

A Systematic Approach for Resilience Assessment in Road Transport Routes Involving Natural and Human Interruptions.

ABSTRACT

This work presents a new approach for resilience assessment in road transport routes interrupted by natural causes (rain, earthquakes) as well as by human influence (accidents). In this way, by knowing the state of preservation of the elements located within a road, particularly bridges, it will be possible to identify which are those with the highest priority to be attended for their conservation, repair, and even replacement, thus relating the cost of maintenance and the number of people benefited. To test this methodology, a case study was proposed. The proposed systematic approach is applied in the federal highway 15 route, which is an international route that passes through seven states of Mexico, ending in Alberta Canada. The study is limited to the Michoacan state of Mexico, which corresponds to 426 kilometers. This study identified the highway bridges within the road and analyzed their deterioration, the cost of repair, and the benefited inhabitants. The most significant scenarios were obtained in terms of repair cost and people benefited, identifying which bridges have priority to be served, having a more accurate decision and distribution of adequate financial resources.

Keywords: *Accidents, Natural disasters, Resilience, Road transportation routes.*

1. INTRODUCTION

Roads and all communication routes are designed, built, and planned to offer a great service to the user. One of the structures of great importance on these roads is the bridge. A bridge can be defined as a structure destined to overcome natural obstacles, such as rivers, valleys, sea; and artificial obstacles, such as railways or roads, to link paths for travelers, animals, and merchandise [1].

The design of bridges considers external factors, such as the type of seismic zone, the ground, materials, transit [2], economical issues, etc. However, situations can arise that interrupt a fluid passage through these bridges, some of these situations appear as natural phenomena (heavy rainstorms and earthquakes) [3], [4] and automobile accidents [5] either due to high speeds, being in a state of drugs or drunkenness, or fatigue of the user, to name a few. This way, the term resilience has been considered, which can help to select those bridges that require maintenance or repair with higher priority, involving minimizing the costs [6], [7], considering increasing the fluidity of the routes and the affected people who make use of these bridges [8], [9]. For example, Pan, Yan, He and He [10] reviewed the recent progress in the study of vulnerability and resilience. Specific definitions of resilience and vulnerability are first given from the perspective of the transportation system's supply and demand.

Resilience is a concept that has had a lot of relevance in recent years, this concept was used for the first time in the 19th century in the area of materials science as the ability of an

object to resist loads without permanent distortion [11]; it comes from the Latin “*resilire*”, which means “bounces back” [12]. At first, resilience was only evaluated qualitatively, but recently some works have evaluated it quantitatively. Fiksel [13] presented a design protocol that involves identifying system function and boundaries, establishing requirements, selecting appropriate technologies, developing a system design, evaluating anticipated performance, and devising a practical mean for system development. Dinh, Pasman, Gao and Mannan [14] proposed six principles and five factors that contribute to the resilience of a process. The principles include flexibility, controllability, early detection, minimization of failure, limitation of effects, administrative controls/procedures, and the main contributing factors, including design, detection potential, emergency response plan, human factor, and safety management.

On the other hand, resilience is a term that has great relevance in the area of process systems engineering. There are reported works where it is qualitatively evaluated for risk analysis and safety issues. Jain, Rogers Pasman, Keim, Mannan [15] presented a novel hazard analysis approach that incorporates both technical and social factors within a single analysis method called Resilience-based Integrated Process Systems Hazard Analysis (RIPSHA), which is based on resilience aspects, early detection, error-tolerant design, plasticity, and recoverability. Jain, Rogers Pasman, Keim, Mannan [16] presented a novel approach, Process Resilience Analysis Framework (PRAF) that consists of a resilience methodology emphasizing dynamics, unforeseen and even unknown types of threats, uncertainty, system degradation, and complex interactions. Gasser et al. [17] presented an overview of resilience definitions used across various scientific disciplines, followed by an in-depth analysis of resilience assessment and quantification for energy systems.

Similarly, several works have been published where resilience is quantitatively evaluated, especially in power systems [18], [19]. Gong and You [20] proposed a general framework for resilience optimization that incorporates an improved quantitative measure of resilience and a comprehensive set of resilience enhancement strategies for process design and operation. Other approaches considered natural disasters that may cause some disruption in the system, for example for food supply chain network [21], [22] and systems that incorporate the resilience assessment in the water-energy-food nexus [23].

