IMPROVED SYSTEMATIC ANALYSIS TO PREDICT ROADWAY SAFETY PERFORMANCE

Final Report

PROJECT SPR 849

RESEARCH

Oregon Department of Transportation

IMPROVED SYSTEMATIC ANALYSIS TO PREDICT ROADWAY SAFETY PERFORMANCE

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Abstract: This study presents the results of a review and developed framework for implementing a data-driven safety analysis in Oregon Department of Transportation's project development process. This framework considered existing best practice methodologies at the federal level from the FHWA and Transportation Research Board as well as those currently being used both other state DOTs. The framework considered available commercial software for conducting safety analysis at both the systemic and predictive levels, and tools developed in house both state DOTs. With the methods and possible solutions documented, the data constraints were outlined and a decision-making framework for a phased implementation reached. The outcomes of this project will allow ODOT to consider a framework towards the successful implementation of DDSA into the project development process, including both agency changes and possible software and data structures required.

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*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

ODOT is tasked with providing a safe, efficient transportation system. Improving roadway safety continues to be at the forefront of all stages of project development, including planning, alternatives analysis, design, construction, and operations. However, a lack of clear guidance on data driven safety analysis in project development (planning, project analysis/design/delivery, work zone etc.) results in greater costs to Oregon and missed opportunities. Performance Based Practical Design (PBPD) modifies the traditional highway design process by taking a "design up" approach where transportation decision makers build up improvements from existing conditions to meet both project and system objectives. Developing a comprehensive PBPD project prioritization framework from a safety performance perspective based on crash and roadway data would allow the agency to focus safety improvements at locations where the improvement will be maximized.

1.1 KEY OBJECTIVES OF THIS STUDY

The main goals of this study are to:

- Review the existing safety analysis procedures occurring in other State Department of Transportation (DOTs) and those provided from the FHWA, AASHTO and the Transportation Research Board.

- Incorporate these findings as to assist in the project delivery lifecycle process based on ODOTs current needs.

- Consider data constraints, tools, methods, policies and potential software solutions that are available and currently being utilized are identified and documented.

- Provide an extra dimension within the existing decision-making processes ODOT employs towards implementing a more data drive safety analysis into their existing project delivery process.

- Layout a potential decision-making framework that will assist in the project delivery process within ODOT that is tailored towards a safety-first approach.

1.2 ORGANIZATION OF THIS RESEARCH REPORT

This research report is structured in the following way:

- Chapter 2.0 reviews the existing literature on performance based practical design, Data-Driven Safety Analysis (DDSA), and safety analysis tools and resources that other State Department of Transportation’s (DOT) are currently using.

- Chapter 3.0 establishes method and procedures towards the integration of DDSA into each of the sub phases of the project development process.

- Chapter 4.0 outlines the existing documentation on DDSA practices with the generation of a flowchart on how to incorporate such procedures into ODOTs project delivery process. This chapter also documents some key practices of this safety-based approach from other state DOTs.

- Chapter 5.0 demonstrated the developed prioritized decision-making framework for ODOT to implement DDSA into its project delivery process and identifies some key next steps for its success.

- Chapter 6.0 reviews the available tools, processes, and software solutions available and used by other agencies to be leveraged towards the implementation of DDSA into the project development process.

- Chapter 7.0 introduces the future potential for ODOT to leverage ongoing initiative by the FWHA's Highway Safety Manual 2nd Edition. This includes incorporating systemic safety within the roadway safety management program and newer methods for systemic safety approaches for pedestrian and bicycle safety that ODOT might be able to implement soon.

2.0 LITERATURE REVIEW

2.1 PERFORMANCE BASED PRACTICAL DESIGN

To accommodate constraints in available funding, state transportation agencies (e.g., DOTs, metropolitan personnel) have adopted innovative strategies focusing on safety and efficiency to deliver roadway projects. Because of the fiscal austerity, agencies no longer have the option to undertake a single project whose outcomes will benefit only a small number of roadway users, rather, these agencies are more interested in the bigger picture – selecting projects that will bring system-wide improvement (e.g., decreasing the number of fatal and serious injury crashes regardless of roadway classification) based on the available funding. In general, DOTs follow guidelines from established design standards such as *AASHTO's A Policy on Geometric Design of Highways and Streets* during the design phase of project delivery process (Performance Based Practical Design, 2021). However, performance based practical design (PBPD) policy encourages practitioners and engineers to focus on purpose and address context-specific solutions (AASHTO, 2011). Missouri Department of Transportation (MoDOT) was the first state agency to introduce such practices for real-world application. Later, the Kentucky Transportation Cabinet (KYTC) adopted a similar approach that led to the Practical Solutions initiative program (KDOT, 2021). The goal of MoDOT and KYTC was to build projects that:

- Conform to the criteria outlined in purpose and need statements,
- Provide detailed attention to the project area context, and
- Ensure short-term and long-term improvement in the transportation network.

The common practice before PBPD was formally introduced was to create design solutions based on the available design standards. If the final design is found expensive, design elements are taken out one at a time until it fits the available budget. However, such practice did not produce satisfactory results all the time. This report will provide a detailed overview of how other state agencies has been incorporating PBPD approaches into their project delivery process based on the recommendation from the Federal Highway Administration (FHWA), and what performance measures different transportation agencies have been considering in order to make long-term investment decisions.

2.1.1 Missouri Department of Transportation (MoDOT)

MoDOT was the first transportation agency in the USA to introduce PBDP policy into their project delivery process. Scarcity in funding available for projects encouraged MoDOT to adopt such practices. In the past, MoDOT focused on design standards only, however such ideology would often lead to overdesign and limited statewide improvement in transportation performance. To address such inconsistencies, MoDOT shifted its policy to design projects with appropriate contextual changes as long as it aligns with project needs and goals (MoDOT, 2006). MoDOT focused on the following criteria for such PBPD approaches:

- Safety will never be compromised; all facilities will be safer upon project completion through application of Crash modification factors (CMF) clearinghouse and performance-based practical design policy (Edarda et al. (2013); Bledsoe and Lee (2021)).

- Developing solutions is a collaborative endeavor that brings together multidisciplinary stakeholders.

- The design speed must equal the posted speed (i.e., a road is not designed for a speed higher than what is posted).

To ensure effective implementation of the above policies, MoDOT issued authorizations for the district offices to accept design exceptions – for example, there may be a design that warrants narrower lane widths than what is required by AASHTO criteria or other established specifications. Specifically, MoDOT outlined approval requirements for such design exceptions by developing Projects of Divisional Interest (PODI) matrix based on guidelines provided by FHWA (https://epg.modot.org). Adoption of PBPD approaches helped MoDOT save an amount of $1.2 billion US dollars during the fiscal year 2005-2009. MoDOT's practical design implementation manual has detailed information on implementing PBPD for different types of projects such as at-grade intersections, shoulder width, median width, roadside ditches, horizontal and vertical alignments, and pavement structures.

2.1.2 Idaho Transportation Department (ITD)

Idaho Transportation Department (ITD) has emphasized aligning project scopes for practical design application with the initial project purpose and need statements. In addition, ITD has observed that if practical design is introduced at the planning stage, it will achieve the most benefit as it would require minimal changes in the design components while also avoiding any subsequent necessary feasibility study which would have increased the project cost. ITD has been successful in implementing PBPD approaches as its staff were already receptive to contextualized design policies due to Idaho's challenging terrain. However, there were no such practices for saving cost during the design phase and later shifting the cost burden to maintenance. If a situation arises where a design exception is required, ITD recommends considering physical, environmental and safety factors before the revised project design is approved (ITD, 2013). The developed guidance document contained all these policies to be applied during the transportation planning phase as well as roadway design stage. The section of the document focused on transportation planning related important layouts such as at-grade intersections/ interchanges, two-way left turn lanes, and passing lanes. On the other hand, the roadway design section provided detailed guidelines for elements such as lane width, right of way, processed materials, shoulder width etc. (AASHTO, 2011).

2.1.3 Utah Department of Transportation (UDOT)

UDOT has acknowledged the benefit of PBPD policies which is similar to the rationales showcased by other agencies. However, MoDOT has limited the implementation of practical design only to planning or scoping phase, UDOT took it farther by applying PBPD during all stages for project development – from initial planning to final construction. With that in mind, UDOT proposed the following goals for practical design implementation:

- Optimize the whole transportation system.
- Meet the goals of the objective statement identified for each project.
- Design the most efficient method for capacity augmentation and safety improvement while achieving the objective statement (UDOT, 2011).

As part of the first goal, UDOT personnel are required to synthesize how specific project goals will assist in the overall network performance improvement criteria, and then communicate these observations to the project team. These practices will help them develop appropriate design methodologies that optimize the entire highway system. Goal 2 enables the designers to go beyond the traditional design standards and introduce contextualized solutions that will both confine to the project level objective statement and achieve network performance improvements in terms of operation and safety (UDOT, 2011). As for goal 3, UDOT emphasizes maximizing cost-savings while achieving the project objective. In summary, UDOT proposes a fine balance between developing context sensitive solutions and value engineering.

2.1.4 Oregon Department of Transportation (ODOT)

The Oregon department of transportation (ODOT) has a dedicated chapter in its *Highway Design Manual* which build upon the existing design standards - FHWA's "Flexibility in Highway Design" as well as AASHTO's "A Guide for Achieving Flexibility in Highway Design". ODOT bears resemblance to other DOTs when it comes to PBPD integration into the project delivery process, for example it emphasizes developing design solutions that aligns with the project needs and objective. ODOT has three major goals for the practical design policy (ODOT, 2012):

- Direct funding toward activities and projects that optimize the entire system.
- Develop solutions that address the purpose and need identified for each project.
- Design projects that improve the entire system, address changing needs, and maintain current functionality by at least meeting goals outlined in project purpose and need statements.

In addition to these above-mentioned goals, ODOT has also highlighted five values to optimize the integration of the PBPD approaches (ODOT, 2012):

- Safety: The issue of safety should never be compromised for the sake of practical design. All the projects, upon completion, should achieve a higher level of safety or at least maintain the existing level of safety. Appropriate systemic or predictive analysis should be ensured to maintain such conformity.
- Corridor Context: ODOT puts emphasis on adopting corridor-based solutions while developing or assessing design criteria. Roadway design must adhere to community values, as well as take into consideration the future land use pattern. In addition, the project needs to be adapted to the natural and built environments.

- Optimize the system: Practical design should ensure optimization of the whole network. Besides ensuring an efficient and safe operation, a completed transportation project should consider an integrated asset management approach for managing pavements, bridges, and other roadway features.

- Public support: ODOT acknowledges public input as an integral part to its practical design approach. Inputs from frequent focus group discussions with the community people are then addressed while drafting the project design. With this, ODOT connects with different road users such as motorists and pedestrians to develop a collaborative solution approach.

- Efficient cost: Like other DOTs, ODOT also limited funding which puts constraints on project delivery process. With the PBPD philosophy, the project design is modified if it is aligned with the project needs and statement. This also enables the DOT to relocate some of the available funding to low priority projects.

In summary, performance-based practical design policy enables state DOTs to consider design exceptions if it fits within the project purpose and ensures that safety is not compromised. In the next section, we discuss how safety analyses are analyzed for different types of projects.

2.2 DATA-DRIVEN SAFETY ANALYSIS (DDSA)

Data-Driven Safety Analysis (DDSA) can be defined as the application of established methods that takes advantage of the real-world data to assess existing safety conditions, prioritize locations that would require immediate funding, and predict the safety impacts of the proposed roadway projects. These methods help local, or state level highway agencies make informed decisions about where/how to allocate the available funding that will produce the most benefit in terms of safety improvement for the whole transportation network. The endeavor to adopt such safety-centric approaches began with the introduction of the Highway Safety Manual (HSM), before that there were no systematic, research-oriented methods available for the practitioners. The methods within this report refer to the available systemic treatments, predictive approaches, and safety analysis tools in practice across different state DOTs in the USA.

2.2.1 Systemic Treatments

Systemic Treatments are applied to prevent crashes on rural roads that often account for a larger portion of all severe crashes in the overall roadway systems. Usually, the density of crashes that take place on rural roads remain low in comparison to the fatal and non-fatal crashes in the whole network. Such underrepresentation often leads to traffic engineers misrecognizing locations of immediate concern (FHWA, 2017). For example, Minnesota DOT experiences a density of fatal road departure crashes of 0.002/mile, a number mostly resulted from the large rural road network. These unique characterizations require cost-effective solutions such as the use of rumble strips, median separation features, high visibility signage, or similar treatments. State DOTs have been advocating for such applications for a long time and spend a significant amount of the available Highway Safety Program (HSP) funding to such systemic treatments (see Table 2.1). Oregon DOT also has produced a comprehensive list of available systemic treatments that practitioners can use to select as appropriate countermeasure in response to a specific crash type (https://www.oregon.gov/ODOT/).

Table 2.1 State-wise Funding Allocation for Systemic Treatments (NCHRP Project 17-189, Task 19 Case Study Synopsis)

State	Fund Allocation	Available
Iowa	90% of HSIP fund	Paved shoulders, & shoulder rumble strips.
Minnesota	60% of HSIP funds	Cable median barrier, shoulder rumble strips, & target speed enforcement.
Missouri	75% of HSIP & HRRR funds	Shoulder improvements & edge line rumble strips
North Carolina	10% of HSIP funds	Cable median barrier & shoulder rumble strips

2.2.2 Available Systemic Treatments

2.2.2.1 Cable Median Barrier (CMB)

CMB - a system of horizontally installed cables - is usually applied to separate two bi-directional roadways. These are widely known for being life-saving and adaptable traffic devices that state DOTs can readily deploy on existing medians to protect motorists from oncoming traffic on congested highways. CMB is dependent on its metal mounts to absorb a vehicle's kinetic energy. When a car hits the barrier, its speed is reduced by quickly adjusting the vehicle's angle of approach, thus dispersing its kinetic energy. Without this device, the vehicle would have otherwise led to a cross-median crash (which has a high propensity for fatal outcomes). CMBs are preferred over other available treatments for being less expensive in terms of installation and maintenance cost as well as easy-to-repair features. There are also practices where CMBs can be used such as on the outside of lanes to prevent traffic from moving off the shoulder (Antonucci, 2005). According to AASHTO's Roadside Design Guide (RDG), median barriers can be installed on high-speed, fully controlled-access roadways for locations where the median is 30 ft in width or less and the average daily traffic (ADT) is greater than 20,000 vehicles per day (vpd). A median barrier is optional for locations with median widths greater than 50 ft and where the ADT is less than 20,000 vpd, for locations where the median is between 30 and 50 feet, an analysis is recommended to determine the cost effectiveness of median barrier installation (https://safety.fhwa.dot.gov/provencountermeasures/median_barrier.cfm).

Figure 2.1: Cable Median Barrier along the midsection of the roadway

Figure 2.2: W Beam Guardrail on the outside of the lane

2.2.2.2 Rumble Strips

According to the definition provided by the FHWA, rumble strips are "...a longitudinal design feature installed on a paved roadway shoulder near the travel lane. It is made of a series of indented or raised elements intended to alert inattentive drivers through vibration and sound that their vehicles have left the travel lane" (FHWA, 2017). Rumble strips can be installed on road shoulders, lane edges, centerlines, and middle of the lanes. Given that rumble strips are a proven safety countermeasure, Oregon DOT recommends using centerline rumble strips as an effective systemic treatment when there is possibility of head-on or sideswipe meeting crashes*, it is expected to act as a source for audible warning and physical vibration inside the car alerting drivers that they are leaving their travel lanes and should take steps accordingly. On the other hand, shoulder rumble strips are installed when there is a high frequency of roadway departure crashes due to collision with fixed objects. Oregon DOT has calculated the crash reduction factor for rural centerline rumble strips and shoulder rumble strips as 12% and 22%, respectively (ODOT, 2012). However, whether the external noise caused by these rumble strip installations cause discomfort to nearby residential areas should be taken into consideration during the planning phase.

