Framework for Considering a Diverging Diamond Interchange to Improve Operations and Safety.

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Abstract- Innovations on intersection design have been the focus of recent developments in the US and around the world. The second installment of the Every Day Counts initiative (EDC-2) from the Federal Highway Administration (FHWA) promoted five new intersection designs. One of them was the Diverging Diamond Interchange (DDI). This innovative design has been implemented in several cities in the US to improve operations and safety. Puerto Rico is currently building its first DDI in the intersection of an arterial street and a freeway in the Municipality of Gurabo. This paper discusses the main characteristics of the DDI and presents a design framework from conception to implementation. This framework considers the geometric, environmental, and cultural influence in the design of a DDI, while also paying attention to the influence of non-motorized users and the continuous evaluation of the intersection by using driving simulation as part of the effective project implementation. Other topics discussed include safety evaluation, signaling, traffic influence, and the use of driving simulation into the determination of operational safety at a DDI. Also, the comparison between the conventional diamond interchange and the DDI, potential DDI issues from an operational point of view, and the objectives or goals of this type of intersection design are presented. A discussion of the benefits of using a driving simulator as a tool to evaluate a DDI and the importance of the data gathered in the process are also explained. Details of the implementation of this framework in Puerto Rico are presented as concluding remarks.

Keywords-- Diverging Diamond Interchange, Safety, Driving Simulator, Framework, Intersection.

I. Introduction

Innovations on intersection design have been effectively implemented to improve safety concerns and reduce urban congestion. The initiatives of the Every Day Counts 2 program (EDC-2) from 2013 to 2014 focused on five innovative intersection and interchange geometric designs to accommodate traffic efficiently. Among these intersections is the Diverging Diamond Interchange (DDI).

DDIs have been implemented in several locations across the United States, improving road safety and the perception of road users. The Missouri Department of Transportation built a DDI in 2011. After its first year in operation total crashes were reduced 46% and more than 80% of the road users expressed that traffic delays had decreased at the intersection[1].

The DDI eliminates the signalized left-turn phase at the two intersections within the diamond interchange by shifting crossroad traffic to the left side of the roadway between ramp terminals. This change improves safety and traffic flow by reducing the number of traffic conflict points and the number of signal phases, respectively. Typical safety benefits of a DDI include: reducing conflict points from 26 for a conventional diamond to 14, spreading out conflict points throughout the interchange, maintaining better sight distance at turns, reducing the opportunity for wrong way entries to ramps, and shortening pedestrian crossings. Operational benefits include unique phase combinations, “Free” or simple left and right turns from all directions, increased left turn lane capacity without needing more lanes, only needing two phases, shorter cycle length, lanes with multiple assignments in all directions, better storage between the ramp terminals, improved U-turn maneuvers from the freeway, and better signal network synchronization compared to a CDI [2].

The main objective of this paper is to present a general framework for the implementation of a DDI from conception to implementation. Also, the details of a DDI will be presented along with a description of the main features of this innovative intersection design.

The elements presented in this framework are of particular importance when a new type of intersection is implemented for the first time in a region; this is the case for Puerto Rico. Driving culture is considered in this framework by including a step for driving simulation in the framework. Using a driving simulator, local drivers can experience the design before its implementation. If necessary, adjustments or changes can be made to the final design and the continuous evaluation process will proceed throughout the intersection’s lifetime.

II. Literature Review

Operational safety for freeways, highways, streets, and intersections has become a difficult task for planners and engineers. Mobility, accessibility, and the interrelation between motorized and non-motorized users, including pedestrians and cyclists, must be considered. These elements are particularly important at complex intersections such as the

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Conventional Diamond Interchange (CDI). New designs such as the DDI aim at improving safety and operations.

Historically, the most used type of urban interchange has been the CDI. CDIs are crucial elements in a roadway system and are mainly used for lower-traffic interchanges without special constraints. The efficiency of a diamond interchange design seems to be reduced when traffic gets heavier on the surface street or ramps, or when there is heavy left-turning traffic.