In the same way, in infrastructure/engineered system science, resilience has been defined as the ability to withstand acceptably, degradation parameters and to recover within an acceptable time and costs [24], [25]. Venkittaraman and Banerjee [26] evaluated the seismic resilience of highway bridges, which are important components of the highway transportation system. To mitigate losses incurred from bridge damage during seismic events, bridge retrofit strategies are selected such that the retrofit not only enhances bridge seismic performance but also improves the resilience of the system consisting of these bridges [27]. Zhang, Wang and Nicholson [28] presented a novel resilience-based framework to optimize the scheduling of the post-disaster recovery actions for road-bridge transportation networks. Koc et. al. [29] introduced a comprehensive resilience assessment framework for transportation systems, which is designed to achieve a holistic analysis of transportation disruptions.

Different contributions to resilience have been made in this area; however, most of them focus on the recovery time of bridges due to the occurrence of a partial or total failure [24]. Thus, there is no analysis of the cost that this entails. Therefore, the objective of this work is to find the associated cost, which includes the maintenance and repair costs of some specific bridges in a certain region to improve the fluidity in the part of transportation services. To solve this problem, a systematic approach is proposed to analyze the possible state of deterioration of each of the bridges on the road; also, the cost of repairing the

deteriorated area, possible interruptions in the system, being of natural origin or human influence. With the above, the number of benefited people is identified, as well as being able to identify which area is the highest priority to attend. This proposed strategy allows the distribution of monetary resources more sensibly and successfully. The priority is determined according to the damage obtained to the bridge and the number of people affected in the event of an interruption in that part. It may happen that the bridge with the highest priority is not the one with the greatest "deterioration", but the one with the most people benefiting from its repair.

2. PROBLEM STATEMENT

Given a transport route, whether, of greater or lesser commercial use, it does not lose its importance as a means of communication for nearby residents. However, considering that such a road is used as a means of commercial or labor connection, a failure within the system could mean significant economic losses.

Sometimes, the lack of knowledge regarding the state of conservation of the road and how to properly distribute the economic resources to meet the needs of the elements located within the communication road, as well as ignoring the priority areas, can influence to make incorrect maintenance decisions.

With the above, it is needed a systematic approach to identify the highest priority areas based on the study of the system's resilience. Determining, this way, the parts of the highest priority bridges for repairing and maintenance considering the distributing associated traffic and distributed resources across this route.

3. METHODOLOGY

A methodology to assess the resilience in the repair and maintenance of bridges through a route where a large number of cars and transport services pass every day is proposed. In this approach, the steps indicated in Figure 1 are considered.

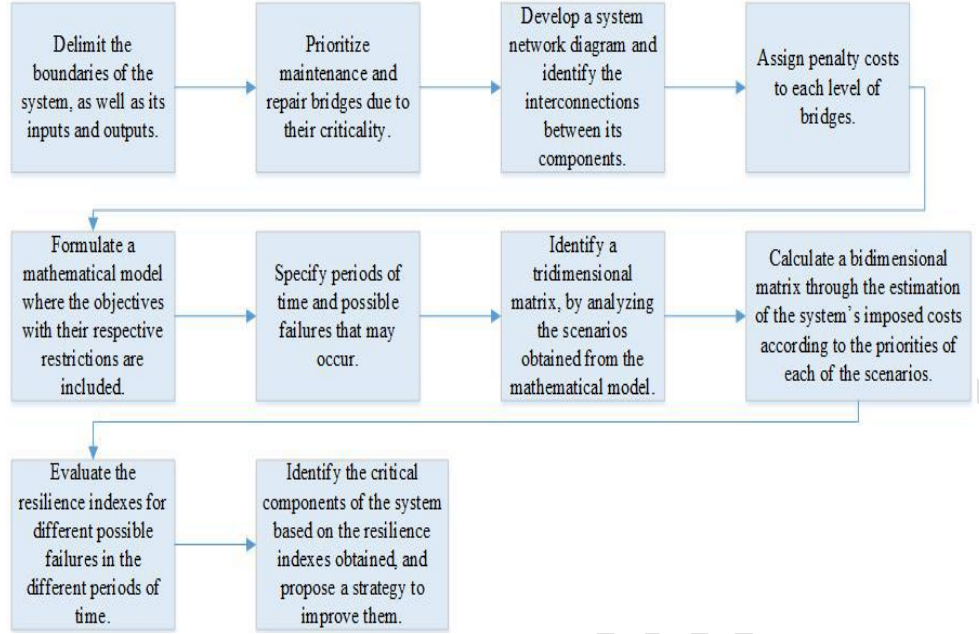


Fig. 1. Schematic representation of the proposed methodology.

