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Lessons Learned for Puerto Rico's Transportation Infrastructure after Hurricane María

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Hurricane María arrived at the Commonwealth of Puerto Rico on September 20, 2017 as a category 4 storm with maximum sustained winds of 155 miles per hour (mph). Rainfall values up to 37.9 inches were registered in the mountainous region during the first 48 hours of the storm.[1] According to NASA, María was the most powerful storm to enter Puerto Rico in more than 80 years (fifth strongest overall entering any U.S. jurisdiction).[2] Also, María is the costliest hurricane to have impacted Puerto Rico with a preliminary cost estimate of $94 billion. At the national level, María ranks (at this moment) as the third most expensive hurricane in U.S. history, surpassed only by Katrina in 2005 with $160 billion and Harvey in 2017 with $125 billion.[3] An independent study conducted by George Washington University and commissioned by the Government of Puerto Rico estimated the loss of human lives to be 2,975 people; caused directly or indirectly by the passage of María in Puerto Rico after the first six months.[4] This death estimate places María as the second worst storm in U.S. history, surpassed only by the hurricane that hit Galveston, Texas in September 1900 that resulted in an estimated 8,000 to 10,000 deaths.

Figure 1. Typical damages suffered by Puerto Rico's infrastructure due to Hurricane María.

Just two weeks before María's landfall, Hurricane Irma impacted Puerto Rico as it passed approximately 50 miles northeast, causing power blackouts and road infrastructure damage. Given the proximity of these two storms, María's impact was catastrophic due to already saturated soil, fragile electrical infrastructure, and the short recovery time with a lack of resilience of essential services, including the transportation infrastructure. This article presents the main effects and damages to Puerto Rico's transportation infrastructure due to Hurricane María, with a discussion of the lessons learned and a look at the challenges ahead as Puerto Rico prepares for the rebuilding and resiliency strengthening of its transportation networks and services.

Damages to the Transportation System

Hurricane María severely affected infrastructure systems and services across Puerto Rico, including the electric grid, the potable water system, the highway system, telecommunications, telephone and internet services, air and maritime transport, freight and supplies, and mass transit services. Figure 1 illustrates representative damages suffered by the infrastructure in different regions of Puerto Rico due to Hurricane María.

Damages to Bridges and Roadways

On a preliminary basis, the Government of Puerto Rico estimated the damages and losses at $94 billion. Of these, $5.85 billion was the estimated cost of the damages sustained by the transportation infrastructure, divided into $4.5 billion for roads, bridges and mass transit, and $1.35 billion for seaports and airports.[5] The Puerto Rico Department of Transportation and Public Works identified 1,500 segments of urban and rural roads with substantial damages.[6] The effects of the hurricane caused the interruption of the road system due to the scouring or collapse of bridges and their approaches, landslides and rock falls, obstructions caused by trees or debris, broken pavements, coastal erosion, and floods due to rains or river overflows. The effect of the winds caused the substantial loss of traffic signals and road signs. A total of 388 bridges (16.6 percent of the total) were affected, with a total estimate in damages between $500 and $600 million. Fifty-seven bridges suffered destructive damages; 26 had a collapse of the structure and 31 had a collapse of the approaches. Landslides and rock falls caused blockages along steep terrain on the rural road system, and in some cases, the road foundation failure and the collapse of the entire roadway. This hindered access on the road network, limiting the access to medical services, shelters, food locations, and gas stations, particularly on the central region of the Commonwealth. The United States Geological Survey estimated that 50,000 landslides occurred in Puerto Rico due to the storm rainfall.[7] Road collapses not only occurred due to landslides in the mountainous area, but also occurred along the shore communities due to coastal erosion and flooding.

Damages to the Signal Systems

The signal system of the Commonwealth includes approximately 1,220 signalized intersections. All signals became partially or totally inoperative due to the damage caused by the hurricane. As of June 2018, only 720 (59.0 percent) of the signals were operational, 121 signals (9.9 percent) were repaired but did not have electricity, 75 signals (6.1 percent) were still under repairs, and 304 signals (24.9 percent) were still unattended.[8]

Damages to Road Signs and Utility Poles

Another significant impact of the winds was the failure of the foundation causing the collapse of overhead roadway signs. These failures are preliminarily attributed to the magnitude of sustained winds and gusts, which exceeded the local structural code for wind loads, that preceded the current standard ASCE 7-16. Other overhead signs did not collapse, but experienced rotation of the arm mast. In these cases, the sign did not necessarily obstruct the path, but was capable of causing additional damage in adjacent utility poles. In other cases, fallen utility poles and power lines obstructed existing traffic routes, necessitating the detour of traffic to other roads, creating significant congestion in said alternate roads.