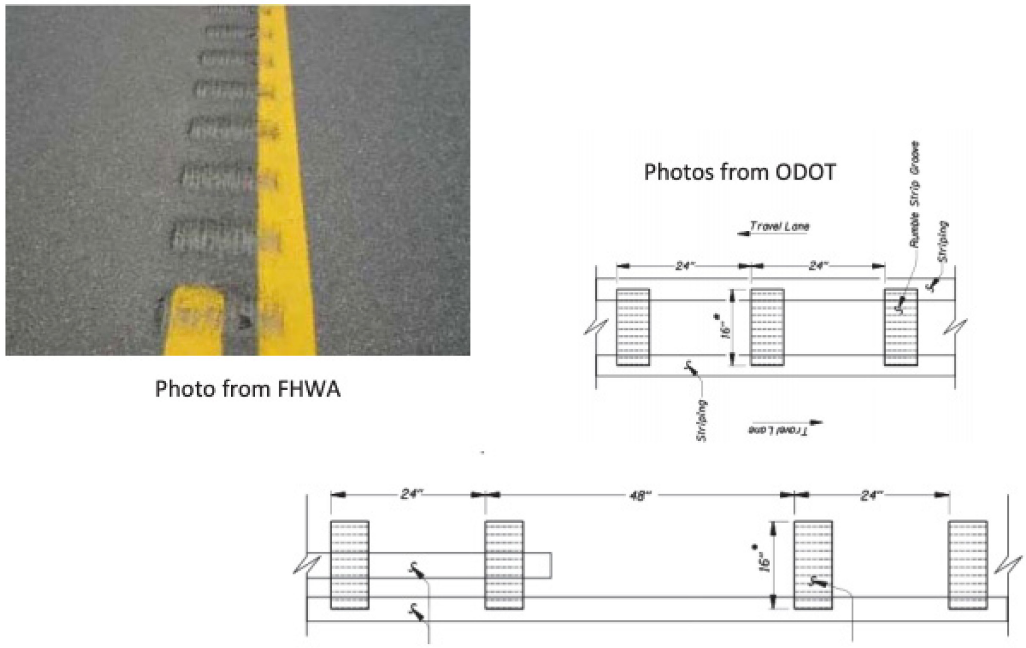


Figure 2.3: Rumble strips (Oregon DOT)

2.2.2.3 Safety Edge

Safety edge treatment is essentially a 30-degree angle placed at the edge of a newly installed pavement structure. The reason behind this installment is to provide a transition-type feature that will allow drivers to return to their original pathway in case they drift off the pavement surface. A 30-degree value is chosen based on research; it is the optimal angle to allow drivers re-enter the roadway safely (FHWA). In addition, a 30-degree angle results in a 1% increase in the amount of asphalt and thus does not substantially increase the overall cost of the infrastructure. Without such arrangement, a vehicle may experience uncontrollable movement leading to fatal crashes if the vehicle is trying to correct its course i.e., getting back to the roadway (FHWA, 2017).

2.2.2.4 High Friction Road Treatment

High friction road treatment (HFST) is basically applying a non-skid surface to the existing bitumen surface though agglomeration of the rock surface with resin, in thit way vehicles get a tighter grip when they apply heavy breaking or turns on horizontal curves (see Figure 2.5). This type of treatment is effective against run-off and rear-end crushes (Transtec Group, Inc, 2010). For example, Pennsylvania, Kentucky, and South Carolina DOTs have observed total crash reduction of 100 percent, 90 percent, and 57 percent, respectively due to the application of HFST (FHWA). Oregon has undertaken such treatment for several of their projects such as OR 219 at SW Laurel Road, OR 224 milepost 10-10.26, OR 219 at SW Midway Road, OR 219 at SW Wolsborn Road.

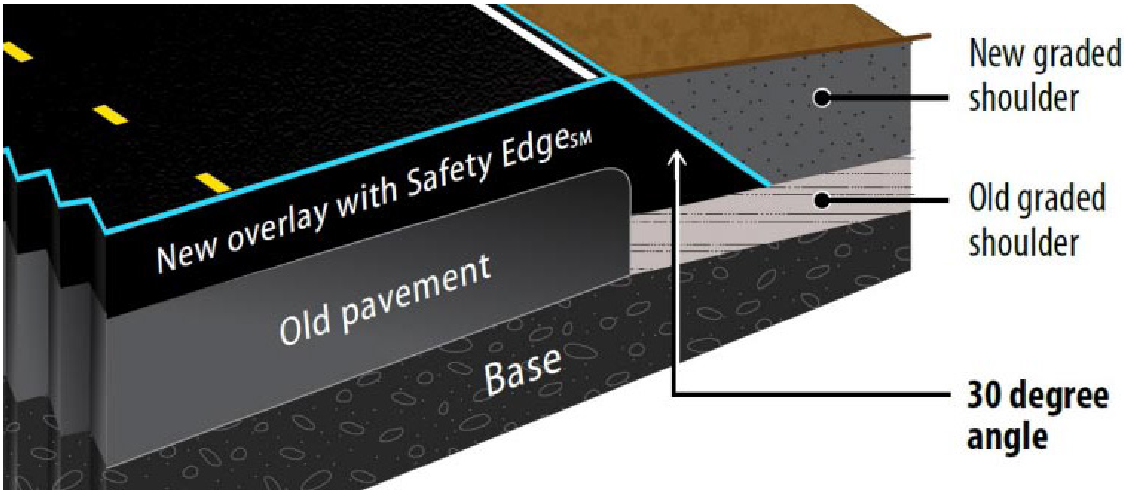


Figure 2.4 Safety edge (FHWA-SA-17-044, 2017)

Figure 2.5 High friction road treatment (WSDOT, 2019)

2.2.2.5 Clear Zone

A Clear Zone is provided along the roadside so that drivers who have had an erratic stop or need to regain control of a vehicle can use this designated area in order to avoid crashes with other traffic and resume travel in a safe way (see Figure 2.6). The area is likely to have a shoulder, a recoverable slope a, and/or a non-recoverable, traversable slope with a clear run-out area at its edge (FHWA, 2017).

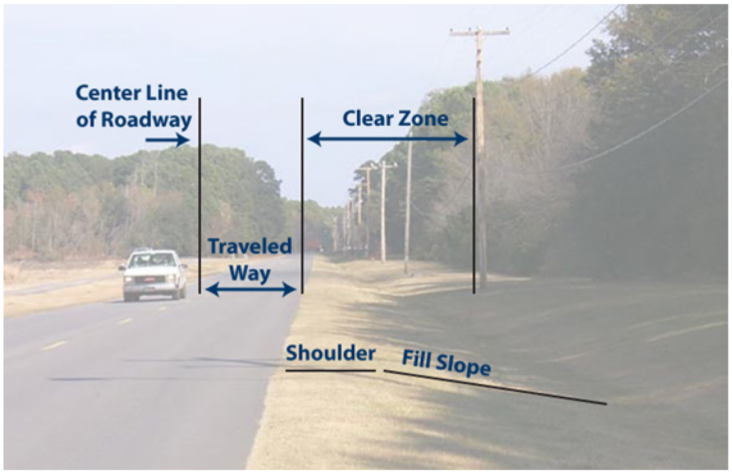


Figure 2.6 Clear zone (FHWA, 2017)

2.2.2.6 Chevron Signage

Chevron signage is provided to warn the drivers of the incoming change in direction of travel or narrowing of the road (see Figure 2.7). Two types of chevron signs such as left, and right-aligned symbols are applied in either direction so that drivers from both sides can be aware of these changes. The use of these signs is especially useful at night, when vision distance is limited and reaction times are shortened (KYTC, 2021).

Figure 2.7 Chevron signage (WSDOT, 2019)

2.2.2.7 Breakaway Signage

Breakaway signage are essentially traffic sign poles that will break or bend when a vehicle makes a contact with it and thus reduces the crash severity. To illustrate, a sign pole is attached to a mount with a bolt, and when a vehicle crashes into it, the bolt is broken while absorbing much of the impact force. Breakaway signage is easy to install and requires low maintenance cost (FHWA, 2017). Engineering judgement If applied while providing this type of systemic treatment.

Figure 2.8 Breakaway signage

2.2.2.8 Retro-reflectivity Sign

This type of reflectivity is coated with a surface of reflective material that reflects light back to the car where it was emitting from, and thus concentrating light redirection. The common interaction can be seen in Figure 2.9 where headlights on a sign make the sign appear brighter and more visible sooner (Neuman, 2003). Such a sign is installed based on Engineering Judgment. MUTCD recommends maintaining uniformity for the installation of such applications in an effort to help drivers safely navigate (regulate, warn, guide).

Figure 2.9 Retro-reflectivity sign

2.2.3 Predictive Safety Methodologies

Most of the DOTs require quantitative predictive safety analysis to ensure that safety and efficiency goals of roadways are achieved. These analyses can be basic such as crash modification factor or safety performance function as well as more complex methodologies such as application of empirical bayes method that takes different types of facilities and variables as inputs. All types of analysis will however adopt a data-driven safety analysis approach and build upon the methodologies presented within the available highway safety manual (HSM). The 2014 supplemental HSM version contains chapters 18 and 19 which synthesized previous research and provided practitioners quantifiable expected safety improvements for different types of facilities. For example, chapter 18 describes the methodologies that can be applied to calculate the expected average crash frequency (in total, by crash type, or by crash severity) for freeway facilities. On the other hand, chapter 19 focuses on ramps, considering a wide range of geometric and operational characteristics. For other types of facilities such as rural two-lane roads, rural multilane highways, and urban and suburban arterials, practitioners use the 2010 HSM version which entails all the necessary safety performance functions (SPFs) and CMFs (crash modification factor) as well a description on how to use Empirical Bayes (EB) adjustments.

The HSM has developed these predictive methods based on extensive research and analysis rather than using design standards. It takes into consideration different local conditions while estimating crashes per year and severity. Oregon DOT has adopted predictive models as outlined in HSM part C and later calibrated these models to adopt for conditions unique for state highways in Oregon. To illustrate, HSM has the following equation to represent rural two-lane highways which can be readily applied if the base conditions meet the local jurisdiction:

$$\boldsymbol{N_{predicted(adjusted)} = N_{SPF} x (CMF_1 \times CMF_2 \times \ldots . \times CMF_n) \times C}$$

(2-1)

Where:

N_{SPF} = Safety performance functions (SPF)

CMF_n= Crash Modification Factors

C= Calibration Factor

This type of crash frequency depends on geometric design as well as current traffic demand depending on local conditions.

2.2.3.1 Crash Modification Factors (CMFs)

CMFs are used to capture the change in the expected number of crashes due to an introduction of a specific treatment or change in geometric design. If the value for CMFs is below 1, it is expected that there will be a decrease in crashes. On the other hand, value is greater than 1 indicates an increase in crashes due to the treatment or feature. For work zones, HSM uses the following function for work zone environment as:

$$CMF_{d,all} = 1.0 + \frac{(\%\, increase\ duration\ *\ 1.11)}{100}$$

(2-2)

where:

$CMF_{d,all}$ = CMF for all crash severities as a function of duration (HSM, 2010)

For consideration of work zone length, Equation 2-2 turns into:

$$CMF_{d,all} = 1.0 + \frac{(\%\, increase\ duration\ *\ 0.67)}{100}$$

(2-3)

where:

$CMF_{d,all}$ = CMFs for all crash severities as a function of length (HSM, 2010)

There are two-fold applications for CMFs:

- CMFs are used to measure the expected effects of changes in conditions on observed crash frequency – these analyses are independent from predictive type approaches.

- In the HSM predictive method, CMFs are used to adjust the base condition predictions from SPFs to account for additional highway facility characteristics. This application is for advanced predictive safety analysis. It should be noted that the CMFs provided in the HSM's Part C sections and calibrated with specific SPFs should only be used with those SPFs. However, within the limitations outlined in the HSM and the CMF Clearinghouse, additional CMFs can be applied to SPF predictions to account for additional features. In general, additional CMFs should be limited to no more than three CMFs that are clearly independent of one another. A lack of independence will frequently limit the analyst to no more than three additional CMFs.

However, all the available CMFs do not cover all traffic situations. In response to that, there is continuing research to develop CMFs for all those remaining situations. All these developed CMFs are periodically updated in CMF Clearinghouse (http://www.cmfclearinghouse.org/) although state DOTs are advised to take special consideration before using CMFs published in the clearing house if these are not published in the HSM yet.

2.3 SAFETY ANALYSIS TOOL AND RESOURCES

State DOTs have been using commercial software or collaborating with different research institutions (e.g., TTI) to integrate Data driven safety analysis into their project delivery process. Figure 2.10 shows the usage spectrum of different safety analysis tools across the USA.

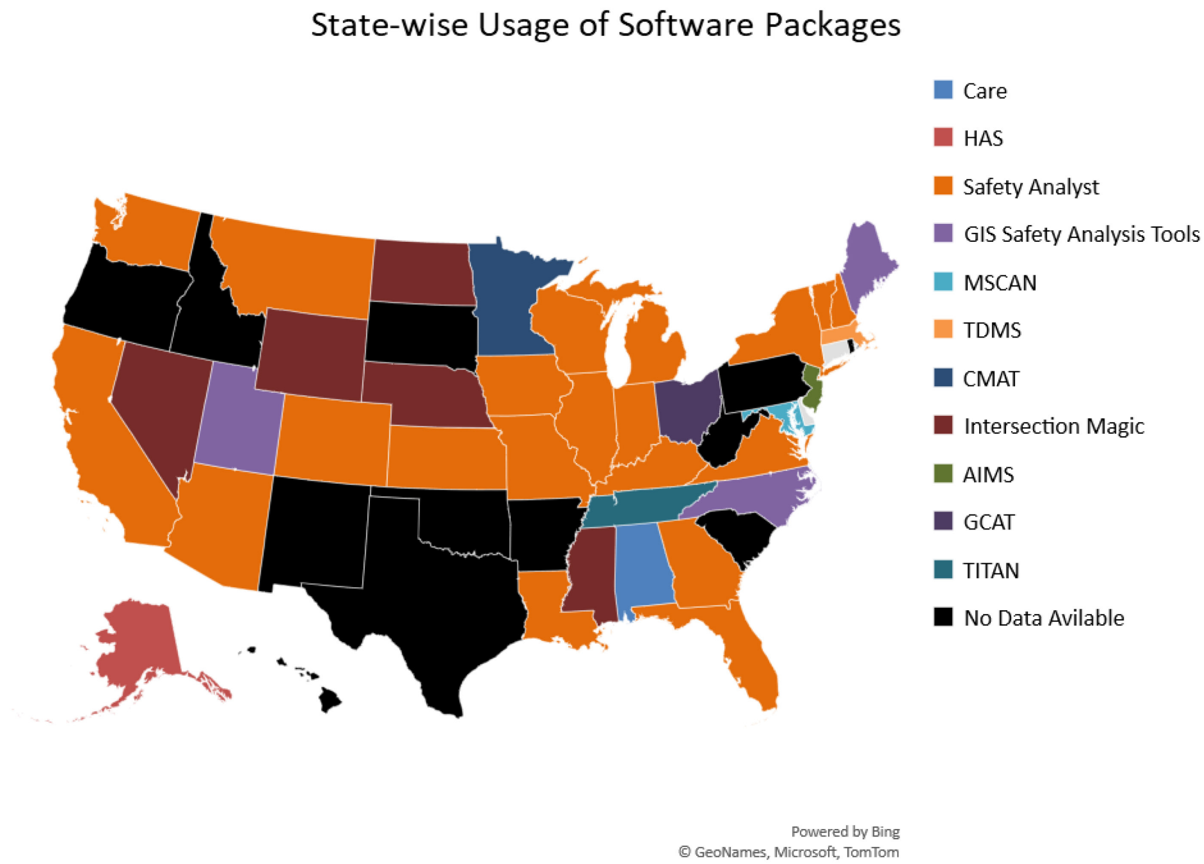


Figure 2.10 Use of different safety analysis tools (https://safety.fhwa.dot.gov/rsdp/toolbox)

2.3.1.1 AASHTOWare Safety power by Numetric, Inc

AASHTOWare Safety (https://www.aashtoware.org/products/safety) is a Software as a Service (SaaS) platform specifically designed to meet the unique needs of state and local transportation agencies in the area of highway traffic safety management. The software platform is built upon the safety data warehouse in a GIS interface. The software consists of three products: AASHTOWare Safety Segment Analytics, AASHTOWare Safety Intersection Analytics, and AASHTOWare Safety Trend Analytics. Both the Segment Analytics and the Intersection Analytics provide functions of crash query, network screening, safety analysis, and SPF manager. The Trend Analytics provides cloud-based, customizable dashboards to the stakeholders, and provides public portals.