Alternatives that could help improve CDIs while limiting geometric changes to intersections are crucial. However, to address the need for the additional right of way generally required for a CDI while still responding to increased traffic demand, a new type of interchange has emerged: The DDI.

According to the FHWA, the DDI is an innovative alternative to the CDI or other alternative interchange forms that can better accommodate left-turn movements onto or off ramps [3]. The primary difference between a DDI and CDI is the inclusion of directional crossovers on either side of the interchange in its design. The key logic of a DDI is to provide efficient navigation for both left-turn and through movements between highway ramps and to accommodate left-turn movements onto the arterial without using a left-turn bay as presented in Fig. 1.

Additionally, a DDI focuses on creating an effective alternative for intersections with high left-turn volumes, reducing points of conflict, and elevating the level of service at lower costs than other alternative interchanges.

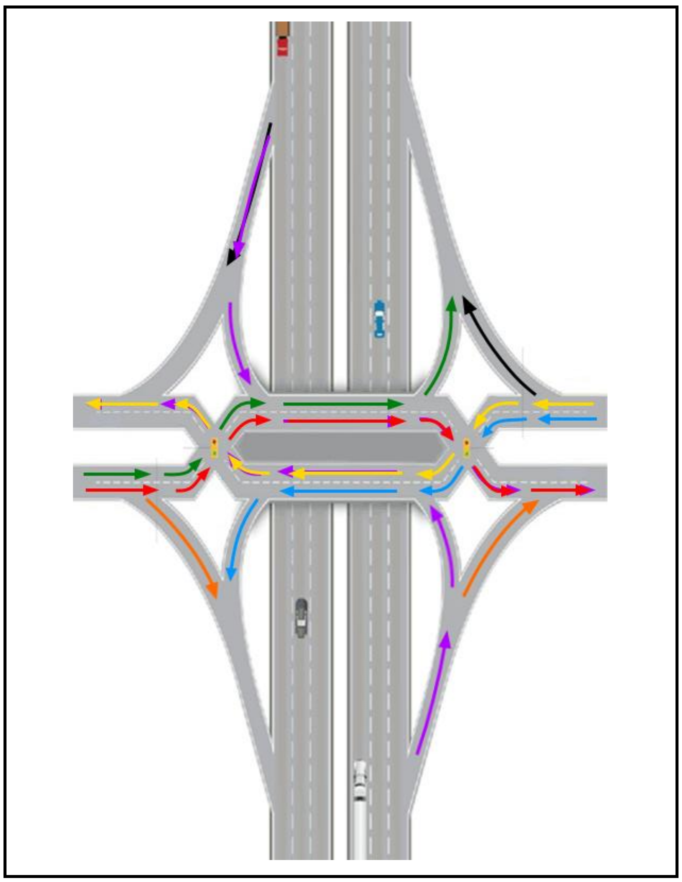

Fig. 1 Schematic of a Diverging Diamond Interchange

A. Safety evaluation

Several researchers have studied and evaluated the effectiveness of DDI's on safety while taking crash data of existing DDI's into consideration [4][5][6]. Safety evaluation methods, including the Comparison Group Method and the Empirical Bayes Method, among others, have been applied to compare and evaluate DDI safety improvements. These evaluations' consistent results have demonstrated that implementing DDI's has significantly decreased the percentage of crashes in comparison to CDI's; supporting the general understanding of how a DDI can contribute to the community. However, a DDI does not eliminate 100 percent of fatalities and injuries.

B. Signaling and Traffic

The 2014 Federal Highway Administration's "Diverging Diamond Interchange-Information Guide" and the *Manual on Uniform Traffic Control Devices* (MUTCD), are considered the primary guides for standards related to traffic control devices and DDI signaling design.