The objective is to minimize the total cost of repairing bridges considering the benefited people. A resilience index that considers the bridge repair costs, as well as the benefited people by it, is proposed:

$$Re_{f,t} = \frac{\left(\frac{ImpCost^{Max}}{BP^{Max}} \right) - \left(\frac{ImpCost_{f,t}}{BP} \right)}{\left(\frac{ImpCost^{Max}}{BP^{Max}} \right) - \left(\frac{ImpCost^{Min}}{BP^{Min}} \right)} \quad (1)$$

To reduce the terms in eq. (1), the relationship between the imposed cost (ImpCost) and the benefited people (BP) was considered as an index (Index).

$$Re_{f,t} = \frac{Index^{Max} - Index_{f,t}}{Index^{Max} - Index^{Min}} \quad (2)$$

Imposed cost related to each possible failure in each period is calculated as follows:

$$ImpCost_{f,t} = \sum_s RepairCost_s AreaBridge_s \quad (3)$$

Where, $RepairCost_s$ (Table 1) is the bridge repair cost, which depends on the level of deterioration that this has based on the classification given by SIPUMEX (Comprehensive system of Mexican bridges) [30], and is the total area to be repaired for each level of bridges.

Table 1. Total area and benefited people for section.

Section	TDPA	Area of repaired bridges according to SIPUMEX classification (m ²)		
		2	3	4
Lim. Mex./Mich.-Entr. Huajumbaro	28,618	14,931	7,465	6,221
Entr. Huajumbaro-Morelia	891	0	446	446
Morelia-Quiroga	30,418	21,293	3,042	6,084
Quiroga-Comanja	4,571	0	2,286	2,286
Comanja-Carapan	13,040	8,693	4,347	0
Carapan-Zamora	45,314	6,473	25,894	12,947
Zamora-Jiquilpan	24,906	0	11,321	13,585
Jiquilpan-Lim.Mich./Jal.	24,215	3,725	20,490	0

3.1 Case study

A case study, which analyzes the existing bridges on Federal Highway 15 that crosses the state of Michoacán, located in the central-west part of Mexico was considered (Figure 2). SIPUMEX is a database that contains the inventory of bridges on federal toll-free highways in Mexico. This one proposes a scale of deterioration, which goes from level zero to five, depending on the damage to each bridge. *0, No damage; 1, Small damage, no repair necessary; 2, some damage, necessary repair, when the occasion arises; 3, significant damage, repair needed soon; 4, serious damage, repair needed very soon; 5, extreme damage, risk of total failure.* In the analyzed section of said highway, there are 83 bridges, of which 31 correspond to level 2, 32 to level 3, and 20 to level 4 in the deterioration scale proposed by SIPUMEX. The road is divided into 8 sections, Table 1 shows the sections as well as the average daily traffic per section (TDPA) and the number of bridges by the level of deterioration in each of the sections.

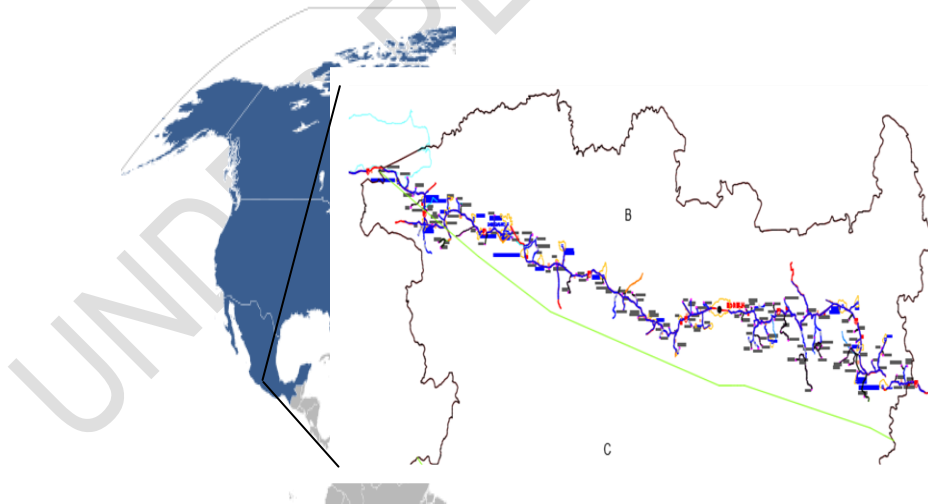


Fig. 2. System boundaries for the analyzed case study.