2.3.1.2 Safety Analyst

Safety Analyst is widely used, but according to AASHTOWare (https://www.aashtoware.org/products/safety/safety-overview/), AASHTO intends to sunset full operation of Safety Analyst on June 30, 2022, license for the Safety Analyst is already discontinued. Safety analyst tool is developed by Federal Highway Administration providing state-of-the-art analytical modules to help highway agencies identify potential safety improvement areas and propose appropriate cost-effective solutions accordingly. There are several modules incorporated into the tool such as network screening tools, diagnosis tools, countermeasure selection tools, economic appraisal tools, priority ranking tools, and evaluation tools. Network screening tools have algorithms embedded into it which help agencies identify locations with high crash frequencies. Once a list of potential sites is provided to the software, diagnosis tools will be used to identify the nature of the problems at the selected sites by producing collision diagrams. These collision diagrams are then fed into the countermeasure selection tool to identify a suite of possible countermeasures. Economic analysis in terms of cost-benefit ratio is then performed for each of these available solutions to find the cost-effective one. Safety Analyst also offers a priority ranking tool that takes a number of proposed projects into consideration and evaluates which projects would be given priority over others given the available amount of funding. After the project is selected, the overall effectiveness to improve network safety is evaluated based on a few empirical bayes formulations.

2.3.1.3 Interactive Highway Safety Design Model (IHSDM)

IHSDM is another widely used safety analysis tool developed by the Federal Highway Administration. IHSDM includes five evaluation modules (i.e., Crash Prediction, Design Consistency, Policy Review, Traffic Analysis, and Driver/Vehicle), as well as an Economic Analysis Tool. As a reference for the predictive analysis, IHSDM uses the procedures outlined in part C of the AASHTO's 1st Edition Highway Safety Manual for evaluating rural 2-lane highways, rural multilane highways, and urban/suburban arterials. As for the freeway instances such as ramp or segments, IHSDM follows HSM 2014 supplements. Users will have flexibility to change crash modification factor according to the types of infrastructure they intend to use - For example in case of road-segments analysis, IHSDM have provisions for on-street parking, roadside fixed objects, median width, lighting, lane width, minor driveways, median barriers and so on; for intersections it can address left- turn lanes, left-turn signal phasing, right turn on red, right turn channelization etc.

2.3.1.4 Intersection Control Evaluation (ICE)

ICE is more of a specialized safety planning analysis tool primarily used for intersection level analysis focusing on selecting a traffic control type, congestion mitigation, multimodal facility enhancement, and change of access to nearby areas. ICE operates in two phases – first, it performs a scoping analysis, and then it does an alternative selection phase based on the outputs from phase 1. In the scoping analysis, ICE evaluates what types of safety improvement criteria is desired for a particular project (e.g., safety, operational efficiency), what types of solutions can be postulated, and whether other design considerations need to be considered. These possible solutions are then carried to the alternative selection procedure to perform benefit-cost ratio analysis to choose the cost-effective solution. Phase 2 also takes other inputs into consideration such as public option, transportation future in the surrounding area etc.

2.3.1.5 GIS Crash Analysis Tool (GCAT)

GIS Crash Analysis Tool (GCAT) is an easy-to-use GIS-based tool that offers two separate modules to the DOT personnel, MPOs, and county engineers: (a) Excel Crash Analysis Module, and (2) Economic Crash Analysis Tool. GCAT provides state crash data search – the data can be spatially located and unlocated. The tool also allows the user to make customized inquiries into the crash database providing a granular level overview of the crash analysis. Based on these defined queries, the GIS Crash Analysis Tool uses GIS (Geographic Information Systems to produce data that is spatially located (with valid latitude/longitude).

2.3.1.6 ViDA Software

ViDA software is developed as part of the United State Road Assessment Program. A star-rating based system is developed to perform network-level safety analyses while considering over 50 roadway design and traffic control attributes. Star ratings can be produced for individual types of road users – vehicle occupants, motorcyclists, pedestrians, and bicyclists. Analysis results from the ViDA is speed-sensitive meaning star ratings will decrease with increasing speed. However, two identical roadways with different traffic speeds will have different star ratings. As inputs, ViDA takes safety-related roadway characteristics such as quality of curve, quality of intersection as well as traffic control characteristics such as traffic volume, pedestrian flow, mean traffic speed. Based on the analysis results, ViDA provides appropriate investment plans that include information about what types of counter measures are cost-effective and ensure safety (Torbic and Kolody, 2021).

2.3.1.7 DiExSyS Vision Zero Suite (VZS)

Vision Zero Suite (VZS) is a software that has been developed mainly based on the guidelines of Highway Safety Manual (HSM) and incorporates the available predictive methods as well as diagnostic pattern recognition to produce a date-driven safety analysis approach. VSZ also offers network screening analysis while also addressing GIS mapping and recognizing infrastructure patterns.

2.3.1.8 Texas DOT's Safety Scoring Tool

Texas DOT has produced an excel-based tool to assist in making safety-driven decisions during the project design process. Such tools help practitioners to understand safety aspects of specific design elements relevant to a particular project and thus ensure optimal safety before the project construction phase is initiated. Different factors such as geometric characteristics, traffic elements as well as roadside features are incorporated into the excel tool and different countermeasure alternatives are evaluated on a score of 1-100.

3.0 ESTABLISH METHODS AND PROCEDURES TO INTEGRATE DATA-DRIVEN SAFETY APPROACH INTO PROJECT DELIVERY PROCESSES

3.1 INTRODUCTION

The **purpose** of this document is to provide guidelines on how to integrate data-driven safety analysis (DDSA) approach into Oregon Department of Transportation (ODOT)'s over-all project delivery process ranging from planning phase to operation and maintenance of the roadway system. As outlined in the "Analysis Procedure Manual" (APM) developed by ODOT, the primary goal for safety-centric solutions is to incorporate a preemptive approach within the planning phase to reduce the potential for fatal and serious injury (Injury-A) crashes. Such consideration also cohorts to the notion adopted by Oregon Transportation Plan (OTP) that states "it is the policy of the State of Oregon to continually improve the safety and security of all modes and transportation facilities for system users including operators, passengers, pedestrians, recipients of goods and services, and property owners."

The Analysis Procedure Manual (APM) was developed following the guidance from the American Association of State Highway and Transportation Officials (AASHTO) Highway Safety Manual (HSM) which was published in 2010 as an agglomeration of 10 years of research and collaboration among safety experts, academics, and practitioners from national and international institutions (AASHTO, 2003). In prior versions, HSM focused primarily on developing meaningful and practical safety metrics – crash frequency and severity – to better capture the efficacy of the proposed design approach. However, recently, HSM has adapted itself to prove detailed understanding on how state DOTs should consider safety-based decision-making guidelines for an effective project development process. With such development in the mandate of AASHTO, ODOT must prepare to address possible implementation opportunities for the safety focused HSM policies during each stage of the project delivery process. Based on the recommendation from Federal Highway Administration (FHWA), we will be following these specific steps related to the project delivery process:

- How agencies can use the HSM in planning.
- The use of the HSM in alternative development and analysis.
- How agencies can apply the HSM in design.
- The application of the HSM in the operation and maintenance of the roadway system.

The HSM highlights four phases that state agencies need to focus on while incorporating safety throughout the project delivery process. Table 3.1 provides a comparative overview of how ODOT documents available safety analysis and what relevant chapters FHWA has offered to facilitate the integration of DDSA framework into project delivery process.

In the *Planning* phase, state transportation agencies evaluate existing conditions and establish project goals and objectives, evaluate the multimodal transportation network to address future traffic demand, identify and prioritize projects, and develop strategies to address long-term (e.g., 20 - 30 years) transportation system and short-term community focused requirements. During this phase of the project development process, locations that require substantial safety improvements are identified. Alternative designs are then created and chosen based on their fit within the project goals. While every project may have a different purpose or objective (e.g., infrastructure repair or rehabilitation), consideration for safety aspects during planning leads to an increase in the likelihood of cost-effective expenditure for resources. Information about how ODOT recognizes each project's scope and goal is detailed in chapter 2 of the Analysis Procedures Manual (APM).

After the scope and purpose is determined, the project delivery process moves onto the most important phase - *Alternatives Development and Analysis*. In such phase, traffic engineers evaluate multiple alternatives for a specific project that are within the project goal and scope. Although the project scope may not have explicitly highlighted the safety aspects (e.g., only limited to right-of-way, or traffic operations, or environmental factors), FHWA has encouraged state agencies to use HSM-based safety analysis while comparing the benefits of design alternatives; such practice will lead to state agencies achieving the most benefit out of the project. HSM contains relevant safety diagnostic analyses in chapter 5 to estimate the benefits of a preferred design alternative in comparison to a no-build scenario.

Once a preferred design alternative is selected, state agencies initiate the *Preliminary and Final Design* phase where traffic engineers can use available tools and practical knowledge to make informed design decisions and also address design exceptions if required. As per the FHWA mandate to make safety-centric project delivery process, it is recommended to incorporate human factor considerations in the design phase (outlined in detail in Chapter 2 of the HSM). In addition, HSM also outlines what safety aspects need to be considered while addressing design exceptions.

The next phase of the project delivery process is *Operation and Maintenance* where FHWA recommends introducing safety-based performance metrics to evaluate how a project performs when it operates or how much the project has achieved in terms of originally developed project goal. Current practice among the traffic practitioners is to consider the impact of changes or upgrades in mobility, decisions related to access, setting maintenance policies and priorities; however, other relevant operational considerations on safety performance also need to be addressed as a part of an informed project delivery scheme. ODOT details its current policies related to evaluation of performance for a specific project in Chapter 9 of the APM.

Table 3.1: Overview of Safety Related Chapters in HSM and APM Chapters

Phases	FHWA	ODOT
Planning	Chapter 2 of HSM	Chapter 2 of APM
Alternatives Development and Analysis	Chapter 5 of HSM	Chapter 10 of APM
Preliminary and Final Design	Chapter 2 of HSM	Chapter 4 of APM
Operation and Maintenance	Chapter 5, 9 of HSM	Chapter 9 of APM

3.2 FRAMEWORK OF APPLYING DDSA IN THE PROJECT DEVELOPMENT PROCESS

3.2.1 Applying DDSA in Planning

According to Oregon Department of Transportation (ODOT) (see Chapter 4 of the APM), transportation planning can be categorized into five types – System wide planning, MMA (Multimodal Mixed-Use Areas), Facility Plan, Development Review, and NEPA (National Environment Policy Act) related project plan. All these types of projects have a clear outline in terms of what amount of safety analysis is required or recommended. For example, the minimum amount of safety analysis required for any type of project is to calculate if the project area is within 5% or 10% locations based on information available from Safety Priority Index System (SPIS) and then estimate if further safety aspects need to be investigated. For Facility Plan, Development Review, and NEPA type projects, there is a variable requirement – only predictive type analysis is recommended, whereas systemic analysis is enough for system wide planning projects or Multimodal Mixed-Use Areas. Figure 3.1 provides the comparative requirement of safety analysis for different types of projects. Therefore, based on the phase-based recommendations presented by FHWA in the HSM and outlined in Table 3.1, ODOT should practice both types of safety analysis – systemic and predictive, regardless of what type of project is undertaken. Table 3.2 provides what type of safety analysis should be integrated for different stages of the project delivery process.

Level of Effort +

Plan or Project Type	Other Methods			Highway Safety Manual (HSM) Methods					Other Tools
					Statistical Crash Data Screening		Predictive Methods		
	State Crash Rate	SPIS	Queue	CMFs	Critical Crash Rate	Excess Proportion of Specific Crash Types	Net Change in Predicted Crash Frequency or Predicted Crashes	Excess Expected Crash Frequency	PlanSafe
System Plans (TSP, RTP etc.)	○	●		●	●	●			○
MMA's	●	●	●	○	○	○			
Facility Plan	○	○	○	○	○	○	●	●	
Development Review	○	○	○	○	○	○	●	●	
NEPA / Project Development	○	○	○	○	○	○	●	●	

Details +

● Best practice or recommended method
○ Supplemental methods

Figure 3.1 Applicability of Safety Analysis Tools by plan or project type (APM, ODOT)

Table 3.2: Comparative view of ODOT practices for safety analysis and FHWA recommendation

Phases	Current ODOT Practice		FHWA Recommendation	
	Systemic	Predictive	Systemic	Predictive
System Level Plan	✓	✗	✓	✓
Development Review	✗	✓	✓	✓
NEPA	✗	✓	✓	✓
MMA	✓	✗	✓	✓

Note:[1] MMA = Multimodal Mixed-Use Areas, NEPA = National Environment Policy Act

Currently, ODOT has developed several tools for the *data collection approaches* – Crash Decoder Tool, Crash Graphing Tool, and Crash Summary Database. These tools are primarily macro-based Excel look-up tables that can co-relate to ODOT crash data sources such as Summary by Year CDS150, Crash Location CDS390, and Comprehensive (PRC) CDS380. Using these crash data, appropriate crash statistics (i.e., Critical Crash Rate (CCR), Excess Proportion of Specific Crash Types (EP)) are applied to infer what Crash Modification Factors (CMFs) are required for the safety analysis of a project.

As FHWA's long term plan to introduce safety management process, several activities related to planning phase are outlined in part B of the Highway Safety Manual (HSM). To illustrate, necessary data should be collected to adopt the following network screening performance measures proposed by the FHWA to have a more safety-centric evaluation - to see if the project under consideration will achieve reduction in the number of number of crashes or crash severity:

- Average Crash Frequency
- Crash Rate
- Equivalent Property Damage Only (EPDO) Average Crash Frequency
- Relative Safety Index
- Critical Rate
- Excess Predicted Average Crash Frequency Using Safety Performance Functions (SPFs)
- Probability of Specific Crash Types Exceeding Threshold Proportion
- Excess Proportion of Specific Crash Types
- Expected Average Crash Frequency with EB Adjustment
- Equivalent Property Damage Only (EPDO) Average Crash Frequency with EB Adjustment
- Excess Expected Average Crash Frequency with EB Adjustment

Selection of appropriate performance measures depends on *data availability*, regression-to-the-mean bias, and what performance threshold is set by the state DOT; therefore, measures should be taken to address such concerns (e.g., collecting traffic volume data, crash data, establishing contextualized safety performance functions) to integrate safety analysis framework into the project delivery process. An example to illustrate the data needs is provided in Table 3.3:

Table 3.3: Data requirements for DDSA integration in the planning phase (HSM)

Performance Measure	Data and Inputs				
	Crash Data	Roadway Information	Traffic Volume	Calibrated SPFs	Other
Average Crash Frequency	■	■			
Crash Rate	■	■	■		
Equivalent Property Damage Only (EPDO) Average Crash Frequency	■	■			EPDO weighting factors
Relative Safety Index	■	■			Relative severity indices
Critical Rate	■	■	■		
Excess Predicted Average Crash Frequency Using Safety Performance Functions (SPFs)	■	■	■	■	
Probability of Specific Crash Types Exceeding Threshold Proportion	■	■			
Excess Proportion of Specific Crash Types	■	■			
Expected Average Crash Frequency with EB Adjustment	■	■	■	■	
Equivalent Property Damage Only (EPDO) Average Crash Frequency with EB Adjustment	■	■	■	■	EPDO weighting factors
Excess Expected Average Crash Frequency with EB Adjustment	■	■	■	■	

Another important consideration during the planning phase will be considering robust and safety focused network screening procedures. For example, HSM has proposed these following types of screening methods to identify and rank the potential locations that could have a safety improvement–

- Sliding window or peak searching methods for segment-level analysis.