Efficient signaling and proper traffic flow analyses are important subjects to determine which variables influence DDI's operational performance [7], [8] Several researchers have developed procedures to optimize the traffic signal design for DDIs; considering variables such as green splits, geometric designs, traffic volumes, and phasing plans, among others. These variables, depending on the DDI's properties, are incorporated into the algorithms developed to maximize intersection capacity and improve safety at the intersection for all users.

C. *Simulation*

Microsimulation is one of the most popular tools to evaluate the DDI. It's also used to analyze and understand how DDI performance is impacted by modifications whenever there are ideas for improving it and how these changes could best be implemented.

FHWA evaluated the first DDI established in Missouri, USA using a driving simulator; they were concerned with how this innovative solution impacted human factors and drivers' safety [3], [9]The use of driving simulators is crucial to identifying dangerous human behavior and other safety issues before exposing drivers to new designs. They can also provide a representation of real environments and situations without jeopardizing the safety and health of human subjects.

The evaluation or implementation of DDIs has never been done in Latin America. This research will highlight the importance of using a driving simulator to evaluate possible outcomes and areas of growth during the planning, construction, and operation of the DDI. The combination of this research literature with the proposed framework will help reduce the impacts of implementing a DDI in Puerto Rico.

III. DIVERGING DIAMOND INTERCHANGE VS CONVENTIONAL DIAMOND INTERCHANGE.

Planners around the U.S. have been very interested in implementing DDIs as an optimal solution to a CDI. However, there are some drawbacks to using this innovative design. A comparison between DDIs and CDIs designs is presented below:

- DDIs have fewer conflict points compared with a CDI, which can translate into fewer crashes.

- The reverse curvature presented in DDI geometry tends to reduce speeds at the location of the crossing-path, which could result in fewer crashes [9].

- DDIs' design is able to combine left-turning traffic with through traffic. This eliminates the left turn-only signal phase of a CDI and reduces delays at the intersection [7].

- DDIs can safely accommodate pedestrians and cyclists through the interchange, creating shorter pedestrian crossing distances for some movements and facilitating two-stage crossing [10].

IV. DDI PROBLEMS FROM THE OPERATIONAL POINT OF VIEW

There are some conflicts that may arise when implementing a DDI design since not every DDI's characteristics will match with the safety goals set for a diamond intersection. It is important to know the implications this decision may have and the problems that may arise, such as:

- A DDI's geometric design makes it challenging to coordinate through traffic in both directions [11].

- There are some unusual sight distance considerations at crossovers and ramp movements that could lead to inconveniences for drivers, pedestrians, and cyclists [12].

- Access control may be required beyond interchange to prevent weaving maneuvers [3].

- Some pedestrians could be unaware of the direction where the traffic is coming from and could be unfamiliar with the location of walkways on DDIs [3].

All of these situations must be examined while considering how some users may not be familiarized with this intersection to allow for an optimal operation of the DDI and ensure users' safety.

V. MAIN GOALS FOR THE DDI

The DDI surges from a societal need, which is why it is so popular. It has taken the flaws of its predecessor and made them into strengths without sacrificing the structure.

DDIs aim to save lives and almost every time conflict points between pedestrians, cyclists and other vehicles are reduced there is also a decrease in crashes and crash-related deaths; all of which positively impacts the surrounding community.

Several studies have researched driver behavior in DDIs, one of which was done by Joe Bared [4]. He explains that some drivers may still be confused about DDIs because they are unfamiliar with this new design. However, he also remarks that velocity is reduced in the DDIs, which decreases crash severity and frequency at the intersection.

The DDI meets the main objective of transportation's structures to improve safety, reduce delays, reduce congestions and provide an innovative system that allows non-motorized users to also enjoy this structure.

VI. DRIVING SIMULATORS AS A TOOL TO EVALUATE AN INTERSECTION

Driving simulators are a tool motivated by advancements in technology that rely on visual, auditory, and dynamic elements to provides a realistic environment which can translate driver actions into vehicle motions. This tool has been used since the second half of the twentieth century, but its influence in passenger cars started to gain steam in the late 1970's [13].