4. RESULTS AND DISCUSSION

For solving the addressed problem, the Pareto curve of Figure 3 was constructed, where each scenario represents damage to one section of the Federal highway. Each scenario represents the total cost of repairing that section versus the people who would benefit from

it. Table 2 shows that scenario I, where all the bridges of all the sections are repaired, entails a cost of \$US 280,659,143, and 171,973 people are benefited. On the other hand, when analyzing the sections individually, it is observed that scenario E (Comanja-Carapan) is the one that represents a lower repair cost \$US 5,580,310 and 13,040 people obtain a benefit, while scenario F (Carapan-Zamora) is the one where a greater number of people is benefited (45,314) for \$US 20,429,128.

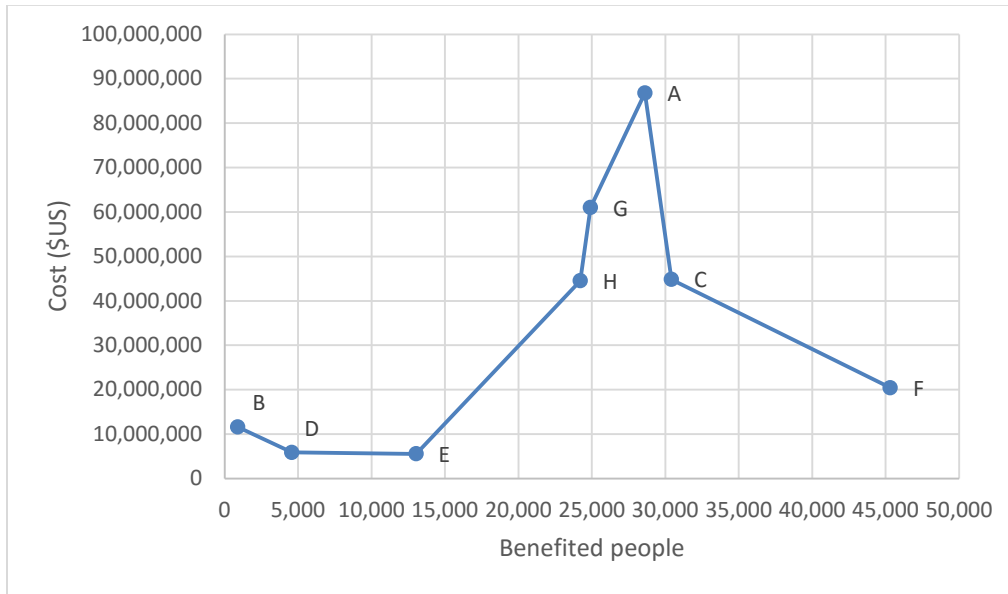


Fig. 3. Pareto curve for the analyzed case study.

Table 2. Values for Pareto curve.

Scenario	Section	Benefited People	Cost (\$US)
A	Lím. Mex./Mich.-Entr.Huajumbaro	28,618	86,786,861
B	Entr.Huajumbaro-Morelia	891	11,606,343
C	Morelia-Quiroga	30,418	44,836,849
D	Quiroga-Comanja	4,571	5,869,114
E	Comanja-Carapan	13,040	5,580,310
F	Carapan-Zamora	45,314	20,429,128
G	Zamora-Jiquilpan	24,906	61,016,866
H	Jiquilpan-Lim.Mich./Jal.	24,215	44,533,671
I	All	171,973	280,659,143

Subsequently, the resilience of the mentioned scenarios was analyzed using equations 1-3. Twelve-time periods were specified, each corresponding to a month of the year, and these were identified as possible failures, which required maintenance previously, car accidents, and natural phenomena (heavy rain, earthquake, etc.).

Afterward, the three-dimensional matrix (Figure 4, Figure 5, and Figure 6) was identified for each of the selected scenarios, where the periods of time, possible failures, and the area of existing bridges according to their level of deterioration are considered. Using the penalty

costs (Table 3) and the probability (Table 4) for every possible failure [31], a two-dimensional matrix was calculated to estimate the imposed costs for each failure mode and each period of time (Tables 5 to 7). Figures 7, 8, and 9 show the imposed costs for the selected scenarios in a graphical way. A greater cost can be noticed in the event of a car crash different from the other failure modes, this is due to the higher incidence that this type of failure presents.