Disruption to transportation services and the logistics of emergency goods and services

For weeks, the damages to the rural road network negatively impacted the mobility of people, goods, and services, as well as the logistics for the distribution of emergency materials and essential supplies. The high demand for goods after the event, such as food, fuel, gas, ice, and cash, also caused obstructions to the traffic flow on roads due to the long vehicle queues that formed at the stores occupying the shoulders or the traffic lanes. The queues resulted in long waiting times (Figure 2), that combined with the restricted space on the traveled way due to the presence of vegetation and debris, caused greater traffic congestion on narrow roads, and consequently delayed the distribution of emergency materials, essential supplies, equipment, and machinery.

Another effect on the highway system was the presence of citizens roaming the roads searching for mobile (cellular) signal due to the collapse of communication antennas. As telephone and cellular services were slowly restored, many citizens set out to look for places with cellular signal reception along the roads, stopping at the roadside (even in expressways and highways) where they could reach the service (Figure 3). In such situations, the presence of shoulders provided some degree of separation between the citizens and the adjacent vehicular traffic.

The interruption of mass transit services around Puerto Rico lasted for weeks, limiting the mobility of low income and transit dependent inhabitants, particularly in major cities. The most critical interruption occurred to the Tren Urbano (heavy rail) in the San Juan Metropolitan Area due to the failure of the electrical system and the structural damages occurring to some of the 16 stations. The rail system does not generate its own electricity, therefore it depended on the reestablishment of the electrical distribution grid of the metropolitan area. The Tren Urbano has an average of 35,000 daily users, therefore a bus-bridge system connecting the major rail stations became an alternate mode of transportation. The rail system resumed operations on a limited schedule three months after the hurricane, with three of its stations closed. [9]

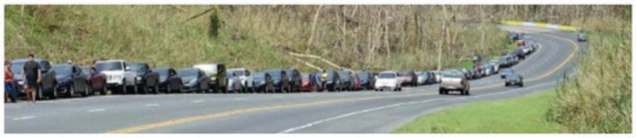
El Nuevo Día newspaper

Figure 2. Queue of vehicles parked along the PR-142 shoulder for a gas service station in Corozal.


WAPA TV

Figure 3. Citizens searching for mobile phone signal on freeway PR-22 in Toa Baja.

Lessons Learned

In the case of coastal road infrastructure, the importance of the rigorous application of laws and regulation of the maritime-terrestrial zone was observed. At the same time, revisions to the Puerto Rico Highway and Transportation Authority (PRHTA) standard drawings for road infrastructure should be conducted, specifically for those components relevant to roads adjacent to the coastline to minimize failures related to coastal erosion. In the case of the bridge infrastructure, it was concluded that the design of bridge abutments requires more rigorous evaluation and application in locations where turbulent flows with scour potential are expected during the useful life of the design. To address the problem of landslides, the PRHTA model plans associated with cut section slopes in clay soils and unstable rock formations should be revisited.

The use of steel mesh to contain rock falls at locations in which numerous landslides occurred must be re-evaluated. The use of benched slopes in cut sections should be incorporated widely in future designs. The use of shotcrete at cut sections on roads of the Central Range should be considered as a cost-effective design alternative. These options have two fundamental benefits, namely the removal of loose material on the soil surface, thus exposing less weathered and thus more solid rock strata, and the creation of an erosion-resistant surface. Fill sections exposed to water erosion should use mechanically stabilized soil with geosynthetics, instead of using loose materials that can be removed by flowing water and/or gravity.

Preventive maintenance of storm drainage systems in urban areas is essential to minimize the potential for flooding. Low areas with clogged drainage systems represent flooding problems that are unnecessary and that divert resources for emergency response that can be used more effectively at more pressing locations. The presence of shoulders along major highways with cut section slopes lower than 800 ft .(240 m) in height minimizes the impact of landslides, allowing the operation of the road with reconfiguration of lanes, providing at least one lane per direction. The shoulders can also accommodate recovery activities more easily. When there are long lines of citizens searching for essential goods and services, these also prevent the blockage of traffic lanes. Shoulders also have the benefit of providing space for electric and telecommunication utility repair activities and thus increase vehicular flow capacity by reducing the need of occupying traffic lanes.

Following the passage of this extreme atmospheric event, the importance of redundancy along primary highway corridors was demonstrated. The redundancy enabled continued movement of people and goods during the recovery process from Hurricane María. Those primary corridors with AADT in excess of 20,000 vehicles per day, such as freeways paired with a parallel multilane arterial roads, have more capacity to divert the flow of heavy vehicles and peak hour traffic when these scenarios occur.

The design of traffic signals mounted in span wires should be revisited. It is pertinent to replace span wire mounted signals with mast-mounted signals in regions exposed to major hurricanes (Category 3 or higher). One design code to consider is that of the State of Florida, which underwent design revisions and updates based on the experience with Hurricane Andrew in 1992. The Government of Puerto Rico also conducted efforts to receive the support of highway police from other U.S. jurisdictions to support the local police to attend the main intersections of the metropolitan areas of San Juan, Carolina, among others, and thus control traffic and reduce delays in major cities of the Island. This request was necessary to allow the local police to focus on and attend other incidents associated with public security and specifically during the curfew period in the first 2 to 3 weeks post-Hurricane María.