Simulators are used to effectively study the interaction between vehicles and their drivers from different perspectives and professions such as engineering, medicine, and psychology. Also, it provides researchers with enough information to obtain a conclusive analysis of their results. This is why it is the preferred option to get a clear idea of how a scenario that is not built in real life could be developed.

Transportation engineers use driving simulators to evaluate driver behavior, geometric characteristics, and external factors which could affect different types of highway, curve, and intersection designs. With this information they can find different, more efficient ways to address operational issues.

How effective a driving simulator could be in evaluating a DDI to obtain relevant information is something important to consider. Some of the benefits of its use are:

- Ability to control and reproduce scenarios without compromising the physical, mental, or psychological integrity of the test subjects.

- Ease of data collection helps to study drivers' performance in simulators and easily identify the areas in need of improvement within the intersection.

- Possible to encounter dangerous driving conditions without test subjects' being physically at risk.

These elements demonstrate the benefits a new DDI designer could gain in using a driving simulator to gain a better understanding of how a DDI's design influences its users.

VII. DRIVING SIMULATOR AT UPRM

The driving simulator of the University of Puerto Rico at Mayaguez (UPRM) is used in this study. This driving simulator equipment is configured as a cockpit simulator with three primary parts: the vehicle, the projectors and screens, and the computer hardware and software. The vehicle consists of a car seat, a gear shift, a steering wheel, and brake and accelerator pedals which are all placed in a wood frame with six wheels to make it versatile for mobile application. The gear shift is located on the right-hand side of the car seat. The steering wheel with a turn signal control is placed in front of the car seat and rests on a wooden countertop that serves as a dashboard. The brake and accelerator pedals are fixed on the floor below the countertop. The simulator has three overhead projectors, each with their respective screen, with a 10° deflection angle between them to create a panoramic view of the roadway. The audio from the simulation comes through a sound-bar system that is in the simulator's wooden frame. Regarding hardware and software, the simulator has connected desktop and laptop computers with NVIDIA graphics and the RTI SimCreator/SimVista simulation software.

VIII. DDI Design Framework from Concept to Implementation

The framework for designing a DDI to replace an existing CDI presented in Fig. 2 incorporates a driver's culture into the design. Direct design experimentation through a driving simulator would allow local drivers to experience the main characteristics of this type of interchange first hand to make sure that the geometry, signage, and markings are well understood. Incorporating simulation, the design may be refined before the interchange is open to the driving population. This is particularly important when a new design such as the DDI is introduced for the first time in a region; as is Puerto Rico's case.