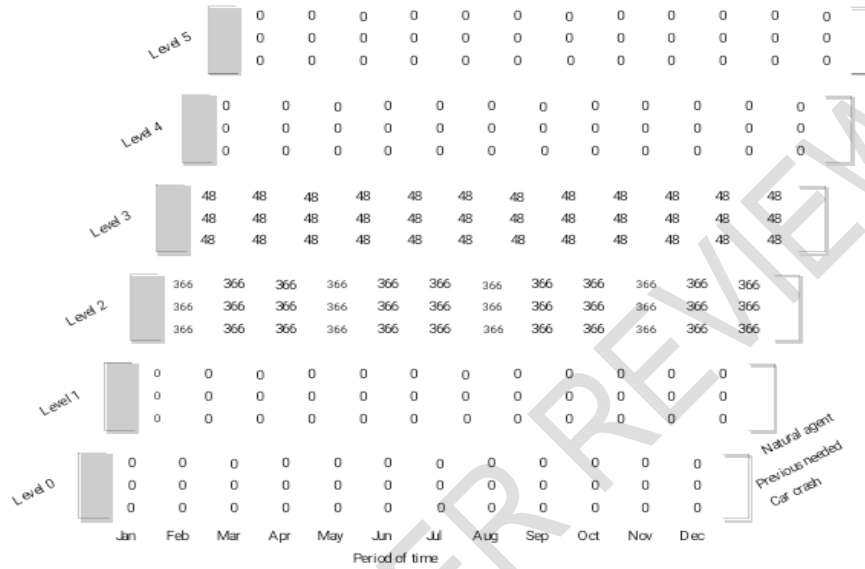


Fig. 4. Three-dimensional matrix for scenario E (Minimum cost)

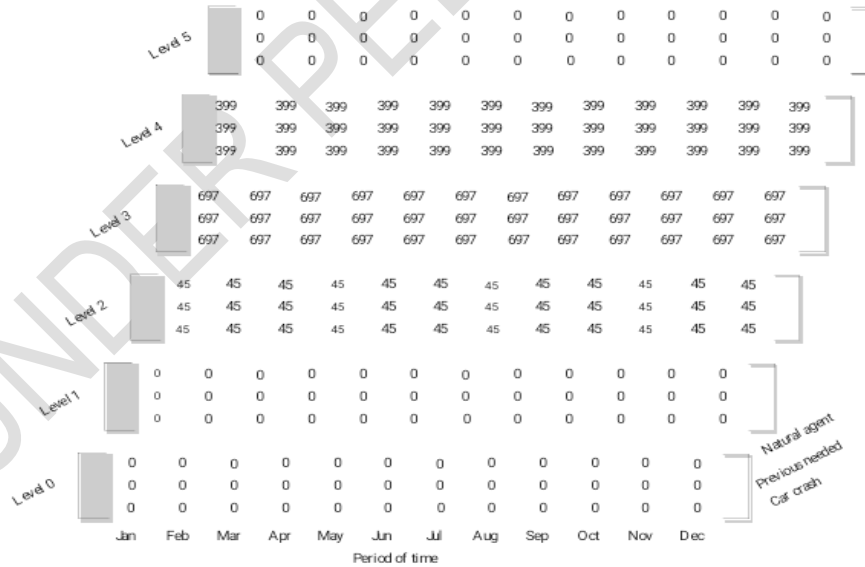


Fig. 5. Three-dimensional matrix for scenario F (Maximum benefit people)

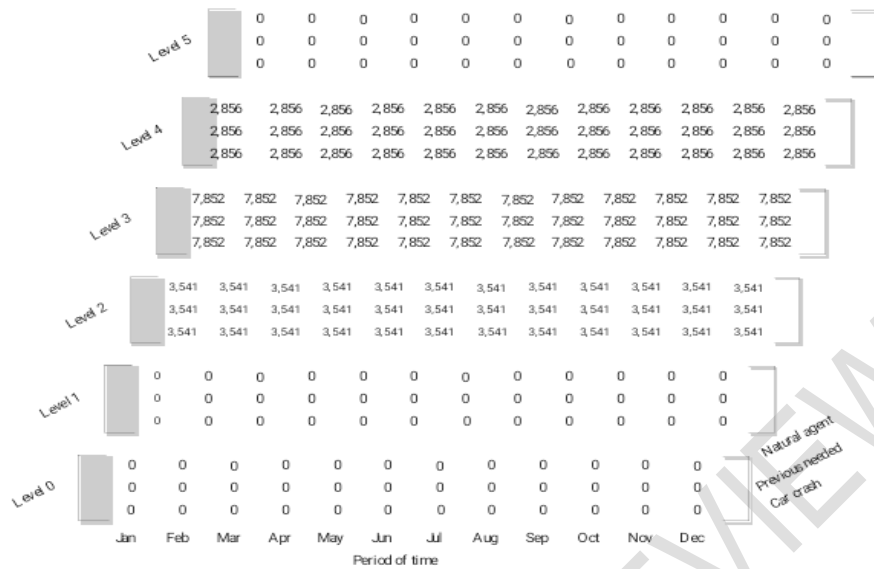


Fig. 6. Three-dimensional matrix for the scenario I (All sections repaired)