The designs of utility poles and luminaires (steel, concrete and wood) that failed at the base and at their upper third portion must be evaluated for their resistance to wind load. This review should consider the properties of the materials, the cross section and the aerodynamic response to gusts. The design of lateral signs and directional signs of overhead signs, in particular those with an impact-yielding base design, must be revisited. A design option whose performance was favorable to Hurricane María was the overhead gantry configuration. The horizontal arm, being fixed at both ends, is not subject to rotation or eccentricity of wind loads and therefore is more stable.

The passage of the atmospheric phenomenon presented Puerto Rican transportation professionals with new transportation challenges, both at the infrastructure and operations aspects. Due to the danger caused by blackouts at signalized intersections, as well as damaged pavements and bridges, long-term Temporary Traffic Control (TTC) is required to provide a safer road environment through warnings and channelization of traffic. Floods also obstruct roads and create the need for temporary diversions, which are a problem that must be addressed with a CTT. The two main challenges of implementing a CTT for the different unanticipated emergency situations caused by the hurricane is to have all the necessary devices for its deployment and be able to complete the execution of the CTT in a reasonable time to cover all the affected places given the magnitude of the event and the number of situations found throughout the island. It should be mentioned that the incorrect use or location of the control devices in a CTT can cause greater traffic congestion and safety problems. To improve the effectiveness of a CTT, the use of intelligent transportation systems (ITS) by solar energy and retroreflective devices should be considered. Examples of these devices may include:

- Portable variable message signs and arrow boards
- Portable traffic signals
- Portable traffic monitoring sensors
- Prismatic reflectors (cat's eyes)
- Retroreflective thermoplastic paints
- Retroreflective signs with fixed and portable mounting

Part 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD) recommends that for incidents on a highway whose anticipated duration exceeds 24 hours, devices and TTC configurations similar to those required and suggested in work zones or road construction.[10] This practice, although beneficial, was not necessarily possible to execute in Puerto Rico due to the shortage of materials and personnel to design, install, and maintain the TTCs. For future natural events it is recommended to develop and pre-plan typical TTC designs for landslides and rock falls, with their corresponding

Figure 4. PR-511 Real Anon roadside damage.

Figure 5. PR-506 downed pole near hospital in Coto Laurel.

materials. In other cases, it is recommended to establish a collaboration with local communities to train volunteer bodies to direct traffic at affected locations, but only at local roads, where vehicular speeds and volumes are low and represent less risk to their safety.

In the long term, the logistics of response and repair of the infrastructure must be improved because they put at risk the safety of every user of the road network. For the implementation of temporary traffic control (TTC), several recommendations for future experiences were identified. These are:

- Develop typical applications specific to common incidents in post-hurricane scenarios.
- Train emergency response personnel in incident management strategies.
- Use flexibility when using TTC plans for emergency situations
- Collaborate with communities to alleviate staff shortages.

Priority should be given to the use of devices that do not depend on logistics to sustain their operation, such as retroreflective devices and solar-powered electronic devices due to the high priority of safety, regardless of difficulties confronted in the response. Cases in which travel through damaged portions of a road result in severe injury or death for workers and the public are especially critical.

Conclusion

Hurricane María should serve as a golden opportunity to rethink and redesign Puerto Rico's transportation infrastructure to be resilient. María was an extreme Category 4 storm that caused severe damages to the transportation systems and hindered for weeks the mobility of the 3.3 million residents of the commonwealth. The unprecedented 2,975 fatalities associated to the storm were mainly the result of the power blackout and the lack of access to essential medical and health services. The damages to the transportation system demonstrated the importance of having a resilient and redundant system for prompt response and recovery. A resilient transportation system is vital for the livability and development of any country, but more so for Puerto Rico, and any Caribbean island, that is entirely dependent on the internal mobility of cargo and people through surface routes. Much of the vulnerability and damage resulting from the hurricane was associated to the exposures of the infrastructure in the coastal and mountainous zones.

Finally, it is imperative that the planning of logistics, distribution, and transportation of essential goods, such as fuel and food, be improved to minimize the effect of obstructions on the supply chain and the road network. It is necessary to rethink the logistics of the distribution network of goods recognizing the limitation of having most of the supply lines concentrated at the Port of San Juan. Another critical aspect is for the public, retailers, and distribution companies to be prepared and store additional quantities of the essential products in anticipation for future high severity natural events. This recommendation is pertinent because in our case post-María several bridges and their approaches, as well as the different road segments connecting each part of the Island were obstructed by landslides, floods, debris, or road furniture, or collapsed reducing the effectiveness of the response and recovery efforts.

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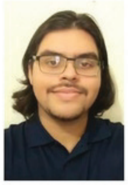

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