- Simple ranking method for node-level analysis (intersections or ramp terminal intersections).

- Combination of nodes and segments for facility-level analysis.

Once network screening process is done, focus should be given to reviewing safety data that will help DOT personnel identify patterns in crash type, crash severity, or roadway environmental conditions. While ODOT has built in house analysis tool - TransGIS, GeoData (meta-data for ODOT GIS databases), FHWA has recommended using the following illustrative approaches to review available safety data:

- Collision diagram - a two-dimensional plan view representation of the crashes that have occurred at a site within a given time period. A collision diagram simplifies the visualization of crash patterns. Crash clusters or patterns of crashes by collision type (e.g., rear-end collisions on a particular intersection approach) may become evident on the crash diagram that were otherwise overlooked. Figure 3.2 provides an example of a collision diagram.

- Condition diagram - a plan view drawing of as many site characteristics as possible (see Figure 3.3). Characteristics that can be included in the condition diagram are roadway configuration, land use pattern, and pavement conditions.

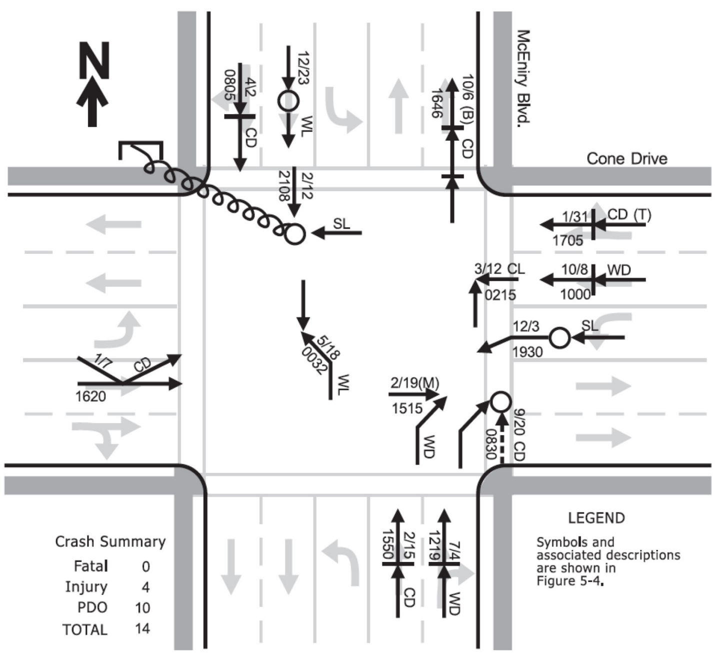


Figure 3.2: An example of collision diagram (adapted from ITE Manual of Transportation Engineering Studies)

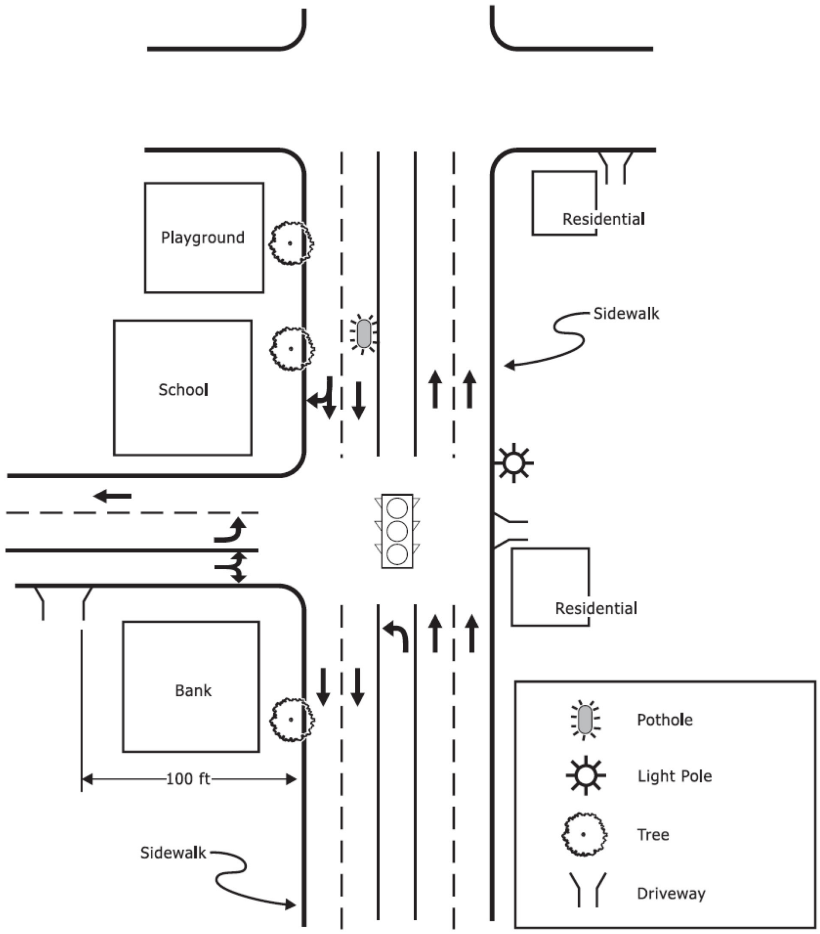


Figure 3.3: Example condition diagram (HSM, 2010)

To facilitate all these processes, FHWA has developed advanced tools - both systemic and predictive - to support application of HSM in the planning phase, these tools offer more illustrative uses such as network screening, diagnosis, countermeasure selection, economic appraisal, prioritization, and countermeasure evaluation. To name a few:

Systemic application examples:

- AASHTOWare SafetyAnalyst (www.safetyanalyst.org) is a tool that can be used to perform planning-level screening. SafetyAnalyst allows the user to select from a variety of safety performance measures and screening methods (listed in Chapter 4, Part B of the HSM) to identify sites or corridors with potential for safety improvement.

- The FHWA Safety Performance Measure Primer is also available as a resource to help identify additional performance measures.

- PlanSafe is a software tool that was developed through NCHRP. While macro-level safety prediction approaches (such as PlanSafe) are not included in the first edition of the

HSM, agencies can use PlanSafe to compare differences in crash frequency or severity across different future development and network scenarios.

Predictive application examples

As for the predictive analysis, ODOT is heavily dependent on Highway Safety Manual (HSM) Part C to perform detailed assessment of safety assessment at segment or intersection level. However, HSM offers predictive models for the following types of roadways:

- Rural two-way, two-lane roads (HSM Part C Chapter 10)
- Rural multilane highways (HSM Part C Chapter 11)
- Urban and suburban arterials (HSM Part C Chapter 12)
- Freeways, interchanges, and ramp terminals (ISATe / HSM Supplemental Chapters 18 and 19)

However, ODOT recognizes that such available prediction models cannot be applied to situations such as:

- Highways or arterials with six or more through lanes.
- Rural freeways with eight or more through lanes.
- Urban freeways with ten or more through lanes.
- Interchange designs other than diagonal or partial clover (Parclo).
- Single-point urban, crossing/diverging diamond, or continuous flow interchanges.
- Freeway ramp terminals on a one-way street, metered entrance, or roundabout.
- All-way stop intersections.
- Yield-control intersections.
- Rural three-leg signalized intersections.

Although ODOT have developed several predictive models to be applicable for Oregon traffic scenarios (e.g., Access management (SPR 720), Roundabouts (SPR 733), Signalized Intersection (SPR 756), and Work Zone (Ongoing)), it is also recommended to obtain solutions from other relevant DOT projects based on guidelines from Practical design policy (Chapter 10 of the APM).

In summary, all above practices can be summarized as:

- Method 1 - Estimate the expected average crash frequency of both the existing and proposed conditions based on HSM Part C predictive methods.

- Method 2 - Applying predictive methods detailed in HSM Part C to estimate the expected average crash frequency of the existing condition and then use an appropriate project CMF from HSM Part D to estimate the safety performance of the project condition.

- Method 3 - If the available HSM Part C predictive method is not readily applicable for the proposed project, ODOT should look up if a Safety Performance Function (SPF) applicable to the existing roadway condition is available (i.e., an SPF developed for a facility type that is not included in HSM Part C). The SPF will be applied to estimate the expected average crash frequency of the existing condition, and an appropriate project CMF from HSM Part D is then used to estimate the expected average crash frequency of the proposed condition. A locally derived project CMF in the context of Oregon can also be used in Method 3.

3.3 APPLYING THE DDSA IN ALTERNATIVES DEVELOPMENT AND ANALYSIS

For analyzing which types of countermeasures is most appropriate, from a cost-perspective and project goals alignment standpoint, Oregon Department of Transportation (ODOT) uses the following resources:

- Set of countermeasures and associated Crash reduction factors (CRFs) as outlined in All Roads Transportation Safety (ARTS) (see Figure 3.4).

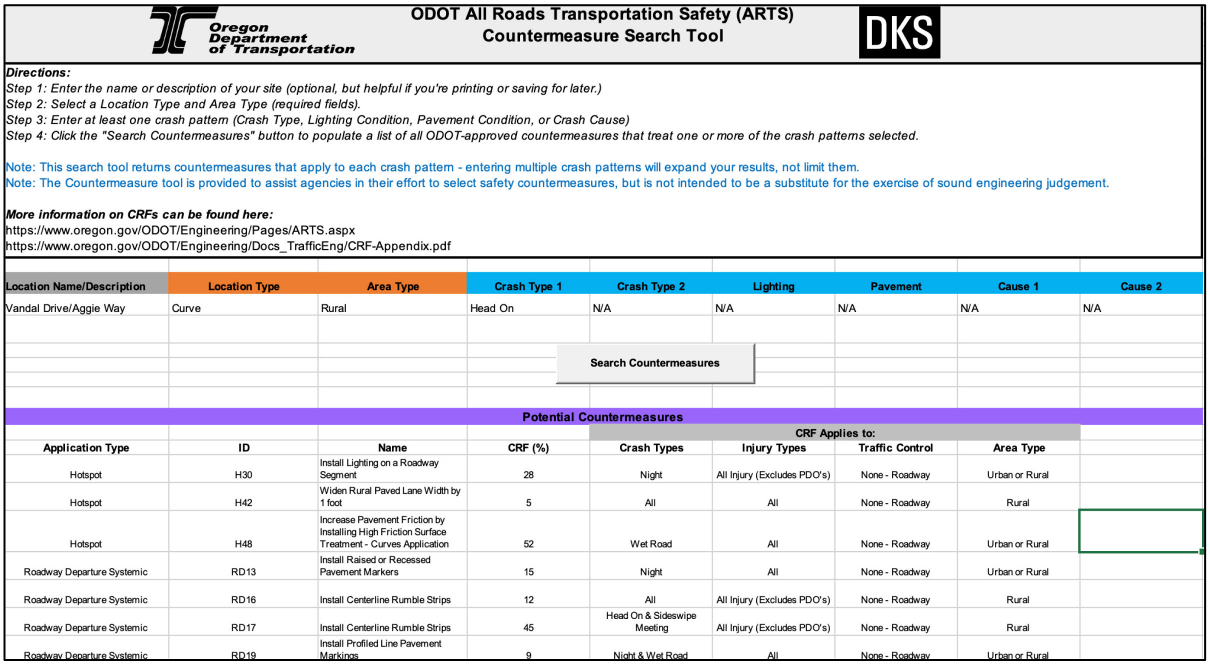
- ODOT Safety Investigations Manual.

- Part D of the Highway Safety Manual (HSM).

- The CMF Clearinghouse (www.cmfclearinghouse.org).

- PedBikeSafe.org (for pedestrian and bicycle safety countermeasures).

To better integrate safety-centric solutions during the project delivery process, FHWA recommends using the predictive methods in HSM Part C to assess the net safety improvements achievable for each of the chosen alternatives. This evaluation also considers a no-build alternative, and, if possible, incorporates economical appraisal for each of the alternatives based on guidance from Part B of the HSM. These tools (e.g., IHSDM software, NCHRP 17 38 spreadsheets) offer a number of user-friendly features - Network screening, Diagnosis, Countermeasure selection, Economic appraisal, Prioritization, and Countermeasure evaluation thus providing transportation engineers more informed safety-centric solutions. Other state DOTs such as Alabama DOT, Virginia DOT, Florida DOT, and Washington DOT have been widely using such approaches during alternatives development and analysis (Van Schalkwyk et al., 2012). For example, Florida DOT District 6 (Tampa) undertook a corridor-widening project on SR 574 and analyzed different design options based on guidelines from the HSM. Such analysis helped quantify the anticipated impact of the design alternatives, resulting in a $1.6 million reduction in overall project right-of-way costs.


Oregon Department of Transportation

ODOT All Roads Transportation Safety (ARTS)
Countermeasure Search Tool

DKS

Directions:
Step 1: Enter the name or description of your site (optional, but helpful if you're printing or saving for later.)
Step 2: Select a Location Type and Area Type (required fields).
Step 3: Enter at least one crash pattern (Crash Type, Lighting Condition, Pavement Condition, or Crash Cause)
Step 4: Click the "Search Countermeasures" button to populate a list of all ODOT-approved countermeasures that treat one or more of the crash patterns selected.

Note: This search tool returns countermeasures that apply to each crash pattern - entering multiple crash patterns will expand your results, not limit them.
Note: The Countermeasure tool is provided to assist agencies in their effort to select safety countermeasures, but is not intended to be a substitute for the exercise of sound engineering judgement.

More information on CRFs can be found here:
https://www.oregon.gov/ODOT/Engineering/Pages/ARTS.aspx
https://www.oregon.gov/ODOT/Engineering/Docs_TrafficEng/CRF-Appendix.pdf

Location Name/Description	Location Type	Area Type	Crash Type 1	Crash Type 2	Lighting	Pavement	Cause 1	Cause 2
Vandal Drive/Aggie Way	Curve	Rural	Head On	N/A	N/A	N/A	N/A	N/A

Search Countermeasures

Potential Countermeasures

				CRF Applies to:			
Application Type	**ID**	**Name**	**CRF (%)**	**Crash Types**	**Injury Types**	**Traffic Control**	**Area Type**
Hotspot	H30	Install Lighting on a Roadway Segment	28	Night	All Injury (Excludes PDO's)	None - Roadway	Urban or Rural
Hotspot	H42	Widen Rural Paved Lane Width by 1 foot	5	All	All	None - Roadway	Rural
Hotspot	H48	Increase Pavement Friction by Installing High Friction Surface Treatment - Curves Application	52	Wet Road	All	None - Roadway	Urban or Rural
Roadway Departure Systemic	RD13	Install Raised or Recessed Pavement Markers	15	Night	All	None - Roadway	Urban or Rural
Roadway Departure Systemic	RD16	Install Centerline Rumble Strips	12	All	All Injury (Excludes PDO's)	None - Roadway	Rural
Roadway Departure Systemic	RD17	Install Centerline Rumble Strips	45	Head On & Sideswipe Meeting	All Injury (Excludes PDO's)	None - Roadway	Rural
Roadway Departure Systemic	RD19	Install Profiled Line Pavement Markings	9	Night & Wet Road	All	None - Roadway	Urban or Rural

Figure 3.4: Countermeasure search tool developed by ODOT (ODOT, 20XX)

Once a number of countermeasures are selected, Highway Safety Manual (HSM) recommends safety-centric economic analysis to facilitate informed decision-making process. While current practice includes using conventional economic metrics such as Net Present Value (NPV), Benefit-Cost Ratio (BCR), Cost-Effectiveness Index, economic appraisal should also include safety metrics:

- Number of fatal and incapacitating injury crashes reduced,
- Number of fatal and injury crashes reduced,
- Convert change in crash frequency to annual monetary value.