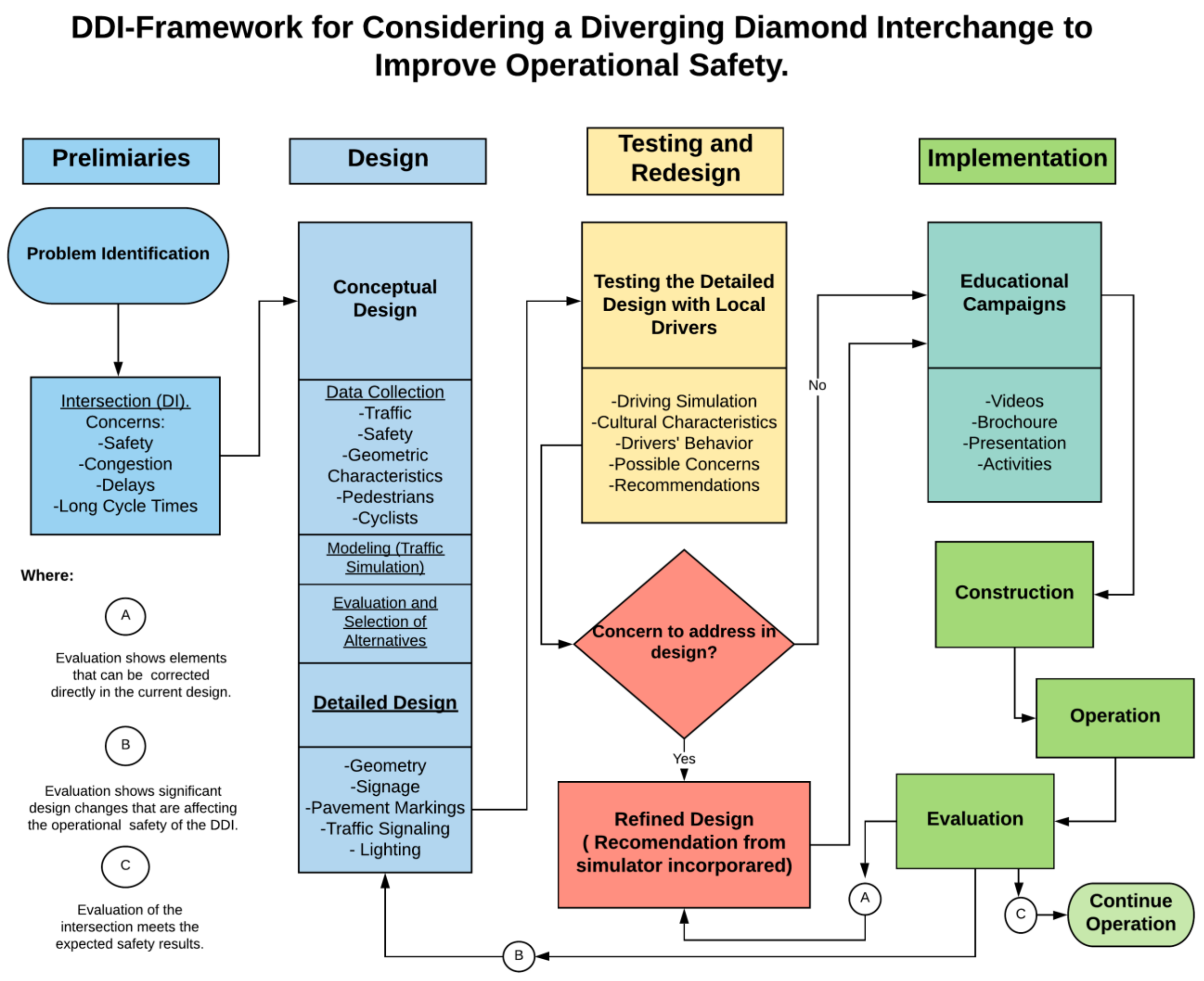

Fig. 2 DDI-Framework for Considering a Diverging Diamond Interchange to Improve Operational Safety.

A brief description of the processes depicted in this framework are presented in Fig. 2.

A. *Problem Identification*

Information that justifies the implementation of a DDI onto an existing CDI must be readily available. This is why data collection plays a fundamental role in analyzing whether to consider this design as a potential solution for an intersection.

The process starts by identifying what modifications the given intersection may need. If there is already a continuous tracing of the CDI's current status in place, the obtained information is an integral part of the process; therefore, defining the need for a change in the intersection. If this is not the case, the problem identification process typically starts with direct observations of the consequences congestion, delays, and frequent crashes may produce at the intersection and its surrounding area. Once the problems have been identified, the data collection process will allow to quantify the problems and prompts the design of alternative solutions

.

B. Conceptual Design

The conceptual design begins taking shape once decision makers identify changing a CDI as a need for the community. Since this is also when it is time to begin thinking about solid alternatives that may bring positive results, important geometric and operational aspects are taken into consideration in the conceptual design to effectively implement the best solution possible.