Table 3. Penalty costs according to level bridge

Bridge Level	Penalty cost (\$US/m ²)
0	0
1	8,963
2	12,614
3	19,965
4	29,827
5	900,012

Table 4. Probabilities for failure mode for period of time

Failure mode	Probability (%)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	0.69	1	1.05	0.98	0.98	0.91	0.94	0.94	0.5	0.84	0.94	0.82
Previously damage	1.05	1.54	1.61	1.51	1.51	1.4	1.44	1.44	0.77	1.3	1.44	1.26
Car crash	4.73	6.93	7.25	6.78	6.78	6.3	6.46	6.46	3.47	5.83	6.46	5.67

Table 5. Imposed costs for the scenario E

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	38,271	56,075	58,619	54,833	54,833	50,988
Previous needed	58,814	86,176	90,085	84,267	84,267	78,359
Car crash	263,961	386,762	404,305	378,194	378,194	351,676
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	52,290	52,290	28,038	47,144	52,290	45,842
Previous needed	80,358	80,358	43,088	72,450	80,358	70,450
Car crash	360,651	360,651	193,381	325,157	360,651	316,182

Table 6. Imposed costs for the scenario F

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	140,107	205,288	214,600	200,741	200,741	186,665
Previous needed	215,315	315,485	329,795	308,497	308,497	286,865
Car crash	966,342	1,415,908	1,480,131	1,384,543	1,384,543	1,287,460
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	191,429	191,429	102,644	172,589	191,429	167,825
Previous needed	294,187	294,187	157,743	265,234	294,187	257,913
Car crash	1,320,319	1,320,319	707,954	1,190,378	1,320,319	1,157,519

Table 7. Imposed costs for the scenario I

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	1,924,817	2,820,288	2,948,212	2,757,813	2,757,813	2,564,439
Previous needed	2,958,044	4,334,197	4,530,790	4,238,186	4,238,186	3,941,010
Car crash	13,275,786	19,452,002	20,334,319	19,021,104	19,021,104	17,687,369
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	2,629,888	2,629,888	1,410,144	2,371,065	2,629,888	2,305,615
Previous needed	4,041,593	4,041,593	2,167,098	3,643,834	4,041,593	3,543,252
Car crash	18,138,787	18,138,787	9,726,001	16,353,635	18,138,787	15,902,217