To name a few but not limited to, the following data need to be acquired as an input to economic appraisal analysis (Council et al., 2005; Harwood et al., 2003):

- Major / minor AADT
- Service life
- Annual traffic volume growth rate
- Societal Crash Costs by Severity Fatal and Injury.

3.4 APPLYING THE DDSA IN DESIGN

In Chapter 10 of the Analysis Procedures Manual (APM) (see Section 10.5), ODOT has outlined what design criteria should be followed while developing geometric designs for a particular project. These design solutions are primarily characterized with cost, maintainability, and traffic operations; however, FHWA recommends integrating science-based human factor fundamentals (see Chapter 2 of the HSM) to identify and develop safety performance-based solutions. Some of the safety-centric questions a designer may consider are as follows:

- Assess the safety impact of a design parameter.
- Evaluate the impact of design exceptions on safety performance.
- Review previously implemented similar projects to evaluate impacts of design criteria.

To illustrate, current practice for the design phase is to consider several geometric elements such as lane and shoulder width, curve radii or roadway grade, with the primary goal of meeting the project-specific needs in a cost-effective manner. However, it is recommended to see how inclusion or exclusion of considering relevant geometric elements affect the safety performance of a project. The predictive method and the CMFs outlined in the Highway Safety Manual (HSM) provide insight into the impact of individual design parameters for a particular highway project, as well as individual treatments. HSM highlights such endeavor as project prioritization methods (chapter 8 of the HSM), three methods are undertaken for such consideration:

- Ranking by economic effectiveness measures,
- Incremental benefit-cost analysis ranking,
- Optimization methods (e.g., Linear programming, Integer programming, Dynamic programming).

Table 3.4 provides an overview about what types of data are required for analysis as mentioned above (Kar et al., 2004):

Table 3.4: Data requirement for DDSA integration in the design phase

Method	Data Input Needs
Ranking by economic effectiveness measures	Annual monetary benefit associated with the change in crash frequency, Service life of the countermeasure, Discount rate (minimum rate of return).
Incremental benefit-cost analysis ranking	Present value of monetary benefits and costs for economically justified projects.
Optimization methods	Present value of monetary benefits and costs for economically justified projects.

However, there may arise situations when constraints related to environmental concerns and available right-of-way may require a designer to consider design exceptions – deviations from established guidelines and criteria. To address such scenarios, FHWA has published “Mitigation

Strategies for Design Exceptions" (FHWA-SA-07-011) that contains guidelines on the quantitative assessment needed to determine the relative Impact an exception may produce.

3.5 APPLYING THE DDSA IN OPERATIONS AND MAINTENANCE

In Chapter 9 of the Analysis Procedures Manual (APM), ODOT has outlined what types of performance measure can be considered to evaluate performance of a transportation facility or infrastructure after it is open for public use. Section 9.6 primarily provides such relevant information, these performance measures include Crash Rate, Change in Crash Frequency Using Crash Modification Factors (CMFs) or Crash Reduction Factors (CRFs), Excess Proportions of Specific Crash Types, Expected or Predicted Crash Frequency etc. However, ODOT should incorporate the more recent FHWA guidelines on how to quantify if a particular operational change resulted in a positive or negative safety impact. To illustrate, HSM Chapter 9 provides an overview of how to use Empirical Bayes (EB) approach for the estimation of treated effectiveness after a certain period a transportation project is in operation. Chapter 9 of the HSM provides state of the art methods in safety performance evaluation. These methods have been found to have higher reliability than traditional approaches. For example, there are three types of design procedures that can be used for safety effectiveness evaluations:

- Observational before/after studies: Observational before/after studies are the most widely used safety evaluation practices. One of the relevant examples will be a project where left-turn lanes were introduced at specific locations on a two-lane highway characterized with significant crash frequency. In general, all observational before/after studies use available crash and traffic volume data for a specific period before and after improvement of the treated site locations. According to FHWA, such observational study can be of two types – projects that use SPFs and projects implemented without the use of SPFs.

- Observational cross-sectional studies: Such types of evaluation analysis are applicable for three scenarios.

  i when treatment installation dates are not available, or

  ii when crash and traffic volume data prior to treatment implementation period are not available, or

  iii when the evaluation needs to explicitly account for effects of roadway geometrics or other related features by creating a CMF function rather than a single value for a CMF. For example, if ODOT has a plan to evaluate the safety performance of intersections with channelized right-turn treatments in comparison to intersections without channelized right turn lanes and there have not been similar prior studies – one configuration is converted to the other, then such observational cross-sectional study may be applied comparing sites with these two different configurations.

- Experimental before/after studies: In experimental studies, sites with similar patterns in traffic volumes and geometric features are randomly assigned to a treatment or nontreatment group. Later, selected treatment is applied to the sites in the treatment group, and traffic data such as crash, and traffic volume is collected for a specific time before and after treatment to illustrate the change in performance. Data may also be collected at the nontreatment sites for the same time, if possible. For example, if ODOT envisages evaluating the safety efficacy of a new and innovative signing treatment, an experimental study is an appropriate treatment to evaluate such practices.

For the above-mentioned analysis, the following data needs to be acquired based on the recommendation from FHWA:

- 10 to 20 sites where the treatment of choice is implemented,
- 3 to 5 years of crash and traffic volume data for the period before treatment implementation,
- 3 to 5 years of crash and traffic volume for the period after treatment implementation,
- SPF for treatment site types.

State agencies are also recommended to adopt appropriate performance measures that provide estimations on the effects maintenance decision changes influence crash rate or severity along the transportation network. The HSM provides relevant tools such as crash modification factors or predictive models that can later be extended to a cost-benefit analysis (see Part B of the HSM).

3.6 ORGANIZATION TOWARDS AN IMPLEMENTAL INTEGRATION FOR DDSA INTO THE PROJECT DELIVERY PROCESS

The AASHTO Highway Safety Manual (HSM) has been developed policies for different stakeholders of a project – planners, designers, and traffic engineers – to measure the safety impacts of decisions throughout the project delivery process on crash frequency and crash severity. Whether a particular project is safety-related or not, FHWA acknowledges that every project can benefit for applying the HSM to different phases of a project delivery process – Planning, Alternatives Development and Analysis, Preliminary and Final Design, and Operations and Maintenance phase (Van Schalkwyk et al., 2012). With such consideration, this report describes and illustrates the application of the AASHTO HSM 2010 into Oregon Department of Transportation (ODOT)'s project delivery process. Table 3.5 provides a summary of the guidelines on how to develop a safety-centric project delivery process for ODOT.

Table 3.5: Framework for DDSA Integration to the Project Delivery Process

Phases	Recommended Tasks	Relevant HSM Chapter	Data Inputs Required
Planning	Introducing both systemic and predictive safety analysis for all types of projects – System Level Plan, Development Review, NEPA, MMA, Facility Plan. Familiarizing ODOT personnel with AASHTOWare, FHWA Safety Performance Measure Primer.	Part B of the HSM	Crash data, Roadway information, Traffic volume, Calibrated SPFs.
Alternatives Development and Analysis	Using predictive methods to select the best cost-effective solution/ treatment. Using IHSDM software, NCHRP 17 38 spreadsheets.	HSM Part C-D	Major / minor AADT, Service life, Annual traffic volume growth rate, Societal Crash Costs by Severity Fatal and Injury.
Preliminary and Final Design	Assessing the safety impact of a design parameter. Evaluating the impact of design exceptions on safety performance. Reviewing implemented projects to evaluate impacts of design criteria.	Chapter 2 of the HSM, FHWA-SA-07-011	Annual monetary benefit associated with the change in crash frequency, Service life of the countermeasure, Discount rate (minimum rate of return).

4.0 IDENTIFICATION AND IMPLEMENTATION OF A DATA-DRIVEN SAFETY ANALYSIS AND SAFETY ORIENTED PROJECT DELIVERY PROCESS

4.1 BACKGROUND

Traditional safety analysis methods are mostly associated with subjective or limited quantitative measures of safety performance. However, such practice may not produce desirable output as it is difficult to measure crash performance alongside other criteria when planning projects. Data-driven safety analysis (DDSA), on the other hand, provide scientifically sound, data-driven models to help transportation agencies identify projects that – if executed – will achieve the most benefit in terms of safety improvement using available resources. It should be noted that key steps for implementation of a DDSA approach are often characterized with limited data availability in crash data, challenges with selection of an appropriate software package which can manage queries of large extents (e.g., large network analysis starting from a planning phase up to operation and maintenance phase). With such observations, we identified the critical issues, impacts or obstacles to implementing a data-driven safety-oriented project delivery process in the following sections. Figure 4.1 illustrates different phases of DDSA integration into the project delivery process.

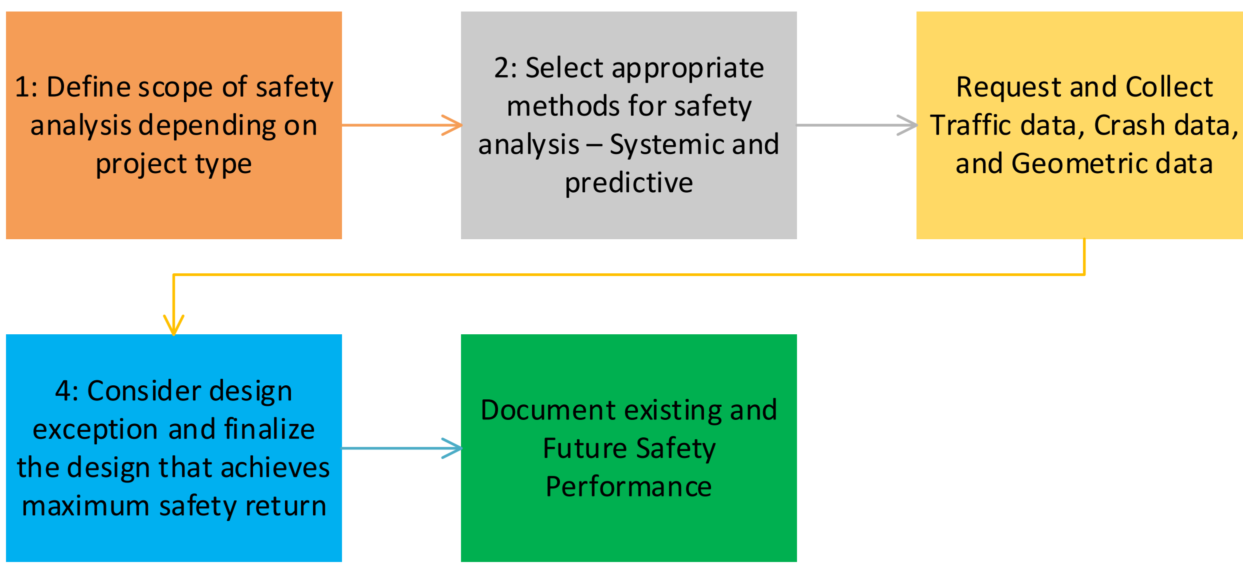


Figure 4.1: Project delivery process flowchart

During the ***Planning*** phase**,** it should be noted that achieving the goal of zero fatal and serious crashes is difficult and requires a substantial amount of effort. Such endeavor often requires effective and efficient use of available project funding and human resources. Therefore, it is important to acknowledge the fact that not all projects will receive the same level of safety analysis. For example, pavement preservation type projects will require less safety analysis in comparison to other projects included in Statewide Transportation Improvement Program (STIP). The reason lies in the notion that ODOT 1R or resurfacing type projects focus on preservation of the overall transportation system, rather than reducing fatal and serious injury crashes. Furthermore, with ODOTs existing project process and the above-mentioned preservation program, although during a specific project, safety improvements are identified; a funding mechanism is triggered that attempts to reallocate funds towards other locations where the same safety improvement might benefit.

These tradeoffs between alternatives need to be outlined while integrating Data-driven safety analysis approach into planning phase. To illustrate, Ohio DOT (as shown in Table 4.1) categorizes transportation projects into (i) Non-complex project assessment; (ii) Complex project assessment without "Safety" in the purpose statement; and (iii) Complex projects assessment with alternative analysis and safety component, and mandates safety analysis for complex type of projects.

For the ***Alternatives Development and Analysis*** phase, a benefit-cost analysis should be incorporated with the initial list of countermeasures while considering engineering factors such as each strategy's effectiveness at reducing desired crash types, implementation and maintenance costs, and alignment with ODOT's policy, practices, and objectives. Current FHWA and AASHTO recommendations are to adopt statistical metrics such as monetary value of project benefits, net present values, cost-effectiveness index (detailed explanation is provided in Chapter 3). These statistical metrics include application of Empirical Bayes (EB) method and calibrated crash modification factors. Other recommended approaches are to assume variance in the costs associated with each of these countermeasure strategies. To illustrate, Michigan DOT considers a normal distribution assuming 99.7% of cost values are within three standard deviations of the mean. To illustrate, Michigan DOT considers a normal distribution assuming 99.7% of cost values are within three standard deviations of the mean. For better understanding, based on the historical success of countermeasures, considering both their effectiveness in crash reduction as well as costs, with this documented dataset a more informed distribution considered the lower and upper bounds of the cost of the countermeasure and its potential safety benefits.

For the ***Preliminary and Final Design*** phase, ODOT authority should keep considerations of the fact whether any design change resulting from accommodating available funding constraint will achieve the most safety benefit. Table 4.1 demonstrates both TxDOT and FDOT utilize HSM spreadsheets for roadway segments and classifications, to explore alternatives and identify an optimal safety score. The optimal safety score considers three predominant elements, geometric, traffic and roadside. Each of these characteristics requires some data input. Examples include horizontal and vertical curve information for the geometric portion, the existence of external or intrusive traffic elements like advanced static curve warnings or rumble strips and lastly side slope or lateral clearance distances for roadside elements.

To correctly score such items, which all already have their own crash modification factor pre-calibrated for ODOTs roadways, there must be data to satisfy the existence of such elements. The lack of existing data is indeed the major obstacle for incorporating such a methodology for ODOT. Appendix A demonstrates a review of what existing data elements ODOT currently has, and where to retrieve such information, to incorporate such HSM scoring spreadsheets that both

TxDOT and FDOT currently use. The identified missing items are either known items that ODOT does not currently possess data for, or items that the research team is unaware of obtaining at this time.

In the ***Operation and Maintenance*** phase, predictive analysis should be introduced to o measure how much the project has achieved in terms of safety improvement after being in operation for a fiscal year. Such analysis will provide guidelines for ODOT personnel to adopt appropriate design policies for future projects.

In the following section, we will first have a brief overview of what types of obstacles or challenges other DOTs have faced while implementing these phases for safety-centric projects. We will also have a brief discussion of how these calculations related to each of these phases are carried out through safety tools as well as what are data requirements for those tools. Finally, we will provide a decision matrix about what steps should be considered for introducing DDSA framework into ODOT project delivery process.

4.2 NOTEWORTHY DDSA PRACTICES AND PROGRAMS

DDSA Toolbox is a collaborative effort by AASHTO, FHWA, the Transportation Research Board, and the industry to provide guidelines about evidence-based safety analysis that aggregates information state and local highway agency practices to address DDSA-based planning, implementation, and evaluation challenges. We have selected Washington DOT, Ohio DOT, Texas DOT, Florida DOT, and IOWA DOT to systematically analyze safety-analysis related strategy applied for different stages of the DDSA implementation (as referred in Chapter 2, 3). Table 4.1 provides detailed information about other DOT practices.

Table 4.1 Impacts of different state DOT's practice for DDSA integration into project delivery process.