The conceptual design process includes at least three principal elements: data collection, modeling including traffic microsimulation, and evaluation and selection of alternatives.

i. Data Collection

A data collection process can help determine the current intersection's status and serve as a base for analyzing alternatives potential operational and safety improvements. There are several aspects and elements of an intersection that are taken into consideration when analyzing the possibility of implementing a DDI including the following:

- Crash frequency and severity records for the intersection and its surrounding area.
- Average Annual Daily Traffic (AADT) reports which include traffic volumes by movement and type of vehicle, pedestrians and bikes volumes including typical movements, and in the case of CDI's, special attention devoted to traffic volumes of left-turns and trough movements at the intersection.
- Current speeds registered at the intersection compared with design speed.
- Sight distance and stopping sight distance at the intersection.
- Horizontal and vertical alignments as well as typical cross sections (including superelevations).
- Intersection geometric characteristics (lane width, shoulder width, intersection grade, angle of intersection).
- Geometric characteristics of ramps and available space between the signalized intersections that form the CDI.
- Verification that the dimensions are appropriate for a possible implementation of a DDI at the intersection.
- Frequency of pedestrians and cyclists use for the intersection. Typical paths and routes that are used for pedestrians to get across the intersection.

These aspects all need to be taken into consideration to gain a clear understanding of the parameters that need to be considered when effectively looking for the best possible alternative to, or when seeking to improve the current status of, the diamond interchange.

ii. Modeling (Traffic Simulation)

Modeling tools are used to simulate and verify the current conditions of the intersection and to quantify the problems identified before. These tools allow researchers to generate and test alternative designs and determine their possible impacts. Innovative alternatives such as the DDI would be considered at this stage. Alternatives also consider other solutions such as changing signal timing or making minor adjustments without drastically altering the intersection's geometric design. All this information serves as the basis for evaluating alternatives.

iii. Evaluation and Selection of Alternatives

The evaluation of alternatives consists of comparing the impacts of each alternative design. Several procedures can be used to carry out the selection of the preferred alternative. Typically, designs that improve operations and safety while also having good cost/benefit indicators are preferred in the selection process. The DDI has proven to be that kind of solution when compared to the CDI.

If a DDI is the preferred option to address the problems identified at an interchange, it is important to check if a DDI has been built in the region before, verify the results of these previous implementations, and check how appropriate it may be to implement this type of solution. If one has not been built in the region yet, it is recommended that special attention be paid to making sure that local drivers understand how to drive along this type of interchange with crossover features.

C. Detailed Design.

At this stage, decision makers have already evaluated and analyzed all possible alternatives and considered and determined that a DDI design would be the appropriate solution to the problems identified in the intersection. The next step is the detailed design where the final geometry is decided.

Some of the most relevant elements to take into consideration while designing a DDI are:

- Geometry (provision of eyebrow blocked path through, sight distance and stopping sight distance, lane width, shoulder width, intersection grade, intersection angle, ramps, horizontal and vertical alignments, and cross sections including superelevations).
- The incidence of vehicles, pedestrians, and cyclists at the intersection in the geometric design of walk or bike paths.
- Traffic signals and their respective timing characteristics. Special care at DDI interchanges should be placed on proactively providing enough visibility and timing to react to diverse conflicts between drivers, pedestrians, and cyclists that could be present in this type of intersection.
- Signage and pavement markings to appropriately inform all users of how to act in the intersection and provide them with enough time to react.

D. Testing of the Detailed Design

This is a new stage included on this framework considering that the first time a new and complex design is implemented in a region, it should be tested before its implementation. The objective of this test is to make sure that local drivers understand the design as they will experience it once it is implemented. A local driving behavior study will be critical to make effective recommendations that could be implemented to improve the DDI's design.

One of the best tools that could be used for studying the behavior of those who normally use the intersection is a driving simulator. When using driving simulation, users are presented with a very realistic environment featuring the design of the DDI. Such study would determine if minor changes should be necessary to improve operation and safety.

A base scenario is developed following all the details and characteristics of the proposed design. Then, a group of experimental scenarios is developed by recreating some typical situations that may lead to driver confusion or conflicts. The main focus of this approach is to know which aspects could be handled in order to get the expected efficiency from the DDI.

