	2	3
B	Line 7	Ave Oumarou Kanazoe & Ave Ouezzin Coulibaly		2	3
C	Section shared by most lines	Avenue Nelson Mandela & Nation Unies roundabout	Flooding of the roundabout is caused by an overflow of the canal as the capacity of the latter is insufficient. The flood depth is over 40cm and takes several hours to decrease.	2	4

Territorial criticality

As the present case study focuses on the planned bus rapid transit system of Ouagadougou, the territorial criticality assessment was focused on the urban issues related to this BRT network. Two criteria were considered and combined to assess the criticality of the services supported by the roads: the projected traffic of the BRT lines (annual average number of passengers) and the urban issues related to BRT service. The projected BRT traffic figures were extracted from the Ouagadougou Public Transport Implementation Study [17] The urban issues were assessed using land-use data obtained from OpenStreetMap [18] and the knowledge of local experts. Each sub-indicator was given a score scaled from 1 to 5, as shown in Table 5.

Table 5 – Criteria used for computing the territorial criticality indicator in the Ouagadougou case study

	Score				
Indicator	**1 pt**	**2 pts**	**3 pts**	**4 pts**	**5 pts**
Traffic (passenger)	Traffic<16500	16501<Traffic< 29100	29101<Traffic <39000	39001<Traffic< 55000	Traffic>55 001
Urban issues	Residential areas with no particular accessibility issues	Mixed residential and commercial areas	Mixed residential and commercial areas, including a few critical facilities (universities, hospitals, etc.)	Business areas, including critical facilities (universities, hospitals, etc.)	Areas with a high concentration of activities (e.g. city center)

The values of the two sub-criteria were added to obtain a territorial criticality score. For example, the section of Avenue Oumarou Kanoze on Line 7 (Zone B) was assigned a territorial criticality score of 2 because the travel demand (5,506,893 passengers per year) on Line 7 is relatively low compared to other lines and also because this section of Line 7 mostly serves residential areas where high capacity buses of the BRT lines are less needed. Hence, the impacts of service disruptions on this section would be limited. On the contrary, the sections of the Nations Unies roundabout and Avenue Nelson Mandela (Zone C) shared by most bus lines were given a score of 9 because they serve the City Centre and attract the highest travel demand (16,400,643 passengers per year) of the planned BRT system.

Composite road criticality index

Finally, a composite road infrastructure criticality index was computed by multiplying the flood resilience and territorial criticality scores. Table 6 shows the values of the Territorial and Composite criticality index values associated to the three sections considered. This table also includes a description of the urban issues identified around those sections. The results show that section C is highly critical (*CCr* = 36/40) compared to the other two sections. Section A is slightly more critical (*CCr* = 15/40) than section B (*CC r*= 10/40).

Table 6 – Territorial and composite criticality values associated to three sections of the Ouagadougou case study

Section ID	Bus line(s) affected	Description of the urban issues related to the transport system	Territorial criticality score (from 2 to 10)	Composite criticality score (from 0 to 40)
A	Line 7 & Line 8	Commercial and residential area (shops and market next to the road, private facilities, stores, banks). Line 8 serves the national road N1 towards Bobo-Dioulasso	5	15
B	Line 7	Serves residential areas. Line 7 is the least important line of the BRT system for transit and accessibility.	2	10
C	Section shared by most lines	City centre Administrative district. Central market, schools, public services, embassies, military camps.	9	36

4. DISCUSSION AND CONCLUSIONS

The present paper developed a framework to prioritize critical road segments for climate-resilience investments, which has the particularity to integrate the vulnerability, resilience and territorial criticality of the road infrastructure. The framework was applied to two case studies: the Cofiroute highway network in France and the planned bus rapid transit network in Ouagadougou.

The comparison of the two case studies showed that the proposed framework can be adapted to the characteristics of the network and the data available. The Cofiroute study relied on flood-extend and watercourse maps, which did not provide information on recovery. Therefore, the resilience index was not included in this case study. The Ouagadougou case study relied on a hydraulic model that provided hydrographs showing the evolution of the flood level through time and therefore allowed to assess resilience. The territorial criticality of Cofiroute road sections was assessed using extensive quantitative data on the territory (including the annual daily traffic, the number of establishments open to the public near a motorway section, and the number of critical infrastructures near a motorway section), while the Ouagadougou case study relied on more qualitative data (project BRT traffic, and expert's assessment of the urban issues around the road sections).