State DOT	Critical issues, obstacles for DDSA integration into project delivery process			
	Planning	**Alternatives Development and Analysis**	**Preliminary and final design**	**Operation and maintenance**
Washington DOT	Preservation projects receive less safety analysis than a safety-centric project. Mobility and economic initiative projects, however, require safety analysis to accommodate performance tradeoff considerations between alternatives. HSM-based predictive analysis is done for the state highway system to identify hotspot's locations.	Mainly uses HSM predictive methods - SPFs and CMFs. Extensive data is collected to calibrate the SPF curves to account for variation in crash frequencies between WSDOT-specific traffic scenarios.	Design analysis include measuring safety impacts of the alternatives to understand the tradeoff decisions while finalizing the effective mitigation measures.	Empirical Bayes formula is used to measure the effectiveness of the safety measures after a traffic project is open for operation.
Ohio DOT (ODOT, 2018)	State-of-the-art statistical methods are used to identify locations with the most potential for safety improvement (PSI). Traffic projects are categorized as – (i) Non-complex project assessment; (ii) Complex project assessment without "Safety" in the purpose statement; and (iii) Complex projects assessment with alternative analysis and safety component. For Non-complex projects, minimal safety analysis is required limited to questions such as - are crash percentages above statewide averages? can safety	ECAT tool is used for identifying site-specific countermeasures to improve the safety scenario of the project. HSM Part D, Chapters 13-17 is also used as a reference to have an insight into the effectiveness of various safety countermeasure.	A variety of safety strategies including engineering, enforcement, driver education and/or other factors is considered while the design analysis is finalized. Project engineers/ consultants also consider if a combination of countermeasures will achieve the maximum safety improvement.	-

State DOT	Critical issues, obstacles for DDSA integration into project delivery process			
	Planning	Alternatives Development and Analysis	Preliminary and final design	Operation and maintenance
	countermeasures be included in the current project?, is location on state or local priority lists?. For the other two types of projects, a variety of systemic and predictive analysis is carried to identify PSIs. Local agencies use a combination of crash frequency, crash severity, and crash rate to identify PSIs. Collision diagram and physical condition diagram is produced to aid in potential countermeasures election.			
Texas DOT	A Highway Safety Improvement Program (HSIP) screening tool is used to categorize state highways into one of four risk categories - very high-risk, high-risk, moderate risk, and low risk. The HSIP tool requires data such as historical fatal and suspected serious injury crashes (i.e., KA crashes), roadway classification system, and the VMT for identifying roadways where a higher opportunity for reducing crashes exists include.	Texas HSIP manual includes detailed countermeasure information. Other recommended sources include the HSM and FHWA CMF Clearinghouse. Design elements such as volume, environment, adjacent land use, or cross section are considered while selecting appropriate countermeasure for each project.	Existing district projects and intersections that falls within the current project are analyzed to identity the segments with very high potential for safety improvements.	-

State DOT	Critical issues, obstacles for DDSA integration into project delivery process			
	Planning	Alternatives Development and Analysis	Preliminary and final design	Operation and maintenance
	A 7-year period crash profile is developed for each project for understanding the factors that contribute to the increase in crash statistics. Crash profile includes two key aspects: crash descriptive statistics and crash density analysis.			
Florida DOT	Crash data for an individual project is compared to the statewide average rates and cluster analysis is then performed to select segments of the highway where a safety problem exists. Several maps such as crash density map, crash frequency heat map, collision diagram are produced to better analyze network-wide safety improvement strategies. HSM predictive method is used to compare the expected average crash frequency to the predicted average crash frequency to measure how much the long-term crash frequency could be reduced in the analysis area. Relevant human factors associated with a project are	HSM predictive methods are extensively used to analyze which countermeasure will achieve the most benefit in terms of safety improvement. Two types of CMFs are considered for the analysis purposes – HSM part C CMFs and countermeasure CMFs.	-	-

State DOT	Critical issues, obstacles for DDSA integration into project delivery process			
	Planning	**Alternatives Development and Analysis**	**Preliminary and final design**	**Operation and maintenance**
	taken into consideration when evaluating the safety performance of a project (using HSM Chapter 2 and NCHRP 600: Human Factors Guidelines for Road Systems – Second Edition).			
IOWA DOT	Basic observed crash data analysis – summary of historical crash data, tables/ graphs for severity, a field review for detailed information about relevant traffic and safety information (e.g., geometric characteristics, traffic control devices, skid marks). Advanced observed crash data analysis – collision diagram, highway condition diagram.	Basic predictive safety analysis for non-complex projects using HSM predictive methods. Advanced predictive safety analysis for complex projects using SPFs and CMFs. Empirical Bayes (EB) adjustments are also applied when required.	-	Qualitative questions are considered - Is traffic being drawn to a facility with a better safety performance? Are reduced trip lengths reducing exposure (vehicle miles travelled)?

5.0 A PRIORITIZED DECISION-MAKING FRAMEWORK FOR PHASED IMPLEMENTATION OF DDSA PRACTICES INTO ODOT'S PROJECT DELIVERY PROCESS

5.1 BACKGROUND

This chapter documents how research findings from previous chapters (e.g., Chapter 3 and 5) can be streamlined to have a systematic integration into the current Oregon Department of Transportation (ODOT)'s project delivery process. It was identified in Chapter 5 that the existing FHWA recommendation is to consider four phases - Planning, Alternatives Development and Analysis, Preliminary and Final Design, and Operation and Maintenance – for such integration. State Transportation agencies across the U.S. had a series of methods and tools to accomplish each of these individual phases, outlined in Table 5.1 of Chapter 5.

What was determined from the analysis in Chapter 3 and 5 is that most of the state DOTs have developed or used a stand-alone software/ tool that helped with the analysis encompassing all these four phases. For instance, tools and methods used within the Alternatives Development and Analysis phase by some agencies were also used within the Preliminary and Final Design phase. TxDOT and FDOT exercise such practice - utilized HSM spreadsheets and Empirical Bayes weighted CMFs in the Alternatives Development and Analysis phase as well as the Preliminary and Final Design phase.

5.2 DDSA INTEGRATION FOR ODOT PRACTICES

The general outline of the proposed framework is to demonstrate how different components that comprise each of the phases can be accommodated in ODOT's current practices. For better description, we divide each phase into different sub-categories, a description is then provided for why each of these sub-categories was chosen for different phases, and the associated steps that ODOT may take to emulate the identified framework, which may include personnel, software, or methodologies. In other words, each of the phases has a series of subcomponents/categories that have associated steps, when merged this makes the framework to incorporate the projects findings into ODOT's current workflow.

5.2.1 Project Planning

To describe how Data-driven Safety Analysis (DDSA) approach can be integrated into ODOT's project delivery process, these assumptions are synthesized from Chapter 2 and 3. The initial step is to identify projects through both a systemic and predictive lens. This requires an extensive data inventory scan, which should identify easily accessible and workable variables for subsequent analysis steps. Potential projects are identified through network screening means and or hotspot/site specific approaches, which leads to the potential safety a project might obtain and then its prioritization.

One of the major outcomes for the planning phase is to identify potential projects that may result in the largest reduction in crashes. The mechanisms to do this alter from agency to agency, as outlined in Chapter 5, but have overlapping major functions to assess the safety potential. This is broken down into three major categories:

- Existing condition analysis,
- Project safety potential, and
- Project prioritization.

Existing conditions analysis:

These methods are meant to create a baseline for comparing the safety of the same highway scenario and roadway classification. It can also be considered as the starting point to identify potential projects to fund that are or may be prone to encountering a safety issue. Most of these analyses take in observed data and output descriptive statistics on crash frequency and severity. Those that are site specific due to an observed volume of crashes are identified through screening mechanisms, whereas the characteristics that produce crashes, where there might not be existing crashes, are considered through systemic means (FHWA 2022; NAP 2020).

The first step involves data inventory - defining the available data sources to identify which systemic and predictive analysis can be readily applied and what are some of the potential areas the agency needs to improve for successful implementation of a data-driven safety analysis approach. It sets the stage for subsequent steps.

- ODOT has been able to develop several data resources which encompass all public roadways in Oregon. These crash data were stored in such a way to facilitate developing crash trees required for systemic analysis (NCHRP20-44). Table 5.1 provides an overview of the current ODOT data availability.

Table 5.1: Example Data Resources from ODOT for Safety Analysis

Data Types	Eugene	Portland	Bend	ODOT
Ped Counts				X
Vehicle Counts		X		X
Zoning	X	X	X	X
Parks	X	X	X	X
Schools	X	X	X	X
Transit Stops				X
Functional Class	X	X	X	X
Ped Facility	X	X	X	X
Bike Facility	X	X		X
Trails/Shared-Use Paths	X	X		X
Road Centerlines	X	X	X	X
Road Lanes			X	X
Road Shoulders				X
Road Speed				X
Marked Crossings	X	X		X
Traffic Signals	X	X	X	X
Enhanced Crossings	X			X
Crashes 2007 - 2017				X
SPIS1 Data 2009 – 2015				X

- These crash data available for analysis dates range from 2007 to 2017 providing a reliable way for the ODOT safety engineers to acquire pedestrian and bicycle crash trees that allows identification of high-risk areas. However, all these data elements are not linked together and therefore an organizational effort is required to develop a comprehensive, accessible-to-all-stakeholders database.

- Balancing between systemic and predictive analysis scope is a challenge when establishing project scope and subsequent work plan. An inter-organizational ODOT team should be assigned with evaluation of the existing data resources (systemic based crash metrics mentioned In Chapter 2, Section 2.1., as well as data availability) to decide on the most feasible combination of both systemic and predictive analyses that will help the project manager take the best-informed decision related to project design scope and timeline of the project.

Project safety potential:

For most agencies, this process is broken down into two categories, network wide screening and systemic approaches, similar to (FHWA, 2022). Network screening is a method in which extensive network wide crash rates are fed into differing GIS-based software, systems to create a priority list to pull projects from (FDOT, OhDOT). The locations and or roadway classifications are categorized to be scored, examples include rural vs. urban or intersection vs. segment based (TxDOT, OhDOT). In some instances, this baseline screening mechanism generates the cause for further, more site-specific analysis which requires a more detailed analysis. This phase can be implemented in the following ways:

- Selection of an appropriate crash metric requires considerable attention as it may lead to potential bias – crash analysis in the context of rural and urban trend provided several discerning perspectives. Being focused on only fatal crashes lead to ODOT identifying urban areas to need immediate safety treatment as urban roadways have fewer, but relatively more severe crashes. Therefore, appropriate safety-related metric should be chosen in line with the project goal and vision.

- Measurement of the project safety benefit can be perceived as a metric for the net potential benefit for the potential project. This variable would come in as a reduction in crashes per VMT, percent reduction or the potential safety improvement (PSI) which is the additional safety that could be reached from an empirical bayes generated SPF curve. Although this comparison metric is similar across agencies, the way they score these projects takes on different mechanisms. TxDOT for instance uses a scoring system for all differing roadway classifications, that includes weightings to compare each of these for better project selection. OhDOT also considers a scoring mechanism that is broken down into two categories, red and blue, which are a function of roadway classification and subsequently crash rates and severities to document those projects with the most PSI. With the potential for safety understood, the last step in this phase is prioritization of projects.

Project Prioritization:

Based on the outputs for the potential safety of a project, measures are considered to weigh the safety of the project as it relates to the cost of implementation. This usually involves a form of a benefit cost analysis, a Safety Improvement Index in the case of TxDOT, or the Strategic Highway Investment Formula for Tomorrow (SHIFT) for the Kentucky Transportation Cabinet (TxDOT 2021; De-Witte 2019). This is a metric to be used for comparison which relates to the agency's organizational goals, the safety of the project may not only include cost and safety variables, but others such as congestion reduction and economic growth. ODOT has predominantly focused on applying systemic analysis for identifying contributing factors – operational and geometrical - leading to fatal and serious injuries. However, there remains challenges to obtain appropriate and relevant crash data that will help apply the list of available HSM predictive approaches (e.g., Average Crash Frequency, Crash Rate, Equivalent Property Damage Only (EPDO), Average Crash Frequency, Relative Safety Index).

Analysis related to project prioritization can be incorporated in the following ways:

- Based on outputs from project safety potential analysis, establish the pattern to the crashes or identify any locations that have concentrated crash occurrence. If no pattern is observed, document these observations, and end the process. Otherwise, determine the prevalent crash types, severities, and find what factors – geometric or underlying human factors – are contributing to the crashes. In addition, developed appropriate collision diagram or condition diagram with detailed layout to help ODOT personnel understand and identify contributing factors (see chapter 3 for details.)

- If there is a series of projects that require more analysis to determine which projects need to be prioritized based on budget constraints as well as ODOT-specific safety goal, optimization techniques such as linear programming, integer programing, and dynamic programing (as detailed in Chapter 3) may be applied to evaluate each project's effectiveness, from both a safety and cost perspective, this may be conducted out a network level as well.

- Aiken to the discussion on the TxDOT tool, the final output from the tool itself is a comparison against the marginal safety that is produced from all cross-sections of potential countermeasures. With this a possible score is developed for the entire project, with its possible alternatives to not only compare internally towards the potential countermeasures for the specific project but a metric to compare other projects as well. An example of this is demonstrated in Appendix A.

5.2.2 Alternatives Development and Analysis Steps:

From the second phase of the generalized project development process, once a project is selected to receive funding, alternatives to design are considered to identify the most cost or safety effective solutions. This phase is broken down into two categories: Countermeasure selection and Evaluation Criteria. Countermeasure selection was documented as it is a function of the type of project that is funded. Some state agencies demonstrated they may fund blanket projects that look at large segments of roadways to invest safety improvements into (ODOT, WSDOT, FDOT, OhDOT non-complex projects). This is considered as systemic treatments alter depending on the roadway classification and/or locations. These treatments typically have state specific crash modification factors associated with them and may utilize software for the analysis. The second major category that is consistent amongst state agencies are site specific projects that were usually predetermined through their network screening process. These locations generally lead to a redesign, which requires more extensive safety evaluation than those from a systemic basis. ODOT can consider the following steps to implement data-driven alternatives analysis:

Countermeasure Selection:

- Based on project objective and available funding for the fiscal year, work with your project manager to identify an appropriate scale and scope of relevant safety analysis work. As mentioned, this is broken down into two sub-components, countermeasure selection and evaluation criteria. The purpose of this step is to undergo both systemic and predictive analysis, with appropriate evaluation metrics to ensure an optimal safety benefit of the chosen countermeasure, which will assist in the final two steps.

- With the help from ODOT's countermeasure selection tool, identify a list a of potential countermeasures relevant to the project. Then apply appropriate safety analysis for each of these countermeasures and document the observation. If the project falls into one of the types as detailed in HSM Chapter 10, 11, 12, 18 or 19 (e.g., rural two-lane roads, rural multilane highways, or freeways, interchanges, and ramp terminals), follows the HSM guidelines. Based on the safety analysis then, select the most appropriate countermeasure and properly document all assumptions with detailed calculation.

Evaluation Criteria:

- The evaluation criteria and analysis are the mechanisms to interpret the anticipated benefit of the chosen countermeasure. It was mentioned that for system treatments this might be baseline CMFs, however for more complex projects this is more in line with SPFs and in almost every agency, aspects of the HSM predictive methods are included. Once the predictive methods are implemented these agencies compare the difference or trade-offs between these two approaches.

- Incorporate monetary analysis into the countermeasure selection tool following guidelines from AASHTO and FHWA to ensure that the selected countermeasure is financially feasible.

- If the project type does not fall within the HSM guidelines (e.g., arterials with six or more through lane or yield-control intersections), apply performance-based practical design policy – identify other DOT projects that matches with the existing condition and compare to see if those analysis observations are relevant – to the existing condition. Typically, the Project manager will consult subject matter experts from ODOT to decide on the best course – determination of similar projects and use CMFs from the project or develop a new CMF altogether.