This stage is where drivers' local culture will have a big influence. The user behavior its particular manifestations will be in play while using the driving simulator. Therefore, the results will best apply to drivers in the region where the behavioral study is conducted. The drivers' familiarity with the environment where they are used to have a CDI, including its movements, signaling and operation, could become a challenge. But this is the most important part, especially to those who will drive along the new interchange for the first time after changing from a CDI to a DDI. The driver behavior study could be the basis for changes in design and for effective educational campaigns used to inform the community of the changes in behavior needed to safely negotiate the new intersection design.

After the testing process is completed, subject's concerns will be taken into consideration for the possible adjustments that will be performed, refining the previous design, and getting a final product that could be safer for the region where it is implemented.

E. Educational Campaigns

When implementing new and complex designs, there is always the risk of drivers not knowing how to navigate the new system. Therefore, educational campaigns should complement good designs. With this addition, drivers will have a better opportunity to become familiar with the changes and therefore achieve the main focus of the DDI's implementation: the improvement of traffic operations and safety.

The educational campaigns may include distributing brochures, presenting short instructional videos, preparing presentations, creating informative activities, and many other strategies to create awareness about the DDI. It is expected that these campaigns increase how well users understand DDIs and, at the same time, positively impact the operation and safety of the intersection.

F. Construction, Operation and Evaluation

Construction

After studying what elements could possibly be refined in the DDI's design and incorporating them, it is time to start construction. Building the DDI while taking the existing structure in the intersection into consideration will mean implementing necessary adjustments to the geometric, environmental and operational characteristics of the intersection in order to increase the positive impacts that this new design will have.

This construction process will be key in obtaining the expected efficiency and benefits and, because of its importance, has to be monitored constantly to make sure that any aspect represented on the design will be taken to the field. For this reason, it is recommended to have at least one consultant who has had experience constructing a DDI in another location because this professional will be aware of any details on this type of project and their experience will be able to identify possible problems as well as address them.

Operation

After the construction stage, the effectiveness of a DDI will be tested in real life to verify that it really addresses the problems identified with the previous design.

Several operational aspects are expected to show the benefits of the DDI over the CDI. Unique phase combinations, simple left and right turns from all directions, and the elimination of through movements between ramps will become very important in achieving the expected operational and safety improvements of the new design. For this reason, a constant follow-up of the DDI's is needed.

Evaluation

The evaluation stage represents a process of continuous operation improvement and monitoring. It is necessary to take traffic and safety data that allow the operation to be continuously evaluated at the intersection. This evaluation process should be geared towards the goal of Towards Zero Deaths (TZD), which means improving the performance of the intersection in such a way that serious crashes or crash related deaths are eliminated. In the event of a crash related death or any situation of such magnitude at the intersection, the redesign feature of this framework should be activated immediately. Any feature of the intersection that may be identified as a reason for such a failure or even the complete intersection should be redesigned if necessary.

As a result of this evaluation, there may be at least three outputs, which are those presented in this framework and represented in Fig.2 by the letters A, B and C.

Case A indicates that the evaluation shows elements which need to be redesigned based on the taken data. Therefore, the process will continue to directly refine the existing design.

Case B indicates that significant changes were observed in the flow patterns or other major factors of the design; causing crashes and deaths at the intersection or its surroundings. In this case, the process should verify the conceptual design and evaluate other alternatives or modify the intersection so that these tragedies do not happen again.

Finally, Case C indicates that, in the process of continuous evaluation, no major problems or inconveniences were observed in neither operation nor safety. In this case, the framework endpoint continues the operation of the DDI according to how it has been implemented.

In the end, the main focus of this whole framework is to provide a helpful guideline to integrate the local driving culture when implementing for the first time in a region complex intersections such as the Diverging Diamond Interchange. This framework takes into consideration possible alternatives and looks for ways to improve efficiency of the design process, that also translates into the improvement of operation and safety aspects of the intersection.