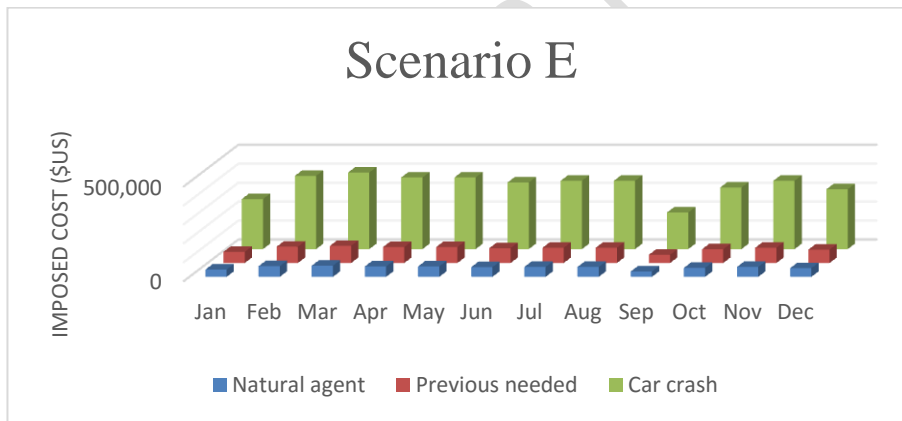


Fig. 7. Imposed costs for the scenario E

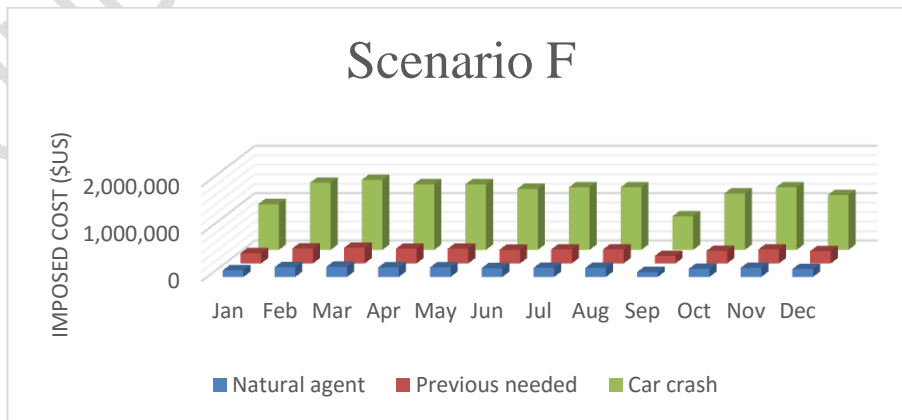


Fig. 8. Imposed costs for the scenario F

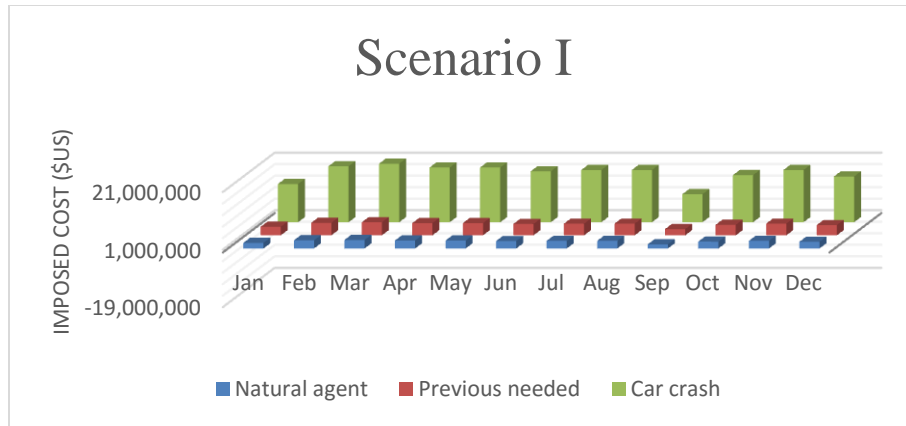


Fig. 9. Imposed costs for the scenario I

According to Cuevas-Colunga et al. [31], in the studied route, 73% of road accidents are caused by damage to the vehicle or carelessness of the driver (recklessness, lane invasion, not keeping distance, not giving way, speeding, among others). 16% of accidents is caused by the lack of road repairs and 11% by natural agents (rain, fog, smoke). Similarly, the greatest number of accidents are reported between February to May, those where there is a greater presence of the natural agents mentioned.

Once the imposed costs were calculated, each one of them was divided between the people who would benefit from the repair of the respective bridges in each section (Tables 8 to 10).

Table 8. Relation between cost and benefited people for the scenario E

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	2.93	4.3	4.5	4.21	4.21	3.91
Previous needed	4.51	6.61	6.91	6.46	6.46	6.01
Car crash	20.24	29.66	31	29	29	26.97
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	4.01	4.01	2.15	3.62	4.01	3.52
Previous needed	6.16	6.16	3.3	5.56	6.16	5.4
Car crash	27.66	27.66	14.83	24.94	27.66	24.25

Table 9. Relation between cost and benefit people for the scenario F

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	3.09	4.53	4.74	4.43	4.43	4.12
Previous needed	4.75	6.96	7.28	6.81	6.81	6.33
Car crash	21.33	31.25	32.66	30.55	30.55	28.41
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	4.22	4.22	2.27	3.81	4.22	3.7
Previous needed	6.49	6.49	3.48	5.85	6.49	5.69
Car crash	29.14	29.14	15.62	26.27	29.14	25.54

Table 10. Relation between cost and benefit people for the scenario I

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	11.19	16.4	17.14	16.04	16.04	14.91
Previous needed	17.2	25.2	26.35	24.64	24.64	22.92
Car crash	77.2	113.11	118.24	110.61	110.61	102.85
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	15.29	15.29	8.2	13.79	15.29	13.41
Previous needed	23.5	23.5	12.6	21.19	23.5	20.6
Car crash	105.47	105.47	56.56	95.09	105.47	92.47