5.2.3 Preliminary and Final Design

If operational and geometric characteristics of the project is significantly different from the current situation, performance-based practical design policy as outlined Chapter 2 must be applied. An example of significant change relative to the current situation will be converting a two-way stop with a roundabout or replacing a diamond interchange with a cloverleaf one. The reason lies with the fact that previous crash history will not be effective to capture future project statistics if the current situation is vastly changed. These are some of the possible ways to summarize available crash data to better understand existing pattern of the project:

- Evaluating the safety impact of a design parameter.

- Assessing the impact of design exceptions on safety performance.

- Reviewing implemented projects to evaluate impacts of design criteria.

5.2.4 Operations and Maintenance

It is necessary to measure the safety performance of a project after it is open for operation. To do such integration we can apply Empirical Bayes (EB) formulation as well as traditional performance metrics such as to measure how much the project has achieved in terms of safety improvement after being in operation for a fiscal year. These metrics include:

- Change in Crash Frequency Using Crash Modification Factors (CMFs),

- Crash Reduction Factors (CRFs),

- Excess Proportions of Specific Crash Types,
- Expected or Predicted Crash Frequency.

5.3 LOGICAL NEXT STEPS

Based on the requirements of the framework, there is need to Identify where to obtain data, or a procedural list on how to incorporate the array of available data sources from ODOT into the software tools/solutions Identified. An example would be considering the HSM spreadsheets. The spreadsheets call for specific data from the ODOT roadway inventory, which may require secondary calculations (e.g., horizontal, and vertical curves related analysis).

6.0 DOCUMENTATION OF TOOLS, PROCESSES, AND SOFTWARE SOLUTIONS FOR INCLUSION IN GUIDANCE MANUALS AND OUTREACH TO ODOT GROUPS FOR IMPLEMENTATION

Highway agencies have been applying commercial, federal, and pooled fund crash analysis software. We have selected five examples to summarize what software are used or the safety analysis. Section 7.1 includes the software list as well as operational requirement of each of these safety tools in terms of data availability, strength, and limitation. We build upon this knowledge to make an implementation framework of including these tools to the ODOT's practices (Please see Section 7.1). We have also highlighted the way these identified tools, processes, and software solutions and include them in ODOT's guidance manuals (i.e., Highway Safety Investigation Manual (HSIM) and Analysis Procedure Manual (APM)).

Table 6.1: Tools/ Software Packages Accessed by State DOTs

State DOT	Key Findings and Obstacles
Washington DoT (WsDOT, 2020)	Spreadsheet tools – Extended spreadsheets: http://safetyperformance.org/tools/ Chapter 10: Rural two-way two-lane highways Chapter 11: Rural multilane highways Chapter 12: Urban and suburban arterials Interchange safety analysis tool enhanced (ISATe) spreadsheet: http://wwwi.wsdot.wa.gov/ Chapter 18: Freeway mainline segments and speed change lanes (Ramp Tapers) Chapter 19: Ramps, ramp terminal intersections, and Collector Distributer (CD) lines. Each spreadsheet is applicable for one scenario only. Interactive Highway Safety Design Model (IHSDM) – Currently a part of Practical Solutions Highway Safety Manual training series developed for traffic engineers. IHSDM is a "one-stop" tool as it incorporates several spreadsheets that may be required for different traffic scenarios. Data requirement is high in comparison to spreadsheet-based approach.
Ohio DOT	GIS Crash Analysis Tool (GCAT) – A user-friendly tool that can accommodate both state system and local system crash data that is spatially located and unlocated. Users can extract crash dataset that matches with a certain set of conditions (e.g., day of the event, weather data). Crash Analysis Module (CAM) Tool – Crash summaries, graphs, and charts are easily produced thorough this tool which helps traffic engineer diagnosis safety issues. Local public agencies use CAM to produce simple collision diagrams. Transportation Information Mapping System (TIMS) – A web-mapping portal where users can share information with each other. Available traffic data include roadway attributes, covering roadway classification, ownership, physical conditions, functional classification, lanes, roadway surface, highway performance monitoring information and more. As for safety data, TIMS provides information pertaining to the crashes collected by officers such as time of day, weather condition, light conditions, and unit details. Economic Crash Analysis Tool (ECAT) – Users can calculate predicted crash frequencies, complete empirical Bayes calculations, predict crash frequencies for proposed conditions, conduct alternatives analyses, and complete a benefit-cost analysis using ECAT.

State DOT	Key Findings and Obstacles
	Required data for safety analysis include geometric data, side slopes, spiral transition curve, superelevation variance, roadside hazard rating, roadside fixed object density (fixed objects / mi), and traffic data.
Texas DOT (Walden et al., 2015)	Screening tool – Available for use in two-lane highways and urban multilane highways. SPFs were developed for Texas-specific corridor, segment, and intersection condition. Statistical relationships were considered to account for dependency between geometric and operational characteristics for the signalized intersections or state roadways. Wet-pavement crash diagnostic tool – Some districts in Texas experience heavy rainfall which influences monthly crash pattern. Such variation cannot be captured through traditional safety analysis tools. The wet-pavement tool, systemic in nature, use roadway and rainfall characteristics to identify locations with the potential for safety improvement. Roadway widening analysis tool – An excel-based tool to identify roadway segments narrower than 26 ft and so require widening for better traffic operation. Additional data include volume thresholds and benefit/cost ratios for different crash rate scenarios.
Florida DOT (Hull et al., 2016)	Interchange Safety Analysis Tool-enhanced (ISATe) – Developed based on HSM Part C predictive methods. Analysis can be done for freeways segments and freeway speed-change lanes, ramps and ramp terminals, interchanges. Safety Analyst Software – Methods from HSM Part B are used for the calculation purpose. Acts as a standalone system-wide analysis program that can also consider site-specific improvement policies. Highway Safety Manual (HSM) Spreadsheets – The HSM spreadsheets are developed in conjunction with NCHRP 17-38: Highway Safety Manual Implementation and Training Materials. The spreadsheets implement the HSM predictive methods for: Rural Two-Lane Roads (segments and intersections) Rural Multilane Highways (segments and intersections) Urban-Suburban Multilane Arterials (segments and intersections) Such default formulations, however, limitations such as: Does not include the effect of weather. Does not account for traffic variability as HSM uses AADT volumes.

State DOT	Key Findings and Obstacles
	Ignores correlation between individual geometric features and traffic control features. HSM assumes independence of these factors on crash occurrences. Does not account for the influence of freeways with 11 or more through lanes in urban areas, influence of freeways with 9 or more through lanes in rural areas, toll plazas, reversible lanes, use of shoulder as through lanes, ramp metering, managed lanes. Does account for ramp or collector-distributor roads with two or more lanes in rural areas, or three or more lanes in urban areas. Does not account for the influence of unique or innovative intersection or roadway designs. Safety Performance for Intersection Control Evaluation (SPICE) – An easy-to-use tool that automates the predictive HSM safety analysis for intersections. A comparative (relative difference) analysis can be done for various intersection design alternatives. Interactive Highway Safety Design Model (IHSDM) – An open-source FHWA software analysis tool that applies the HSM predictive method. Software offers multiple modules which allow for safety analysis in rural highways (two-lane and multilane); arterials (urban and suburban); freeways (segments, ramps, and interchanges); and intersections.
IOWA DOT (IOWA DOT, 2017)	Interactive Highway Safety Design Model (IHSDM) – analyzing multiple facility types based one model only, directly importing project alignment data, automatic corridor segmentation, offers a high-resolution highway graphical viewer, and has a calibration module to help implement HSM calibration procedures. ISATe (freeway elements only) – a macro-enabled Excel workbook for analyzing freeway segments, ramps, and ramp terminals, Easy-to-use and intuitive. NCHRP 17-38 HSM Spreadsheets (non-freeway elements only) – Macro-enabled Excel workbooks. Applicable for rural two-lane, two-way roads; rural multilane highways; and urban/suburban arterials

6.1 DDSA INTEGRATION FOR ODOT

The following six steps describe how Data-driven Safety analysis approach can be integrated into ODOT's project delivery process. These assumptions are synthesized from Chapter 2 and 3.

STEP 1. Based on project objective and available funding for the fiscal year, work with your PROJECT MANAGER to identify an appropriate scale and scope of relevant safety analysis work. Upon agreement on critical issues related to DDSA, the Project manager will reach out to ODOT staff from Design, Traffic, and Safety team to determine if steps 2 to 4 should be pursued or skipped.

STEP 2. If the operational and geometric characteristics of the project are significantly different from the current situation, skip steps from 2 to 4 and go directly to step 5. An example of significant change relative to the current situation will be converting a two-way stop with a roundabout or replacing a diamond interchange with a cloverleaf one. The reason lies with the fact that previous crash history will not be effective to capture future project statistics if the current situation is vastly changed. These are some of the possible ways to summarize available crash data to better understand existing pattern of the project:

- Identify relevant HSM predictive methods that are applicable for the existing condition to calculate the predicted crash frequency and determine whether the project area has any area that is performing better or worse than anticipated.

- To visualize available crash data, create charts or apply other appropriate data visualization approaches. These charts will include data such as type of crashes, crash severity, number of people involved, road condition, weather information, time of day, or day of the week.

- Geocode the crash data as a map format. Mapping helps visualize the crash data on a network level to better analyze the relationship among geometric data, operation characteristics, and roadside conditions. This can be done, but not limited to, in GIS, Excel, Tableau, or through a simple aerial photo.

STEP 3. Based on analysis from step 2, establish the pattern to the crashes or identify any locations that have concentrated crash occurrence. If no pattern is observed, document these observations, and end the process. Otherwise, determine the prevalent crash types, severities, and find what factors – geometric or underlying human factors – are contributing to the crashes. In addition, developed appropriate collision diagram or condition diagram with detailed layout to help ODOT personnel understand and identify contributing factors (see chapter 3 for details.)

STEP 4. With the help from ODOT's countermeasure selection tool, identify a list a of potential countermeasures relevant to the project. Then apply appropriate safety analysis for each of these countermeasures and document the observation.

- If the project falls into one of the types as detailed in HSM Chapter 10, 11, 12, 18 or 19 (e.g., rural two-lane roads, rural multilane highways, or freeways, interchanges, and ramp terminals), follows the HSM guidelines. Based on the safety analysis then, select the most appropriate countermeasure and properly document all assumptions with detailed calculation.

- Incorporate monetary analysis into the countermeasure selection tool following guidelines from AASHTO and FHWA to ensure that the selected countermeasure is financially feasible.

- If the project type does not fall within the HSM guidelines (e.g., arterials with six or more through lane or yield-control intersections), apply performance-based practical design policy – identify other DOT projects that matches with the existing condition and compare to see if those analysis observations are relevant – to the existing condition. Typically, the Project manager will consult subject matter experts from ODOT to decide on the best course – determination of similar projects and use CMFs from the project or develop a new CMF altogether.

STEP 5. Perform a network-level analysis to determine which projects need to be prioritized based on budget constraints as well as ODOT-specific safety goals. Apply optimization techniques such as linear programming, integer programing, and dynamic programing (as detailed in Chapter 3) to evaluate each project's effectiveness.

STEP 6. Apply Empirical Bayes (EB) formulation as well as traditional performance metrics such as Change in Crash Frequency Using Crash Modification Factors (CMFs) or Crash Reduction Factors (CRFs), Excess Proportions of Specific Crash Types, Expected or Predicted Crash Frequency to measure how much the project has achieved in terms of safety improvement after being in operation for a fiscal year.

To implement the above procedure, the following data need to be collected as part of the traffic procedures as detailed in the APM.

Table 6.1: Required Data for Phase Implementation of the Identified Tools and Processes

Feature	Data Item & Location
General Site Features	• Design Speed* • Posted Speed (available in https://ecmnet.odot.state.or.us/SpeedZone/Search/Index) • Design Year AADT Range • E-Max (%)- Cross-slope/superelevation for the section
Geometric Elements	• Land Width: https://www.oregon.gov/ODOT/DATA/Pages/Road-Assets-Mileage • Shoulder Width: Highway Inventory Detail • Horizontal Curve Data: https://www.oregon.gov/ODOT/Engineering *Horizontal Curves* • Radius (feet) – Central Angle from "Horizontal Curve Info" • Given Tangent length, T and central angle, Delta. • R = T/(Delta/2) • Length of Horizontal Curve (feet) *Vertical Curves* • Vertical Grade Information • Approach Grade • Length • Rate of change, K (ft/ft) L/(g1-g2)
Traffic Elements	• Advance Static Curve Warning Signs* • Advance Curve Warning Flashers* • Chevron Signs on Horizontal Curves* • Post-Mounted Delineators* • Edge line Pavement Markings or Profile Markings* • Shoulder Rumble Strips* • Centerline Rumble Strips* • Driveway Density (driveways per mile) * • Lighting* • Pavement Friction (skid number) * • Fixed Object Type*
Roadside Elements	• Roadside Side slope (Fore slope) * • Roadside Backslope* • Safety Edge* • Roadside Lateral Clearance to Obstruction (ft) * • Roadside Obstruction Type*

Note: * - Not available in ODOT database

7.0 ADOPTION OF FUTURE HIGHWAY SAFETY MANUAL 2ND EDITION INTO THE DDSA FRAMEWORK

FHWA defines Data Driven Safety Analysis (DDSA) as employing newer, evidence-based models that provide state and local agencies with the means to quantify safety impacts to provide scientifically sound, data-driven approaches to identifying high-risk roadway features and executing the most beneficial projects with limited resources to achieve fewer fatal and serious injury crashes (https://safety.fhwa.dot.gov/rsdp/ddsa.aspx). The Highway Safety Manual and its predictive methods and models are the base of the DDSA described in this project.

Performance-Based Practical Design (PBPD) is articulated by FHWA as modifying a traditional design approach to a "design up" approach where transportation decision makers exercise engineering judgment to build up the improvements from existing conditions to meet both project and system objectives. ODOT needs a comprehensive PBPD project prioritization framework from a safety performance perspective based on crash and roadway data allowing the agency to focus safety improvements at locations where the improvement will be the most cost-effective. The HSM predictive methods and models could be incorporated into the PBPD project prioritization framework to provide safety performance of proposed improvement projects.

The Highway Safety Manual 2nd Edition plans to add systemic safety to incorporate systemic safety in the roadway safety management program. The systemic safety to be included is based on the NCHRP 17-77 project report Guide for Quantitative Approaches to Systemic Safety Analysis written by Torbic D.J. et al (2020). The systemic approach evaluates safety risk across a roadway system rather than at certain locations, and crashes alone are not always sufficient to determine what countermeasures to implement according to FHWA (https://safety.fhwa.dot.gov/systemic/index.cfm).

Compared with the crash-history-based approach, the systemic safety management approach uses crash prediction models or rating systems to estimate potential crash reduction. The NCHRP 17-77 project report Guide for Quantitative Approaches to Systemic Safety Analysis (Torbic, D.J. et al, 2020) describes three approaches to systemic safety management: (1) Application of the FHWA Systemic Safety Project Select Tool; (2) Application of safety performance functions (SPFs) using in-house analysis tools or Safety Analyst software; and (3) Application of the U.S. Road Assessment Program (usRAP) methodology using the ViDA software.

The systemic safety approach is consistent with the project prioritization framework of Performance-Based Practical Design by both using safety performance and system objectives. Therefore, the three approaches of systemic safety could be used to estimate safety performance for PBPD project prioritization framework. The systemic safety approach fits in the planning phase of the DDSA framework of this project. It is recommended that ODOT could implement the systemic safety approach soon.

In addition to the system safety approach, Highway Safety Manual 2nd Edition plans to incorporate the Safety Performance Calibration Procedure, and the process to select, apply, and develop Crash Modification Factors. Because of the crash self-reporting and low sample size, research is needed to verify these procedures of HSM 2nd Edition to implement in the DDSA framework.