The results show that the consideration of the vulnerability, resilience and territorial criticality of the road segments leads to a composite criticality index that can discriminate between several sections. For example, sections A and B of the Ouagadougou case study presented the same vulnerability and resilience scores but different territorial criticality scores, which allow the discrimination between the two sections. In contrast, sections A and C of the Cofiroute case study presented the same territorial criticality scores but different vulnerability scores, which allowed the discrimination between the sections. Therefore, the proposed composite criticality index is a powerful tool to prioritise the sections that should be considered for resilience investments. The sub-indices can then be used to understand the final value of the composite criticality indicator and support decision makers in identifying appropriate solutions.

Although the framework can consider several types of climate hazards (snow events, high winds, etc.), the case studies focused on floods. The framework should hence be extended in the future to consider multiple hazards.

ACKNOWLEDGEMENTS

Part of the work presented in this paper was carried out as part of technical assistance projects provided by RESALLIENCE and funded by VINCI Autoroutes (Cofiroute's case study) and the World Bank (Ouagadougou's case study). We also acknowledge the contributions of Louis Berger international (WSP) and AGEIM Ingénieurs Conseils to the technical assistance related to the Ouagadougou case study.

REFERENCES

1. UK Department for Transport. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf (2014). *Transport Resilience Review - A review of the resilience of the transport network to extreme weather events*.
2. World Bank Group. (2010). *Inondations du 1er Septembre 2009 au Burkina Faso - Evaluation des dommages, pertes et besoins de construction, de reconstruction et de relèvement (French).*
3. IPCC. http://ebooks.cambridge.org/ref/id/CBO9781139177245 (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. doi:10.1017/CBO9781139177245.
4. Shivaprasad Sharma, S. V., Roy, P. S., Chakravarthi, V. & Srinivasa Rao, G. (2018). Flood risk assessment using multi-criteria analysis: A case study from Kopili river basin, Assam, India. *Geomatics, Natural Hazards and Risk* Vol **9**, pp 79–93.
5. Pregnolato, M., Ford, A., Glenis, V., Wilkinson, S. & Dawson, R. (2017). Impact of Climate Change on Disruption to Urban Transport Networks from Pluvial Flooding. *Journal of Infrastructure Systems* Vol **23**, pp 04017015.
6. Sohouenou, P. Y. R. & Neves, L. A. C. (2021). Assessing the effects of link-repair sequences on road network resilience. *International Journal of Critical Infrastructure Protection* Vol **34**, pp 100448.
7. Demirel, H., Kompil, M. & Nemry, F. (2015). A framework to analyze the vulnerability of European road networks due to Sea-Level Rise (SLR) and sea storm surges. *Transportation Research Part A: Policy and Practice* Vol **81**, pp 62–76.
8. Mason, D. (2016). RESILIENCE PLANNING IN ROAD NETWORK.
9. CEREMA. (2019). *Vulnérabilités et risques : les infrastructures de transport face au climat*.
10. Selouane, K., Gonzva, M. & Soto, D. (2019). Adapter les infrastructures de transport pour améliorer la résilience des territoires. *Revue Générale des Routes et de l'Aménagement* pp 26–29.
11. Etalab. https://www.data.gouv.fr/fr/. Plateforme ouverte des données publiques françaises.
12. Ministère de la Transition écologique. https://www.georisques.gouv.fr/. Base de données Géorisques.
13. Institut national de l'information géographique et forestière (IGN). https://www.ign.fr/. Base de données de l'IGN.
14. Garbolino, E. (2009). Contributions à l'étude du risque de transport sur route de marchandises dangereuses dans un espace transfrontalier.
15. SEPIA Conseils. (2021). *Aerial Surveying, Digital Terrain Model and Flood Hazard Assessment in Ouagadougou - Atlas des zones inondables*.
16. Pregnolato, M., Ford, A., Wilkinson, S. M. & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment* Vol **55**, pp 67–81.
17. Nodalis, Urbaplan, Stratec & Transitec. (2021). *Ouagadougou Public Transport Implementation Study (OPTIS)*.
18. OpenStreetMap contributors. www.openstreetmap.org. OpenStreetMap®.