As well in Figures 7, 8 and 9, and Tables 8, 9, and 10, it is shown that the relation between costs and benefited people is greater in the case of a car crash than in the other failure modes, since if the repair of a bridge is presented in a place where the incidence of a car crash is higher, the greater the number of benefited people, by repairing those sections and seeking to reduce the number of accidents. Finally, the maximum relationship is identified to calculate the resilience in each of the points (Tables 11 to 13) according to Equation 2. The resilience calculation allows identifying those aspects to which more importance should be taken. In the case of scenario E (minimum cost), it can be observed that from February to May there are lower indexes of resilience, so it is important to take preventive measures and repair the damage caused on these dates to reduce repair costs and accidents.

Table 11. Resilience indices for scenario E

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	0.975	0.964	0.962	0.964	0.964	0.967
Previous needed	0.962	0.944	0.942	0.945	0.945	0.949
Car crash	0.829	0.749	0.738	0.755	0.755	0.772
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	0.966	0.966	0.982	0.969	0.966	0.97
Previous needed	0.948	0.948	0.972	0.953	0.948	0.954
Car crash	0.766	0.766	0.875	0.789	0.766	0.795

Table 12. Resilience indices for scenario F

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	0.974	0.962	0.96	0.963	0.963	0.965
Previous needed	0.96	0.941	0.938	0.942	0.942	0.946
Car crash	0.82	0.736	0.724	0.742	0.742	0.76
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	0.964	0.964	0.981	0.968	0.964	0.969
Previous needed	0.945	0.945	0.971	0.95	0.945	0.952
Car crash	0.754	0.754	0.868	0.778	0.754	0.784

Table 13. Resilience indices for the scenario I

	Jan	Feb	Mar	Apr	May	Jun
Natural agent	0.905	0.861	0.855	0.864	0.864	0.874
Previous needed	0.855	0.787	0.777	0.792	0.792	0.806
Car crash	0.347	0.043	0	0.065	0.065	0.13
	Jul	Aug	Sep	Oct	Nov	Dec
Natural agent	0.871	0.871	0.931	0.883	0.871	0.887
Previous needed	0.801	0.801	0.893	0.821	0.801	0.826
Car crash	0.108	0.108	0.522	0.196	0.108	0.218

Similarly, for scenario F (maximum benefited people), the lowest resilience indices are found in the event of a possible deterioration through a car accident. Remarkably similar values are presented throughout the year, except for January and September, so if we want to increase the number of people benefited who make use of bridges, it is advisable to carry out necessary repairs throughout the year.

On the other hand, in the scenario I, the one in which all the bridges of all the sections are repaired, we can observe in the event of a car accident, extremely low resilience values, thus the ratio of the cost of repair to people benefited by it is not particularly good.

However, for both scenarios E and F, good resilience indices are presented, which means that the cost-benefit relationship is good to considering the repair of all the bridges in these two sections.

5. CONCLUSION

In this work, a methodology for a new approach to assessing resilience in road transport routes has been presented. A specific route has been analyzed as a case study to test this methodology. A federal highway route was analyzed, called "a commercial corridor" that crosses seven states of Mexico, reaching the USA, and ending in Canada. However, only the section corresponding to the state of Michoacan was taken into account. The highway section was divided into eight sections of which all the bridges located in each corresponding section were evaluated. In this way, it was estimated which bridges according to their state of conservation and the number of benefited people were a priority for their attention.

In the three scenarios studied; scenario E (Comanja-Carapan), which represents a minimum cost, was identified as the one where the resilience indexes are lower from February to May. This means that, in that period, the system could be affected by being interrupted by the damages caused. Therefore, it is recommended to carry out preventive measures to attend to the damages caused in that period to reduce repair costs and decrease accidents.

Similarly, in scenario F (Carapan-Zamora), identified as the one that benefits the most people, low resilience indices are observed in terms of deterioration due to accidents. The values are remarkably similar throughout the year, except for January and September. Thus, it is necessary to make repairs throughout the year to reduce road accidents.

Referring to scenario I, which is the one in which all the bridges on federal highway 15 are repaired, it presents extremely low rates of resilience in case of accidents. Thus, the relationship between the cost of repair and benefited people is not particularly good.

However, scenarios E and F present good resilience indices, which indicates that the cost-benefit is good, so it can be suggested to consider repairing all the bridges in these two sections.

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