IX. Diverging Diamond Interchange on PR-30 with PR-189 - Municipality of Gurabo, Puerto Rico.

The Puerto Rico Highway and Transportation Authority (PRHTA) is constructing a Diverging Diamond Interchange in the intersection of PR-30 with PR-189, in the Municipality of Gurabo, as part of the implementation of an Every Day Counts Initiative. The EDC program of the FHWA enhances safety, improves the infrastructure, deploys innovations, and serves the road users efficiently and effectively.

This project was initially planned to improve the condition of the PR-30 bridge over the road PR-189. As part of the design process and as a pilot project, PRHTA decided to incorporate a DDI into the PR-189 road to improve the safety and operation in the interchange (project AC-800470).

This location is a high-volume facility with important traffic generators, such as University of Ana G. Méndez (Turabo), Turabo Industrial Park, and home developments. This interchange represents an important access point to the PR-30 for citizens from Caguas, Gurabo, and San Lorenzo.

Why a DDI in Puerto Rico? One of the PRHTA's goals is to evaluate innovative solutions for our operational problems. The DDI eliminates the signalized left-turn phase at the two intersections within the interchange by shifting the crossroad traffic to the left side of the roadway between the ramp terminals. This change in the crossroad configuration improves safety by reducing the number of traffic conflict points and improves traffic flow by reducing the number of signal phases.

In the design phase, PRHTA performed a traffic impact study to compare the operation and capacity of the current diamond interchange with the proposed DDI. The results demonstrated that the DDI will a provide better level of service than the existing condition.

The project AC-800470 was designed from 2014-2015 by an external consultant and began construction on September 29, 2016. The current cost of the project is $11,921,845 and the funding comes from federal funds. The proposed termination date is June 30, 2020 and the percentage of work certified until February 2019 is 13%.

To explain the concept of the DDI to road users, PRHTA did an informative session with the community in the University of Ana G. Méndez (Turabo). Students and citizens from the nearby municipalities participated in the meeting and received information about the direction of traffic and movement control in the DDI.

Currently, PRHTA is planning a behavioral simulation study on this interchange with the University of Puerto Rico – Mayagüez for the year 2019. The purpose of this study is to obtain feedback on future users to improve the delineation or signing of the DDI and develop an effective communication plan that answers citizens' doubts.

When the project opens to the public, PRHTA will monitor the operation and frequency of crashes in the new DDI to document the results of this pilot project. Based on the results, more DDIs or innovative intersection designs can come to the Island in the future. At this moment, no other intersections have been evaluated for the implementation of a DDI.

X. Conclusions and Recommendations

This research provides a conceptual framework that can be effectively applied from conception to implementation in complex intersections where a DDI can be considered to improve operational safety. This framework is robust since it considers success stories that have been implemented in the United States, primarily in the southeastern region, that has similar climatic, topographic and traffic characteristics to the context of Puerto Rico. Elements such as left turning lanes, radius, eyebrow, and other pertinent elements are incorporated in the DDI as part of an EDC initiative of the FHWA, and have also been incorporated in this framework.

Further studies need to be conducted to determine how the availability of only a limited right of way affects the design and operation of a DDI. Studies are also required to understand better cultural aspects, associated with ethnic groups, and differences between American and Latin driving cultures concerning the implementation of new complex intersection designs. Also, studies of Latin-American driving cultures and driving behavior characteristics will allow for a better understanding of the adjustments needed to adapt and contextualize key design elements of the detailed geometric design of these kind of facilities. For example, a better understanding of cultural differences in perception-reaction times will be needed for DDI, beyond what is indicated in the AASHTO's Geometric Policy (Green book). An initial effort will be made through the study that will be performed using the UPRM's driving simulator. Some of the previously presented concerns will be explored with Puerto Rican subject drivers. The simulator will also be used to develop an awareness campaign stressing the correct way of driving along the DDI. This campaign will contribute to a better understanding of this type of interchange and its future implementations all over Puerto Rico.

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