Furthermore, the Highway Safety Manual 2nd Edition plans to include the pedestrian and bicycle safety analysis based on the recently published NCHRP report Pedestrian and Bicycle Safety Performance Functions (MRIGlobal, 2022) and the NCHRP report Systemic Pedestrian Safety Analyses. It is recommended to include these pedestrian and bicycle analysis procedures in the DDSA framework.

8.0 CONCLUSION

The objective of this study was to identify the data needs, tools, methods, policies, and potential software solutions that would be required towards the successful implementation of a data-driven safety analysis approach into ODOTs project delivery process. The existing processes other state DOT, FHWA and Transportation Research Board implemented and consider as best practices were introduced and documented. From the extensive literature review, a framework was proposed towards the implementation of DDSA into each of the phases of the existing project development process of ODOT. This includes methodologies data constraints and potential software that can be leveraged on behalf of ODOT generating a more safety centric consideration for project development and selection.

The implementation of this project was destined to be determined by ODOT research staff and its eventual incorporation into ODOTs existing safety-based manuals such as the Analysis Procedures Manual, the Blueprint for Urban Design Manual all being housed under ODOTs ProjectWise folder structure. With these findings, ODOT research staff will have the tools necessary to consider the best approach to make structural changes within its department on how to best transition its existing project development process to better incorporate safety and the potential safety projects might produce. Lastly, this project developed training and outreach material to make an easily accessible and transparent depiction on how a path towards the implementation of DDSA could occur and what might be required for its existence.

8.1 RECOMMENDATIONS AND FUTURE WORK

Throughout the process of reviewing practices from other state DOTs and federal officials, there were a series of overlapping methodologies that persisted. Indeed, the DOTs were primarily implementing best practices from the FHWA however their approaches of where each method was introduced in the project development process varied and, in some cases, did not incur the same 4-phase solution mentioned in this research. Although 4-phases are mentioned in this research, it might be an opportunity to consider varying degrees of phases within the project development process itself at ODOTs level and to further document how this might be more beneficial towards a DDSA integration.

Another area of critical focus during this project was an evaluation of possible technologies offered by vendors and some in-house based solutions developed by individual state DOTs. It was identified TxDOT developed their own toolset and subsequent scoring mechanism for project possible potential for safety. Their scoring apparatus not only considered safety but weighted the possible economic configurations during the initial planning phase. Moreover, possible alternatives within the second phase of the generalized project development process had all possible countermeasures, with each calibrated expected safety. Such early evaluations on a project's safety would incur having design engineers operating in these early stages with the safety engineering which might need to be a future consideration if attempting to employ such scoring or alternative mechanisms to calculate the potential for a project.

Lastly, as mentioned in Table 6.1, there is a series of required data to implement each of the various software solutions. If in a future project it is identified the software desired to be widely utilized at an agency level, a distinct document would need to be generated that would guide design and safety engineers towards the successful completion of an evaluation. This would need to consider all calculations required and a step-by-step guide on where to retrieve such data inputs for the software. Although there is data available for most of the methodologies that might be utilized within the software, it is already documented in this report extra data sources are needed. The creation of that data repository and guidance manual on how to implement the chosen software would create an efficient scoping process to assist design and safety engineers.

9.0 REFERENCES

Neuman, T. R. (2003). Guidance for implementation of the AASHTO strategic highway safety plan (Vol. 21, No. 500). Transportation Research Board.

Idaho Department of Transportation (ITD). (2013). Roadway Design Manual. Retrieved from https://apps.itd.idaho.gov/apps/manuals/RoadwayDesign/Roadwaydesignprintable.htm

Kentucky Department of Transportation (KYTC). Overview of Performance-Based Practical Design (PBPD). 2018, DOI: https://doi.org/10.13023/KTC.RR.2018.03. Retrieved from https://www.fhwa.dot.gov/design/pbpd/documents/pbpd_brief.cfm

Ohio Department of Transportation (ODOT), Safety Analysis guidelines. 2018. Retrieved from https://www.transportation.ohio.gov/programs/highway+safety/highway-safety-manual-guidance/safety-analysis-guidelines-cf

Kansas Department of Transportation (KDOT), Performance Measures . accessed 11 October 2017. Available at: https://www.ksdot.gov/Assets/wwwksdotorg/bureaus/burProgProjMgmt/STIP/assetsfor2023stip/2023STIP-5-PerformanceMeasures-Combineddata4P-ver4-Rev4fedrvw-1.pdf

American Association of State Highway and Transportation Officials. (2010) "Highway safety manual." Washington, DC, USA 19192 (2010).

Oregon Department of Transportation. (2012). Highway Design Manual. Retrieved from https://www.oregon.gov/odot/engineering/pages/hwy-design-manual.aspx

American Association of State Highway and Transportation Officials. (2003). *A Manual of User Benefit Analysis for Highways* (2nd ed.). Washington, DC: Author.

American Association of State Highway and Transportation Officials. (2010). *Highway Safety Manual* (1st ed.). Author.

American Association of State Highway and Transportation Officials. (2011). *A Policy on Geometric Design of Highways and Streets* (6th ed.). Washington, DC: Author.

Bledsoe, J. F., Lee, H. S., & Applied Research Associates, Inc. (2021). *HFST Before and After Safety Analysis* (No. cmr 21-003). Retrieved from https://rosap.ntl.bts.gov/view/dot/56935

Council, F., Zaloshnja, E., Miller, T., & Persaud, B. (2005). *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries* (No. FHWA-HRT-05-051). Washington, D.C.: Federal Highway Administration, U.S. Department of Transportation. Retrieved from Federal Highway Administration, U.S. Department of Transportation website: https://www.fhwa.dot.gov/publications/research/safety/05051/

De Witte, S. (2019). *DDSA in Planning.pdf*. Kentucky Transportation Cabinet. Retrieved from https://transportation.ky.gov/Highway-Design/Conference%20Presentation/DDSA%20in%20Planning.pdf

Edara, P., Sun, C., & Breslow, S. (2013). Evaluation of J-turn Intersection Design Performance in Missouri. *Missouri Department of Transportation. Organizational Results*, *cmr 14-005*. Retrieved from https://spexternal.modot.mo.gov/sites/cm/CORDT/cmr14-005.pdf

Federal Highway Administration. (2017a). *Performance-Based Practical Design Start-Up Guide*. US Department of Transportation. Retrieved from https://www.fhwa.dot.gov/design/pbpd/documents/hif17026.pdf

Federal Highway Administration. (2017b). *Safety Effects of the SafetyEdge* (No. FHWA-SA-17-044). US Department of Transportation. Retrieved from US Department of Transportation website: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-1/pdf/safety_edge_techbrief.pdf

Harwood, D. W., Torbic, D. J., Richard, K. R., Meyer, M. M., & Midwest Research Institute. (2010). *SafetyAnalyst: Software tools for safety management of specific highway sites* (No. FHWA-HRT-10-063). Retrieved from https://rosap.ntl.bts.gov/view/dot/971

Hull, R. E., Wemple, E., Fish, J., Silverman, K. K., & Perez-Bravo, D. (2016). *State Policies and Procedures on Use of the Highway Safety Manual* (No. FHWA-SA-16-119). Washington D.C.: Federal Highway Administration. Retrieved from Federal Highway Administration website: https://safety.fhwa.dot.gov/hsm/spp/fhwasa16119.pdf

Idaho Transportation Department. (2013). *Roadway Design Manual*. Author. Retrieved from https://apps.itd.idaho.gov/apps/manuals/RoadwayDesign/files/Roadwaydesignprintable.pdf

Iowa Department of Transportation. (2017). *Iowa DOT Data Driven Safety Guidance*. Author. Retrieved from https://iowadot.gov/ijr/docs/SafetyGuidance.pdf

Kar, K., & Datta, T. K. (2004). Development of a Safety Resource-Allocation Model in Michigan. *Transportation Research Record*, *1865*(1), 64–71. doi: 10.3141/1865-10

Missouri Department of Transportation. (2006). *Practical Design: Meeting our customer's needs*. Jefferson City, MO: Author. Retrieved from Author website: https://spexternal.modot.mo.gov/sites/cm/CORDT/PracticalDesignImplementation.pdf

NCHRP. (2003). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan* [Series]. Retrieved from https://www.trb.org/Main/Blurbs/152868.aspx

Neuman, T. R, Pfefer, K. L., Slack, K., Hardy, F., Council, H., McGee, L., … Prothe, K. (2012). Design Standard Policies and Processes. In *Highway Design Manual* (pp. 1-1-1–35). Oregon Department of Transportation.

Neuman, Timothy R., Pfefer, R., Slack, K. L., Kennedy Hardy, K., Forrest, C., McGee, H., … Eccles, K. (2019). A Guide for Addressing Run-Off-Road Collisions. *Washington Department of Transportation*, *6*.

Texas Department of Transportation, Traffic Safety Division. (2021). *Highway Safety Improvement Guidelines*. Author. Retrieved from https://ftp.txdot.gov/pub/txdot-info/trf/hsip/hsip-guidance.pdf

Torbic, D. J., & Kolody, K. (2021). *TRB Webinar: Reducing Crashes through Systemic Safety Analysis*. Transportation Research Board. Retrieved from https://www.nationalacademies.org/event/08-04-2021/trb-webinar-reducing-crashes-through-systemic-safety-analysis

Transportation Research Board, & National Academies of Sciences, E., and Medicine. (2005). *A Guide for Reducing Work Zone Collisions*. *17*. doi: 10.17226/13889

Transportation Safety and Systems Analysis Division, Traffic Operations Division, & Development Division. (2020). *Safety Analysis Guide* [Multimodal Development and Delivery]. Washington State Department of Transportation. Retrieved from Washington State Department of Transportation website: https://wsdot.wa.gov/publications/fulltext/design/ASDE/Safety-Analysis-Guide.pdf

Utah Department of Transportation. (2011). *Practical Design Guide: Planning and Designing Practical Transportation Solutions for Utah*. Author.

Van Schalkwyk, I., Wemple, E. A., & Neuman, T. R. (2012). *Integrating the HSM into the Highway Project Development Process* (No. FHWA-SA-11-50). Federal Highway Administration. Retrieved from Federal Highway Administration website: https://highways.dot.gov/safety/data-analysis-tools/hsm/integrating-hsm-highway-project-development-process

Walden, T. D., Lord, D., Ko, M., Geedipally, S., & Wu, L. (2015). *DEVELOPING METHODOLOGY FOR IDENTIFYING, EVALUATING, AND PRIORITIZING SYSTEMIC IMPROVEMENTS*. Austin, TX: Texas Department of Transportation, Traffic Operations Division. Retrieved from Texas Department of Transportation, Traffic Operations Division website: https://ftp.txdot.gov/pub/txdot-info/trf/trafficsafety/engineering/systemic-improvements.pdf

APPENDIX A: TEXAS DOT PROJECT SELECTION TOOL

Case Study 2 Alternatives Assessment: Texas DOT

Consider Potential Alternatives for Each Category.

Geometric Design Elements	
	Configuration of Multilane Roadway
	Median Width (feet)
	Lane Width (feet)
	Average Outside Shoulder Width (feet)
	Average Inside Shoulder Width (feet)
	Number of Lanes per Direction of Travel
Yes	Horizontal Curve Present?
	Horizontal Curve Data for Controlling Element:
	Radius (feet)
	Length of Horizontal Curve (feet)

➕

Traffic Elements
Advance Static Curve Warning Signs
Chevron Signs on Horizontal Curves
Post-Mounted Delineators
Edgeline Pavement Markings or Profile Markings
Shoulder Rumble Strips
Centerline Rumble Strips

➕

Roadside Elements
Roadside Sideslope (Foreslope)
Roadside Backslope
SafetyEdge
Roadside Lateral Clearance to Obstruction (ft)
Roadside Obstruction Type

https://www.txdot.gov/inside-txdot/division/design.html

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Case Study 2 Alternatives Assessment: Texas DOT

Consider Potential Geometric Variations

Decrease Median Width Vs. Increase radius of Horizontal Curve

	Geometric Design Elements	Existing	Standard (Based on Multi-lane Divided)	Design 1	Design 2	Marginal Safety for Design 2 (compared to standard)
	Configuration of Multilane Roadway	Divided	Divided	Divided	Divided	+0%
	Median Width (feet)	10	30	30	10	-10%
	Lane Width (feet)	11.0	12.0	12.0	12.0	+0%
	Average Outside Shoulder Width (feet)	3.0	8.0	5.0	8.0	+0%
	Average Inside Shoulder Width (feet)	3.0	4.0	4.0	4.0	+0%
	Number of Lanes per Direction of Travel	2	2.0	2	2	
Yes	Horizontal Curve Present?	--	--	--	--	
	Horizontal Curve Data for Controlling Element:	--	--	--	--	
	Radius (feet)	4000.00	2445.00	3800.00	3500.00	+6%
	Length of Horizontal Curve (feet)	500.00	500.00	525.00	500.00	

https://www.txdot.gov/inside-txdot/division/design.html

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Case Study 2 Alternatives Assessment: Texas DOT

Consider Potential Traffic Elements

No Shoulder Rumble Strips Vs. **Advance Static Curve Warning Sign or Edgeline Pavement Markings**

Traffic Elements	Existing	Standard	Design 1	Design 2	Marginal Safety for Design 2 (compared to standard)
Advance Static Curve Warning Signs	No	No	No	Yes	+7%
Chevron Signs on Horizontal Curves	No	No	No	No	+0%
Post-Mounted Delineators	Yes	No	No	No	+0%
Edgeline Pavement Markings or Profile Markings	No	No	No	Yes	+13%
Shoulder Rumble Strips	No	Yes	Yes	No	-9%
Centerline Rumble Strips	Yes	No	No	Yes	+0%

https://www.txdot.gov/inside-txdot/division/design.html

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Case Study 2 Alternatives Assessment: Texas DOT

Consider Potential Roadside Elements

Roadside Lateral Clearance Vs. **Increase Roadside Side slope**

Roadside Elements	Existing	Standard	Design 1	Design 2	Marginal Safety for Design 2 (compared to standard)
Roadside Sideslope (Foreslope)	1V:8H	1V:4H	1V:8H	1V:8H	+6%
Roadside Backslope	1V:5H	1V:4H	1V:5H	1V:5H	+0%
SafetyEdge	Yes	No	Yes	No	+0%
Roadside Lateral Clearance to Obstruction (ft)	10.0	30.0 ft	20.0	20.0	-8%
Roadside Obstruction Type	Other Fixed Object	None	None	Other Fixed Object	+0%

https://www.txdot.gov/inside-txdot/division/design.html

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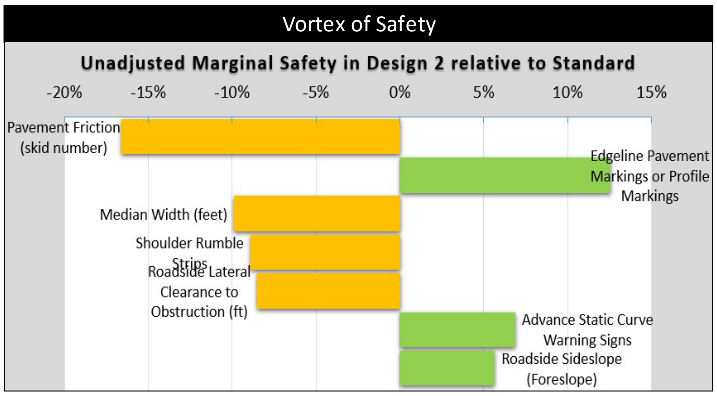
Case Study 2 Alternatives Assessment: Texas DOT

Compare Marginal Safety From All Categories



Summary Results

SCORE SUMMARY FOR DESIGN 2 OPTION	
GEOMETRIC DESIGN:	25.0
TRAFFIC CONTROL:	13.0
ROADSIDE:	21.0
OVERALL SAFETY SCORE:	59.0