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Application of IHSDM: KY 30 Case Study

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We provide services to the transportation community through research, technology transfer, and education. We create and participate in partnerships to promote safe and effective transportation systems.

Application of IHSDM: KY 30 Case Study

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16. Abstract

A section of KY 30 in Jackson and Owsley Counties is targeted for redesign to provide a safer and more efficient corridor that will support economic activity in eastern Kentucky. Data for the existing KY 30 alignment and eight alternative alignments developed by HMB Professional Engineers Inc. were provided to researchers at the Kentucky Transportation Center (KTC). KTC researchers also developed a new alternative that modified the existing alignment to improve the safety of various locations. Researchers applied safety analysis procedures from Part C of the Highway Safety Manual (HSM) to the existing and alternative alignments of KY 30 using the Interactive Highway Safety Design Model (IHSDM). The resulting crash predictions were used to analyze each alternative and perform a benefit-cost analysis.

Each alignment's safety benefits were derived by calculating the total reduction in crashes (i.e., subtracting the number of crashes anticipated for an alternative from the number of crashes that would be expected if the segment were not redesigned). Comprehensive crash costs from the National Safety Council (NSC) were applied to the reduction in crashes to estimate, in monetary terms, the safety benefit. This figure was compared to the estimated cost of each project. KTC's modified existing alignment had a benefit-cost (B/C) ratio of 0.14, meaning project's cost outweighs the expected safety benefits. The other new build alternatives had negative B/C ratios, meaning the cost of crashes is expected to *increase* after their implementation. The increase in crash costs for the new build alternatives is due to the increase in crash severity expected on the new alignments coupled with the current alignment remaining a source of crashes (as the latter would remain open to facilitate the mobility of residents).

IHSDM analysis only captures expected safety benefits, however. The selected alternative may be economically justifiable based on a holistic evaluation of the potential benefits it offers — in addition to safety benefits. The potential non-safety benefits of each project alternative should be analyzed to inform and improve the decision-making process for the KY 30 redesign.

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Executive Summary

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Introduction to IHSDM

The Interactive Highway Safety Design Model (IHSDM) is a decision-support tool created as a part of the Federal Highway Administration's (FHWA's) Data-Driven Safety Analysis initiative. It is used to evaluate the safety and operational effects of geometric design decisions on highways. The software consists of six evaluation modules: crash prediction, design consistency, intersection review, policy review, traffic analysis, and driver/vehicle response — all are supported by nationally accepted research and design policies (1).

The crash prediction module implements Part C of the Highway Safety Manual (HSM) using safety performance functions (SPFs) and crash modification factors (CMFs) from the HSM to predict crash frequency and severity on existing alignments, compare the safety of design alternatives, and assess the safety and cost effectiveness of design decisions (2). The current version of IHSDM can apply the crash prediction module on all roadway types covered in HSM Part C, including rural two-lane highways.

KY 30 IHSDM Application Summary

This research applied the safety analysis from HSM Part C to the existing and eight proposed alignments of KY 30 in Jackson and Owsley Counties. IHSDM was used to provide insight into the expected safety performance of each alignment. This study also demonstrates how the HSM can be implemented in the design phase of Kentucky Transportation Cabinet (KYTC) projects. This section of KY 30 is a part of the I-75 to Mountain Parkway corridor that connects population centers in eastern Kentucky. The segment has been targeted for improvements due to the presence of several geometric deficiencies (relative to guidelines contained in AASHTO Green Book design policy). These include reverse curves, vertical curves with insufficient sight distance, lack of clear zone along the roadway, and access points with limited visibility. The goal of the redesign is to provide a safer and more efficient corridor and make the infrastructure improvements needed to support economic activity in eastern Kentucky (3). This study evaluated current and proposed alignments to determine which alternative has the highest expected safety performance.

IHSDM Data Inputs

IHSDM contains many data fields, which let users achieve their desired level of detail when modeling roadways. Certain modules have minimum data requirements that must be satisfied for the module to operate. The crash prediction module requires the following inputs for each alignment:

- Horizontal alignment
- Vertical alignment
- Lane profile
- Shoulder profile (including edge line rumble strips)
- Cross slopes for tangent sections
- Annual average daily traffic (AADT)
- Design speed
- Driveway density
- Roadside hazard rating

In addition to the minimum inputs, the following data can be included in IHSDM to enhance crash predictions if they apply to a given alignment:

- Ramp connections
- Intersections
- Lane offsets
- Roadway lighting
- Speed enforcement device presence

- Centerline rumble strip
- Site-specific crash data

The existing and proposed alignments of KY 30 contain intersections with other roadways; however, a lack of alignment and stationing information for the intersecting roadway segments made the inclusion of intersections in the crash prediction modules for each alignment impractical given the scope of this study. Therefore, all intersections were excluded from this analysis.

Process for Existing Alignment Input
Kentucky Transportation Center (KTC) researchers acquired horizontal and vertical alignments for the existing KY 30 corridor from KYTC in the form of .alg and .dgn files. These files were opened in InRoads and converted to .landxml files. IHSDM requires .xml files in a specific IHSDM format to import highway data into the program; however, the software is able to read data from a .landxml file. The .landxml alignments were imported into IHSDM. Supplemental information related to the current KY 30 alignment was needed to satisfy the minimum data requirements, and the majority of these data was found in the Design Executive Summary (DES) from HMB (the consultant under contract with KYTC for KY 30 design analysis). The following data from the DES were used to model the existing KY 30 corridor in IHSDM:

- AADT for the 2017 (1300) and 2038 (1800)
- DHV of 210
- 10' thru lanes
- 2% cross slope on all tangent sections
- Shoulders of 0-2' (IHSDM was programmed as 0' shoulders along the entire alignment due to the scarcity of actual shoulders) with rumble stripes
- 55 mph design speed
- Maximum superelevation of 8%

Two assumptions were made about the existing alignment to satisfy the minimum input requirements for a crash prediction module in IHSDM. Driveway density was counted as 10/mile based on an inspection of the existing alignment using aerial photography and considered constant across the entire alignment. A roadside hazard rating of four was assumed along the entire alignment. Roadside hazard ratings are used to categorize the roadside accident potential of two-lane highways on a scale from one (best) to seven (worst). The ratings are based on roadside design factors including clear zone, guardrail presence, side slope, distance to obstacles, and vehicle recoverability upon exiting the roadway (4). A rating of four was assumed on the existing KY 30 alignment due to the lack of shoulders, proximity of trees to the roadway, and steep slopes along the road.

Process for Alternative Alignment Input
Researchers also obtained horizontal and vertical alignments for the eight alternative KY 30 alignments (Alternatives 1, 1a, 1 to 2 Crossover, 2 to 1 Crossover, 2, 2a, 2a, and 3) in .alg and .dgn format from KYTC. These alignments were converted from .alg to .landxml in InRoads and imported into IHSDM. The supplemental information needed to complete a crash prediction module found in the DES for the alternatives is as follows:

- AADT for the 2017 (1300) and 2038 (1800)
- DHV of 210
- 11' thru lanes
- 2% cross slope on all tangent sections
- Paved shoulders of 10' (assuming rumble stripes), 2' unpaved with 4% slopes (outside shoulders only because it is an undivided highway), totaling 12' of shoulder

- 55 mph design speed
- Maximum superelevation of 8%

Assumptions were made about the two remaining data requirements: roadside hazard rating and driveway density. The roadside hazard rating was set at three for all alternative alignments due to their improvements in shoulder width, clear zone, and roadside slopes. The same driveway density of 10/mile for the existing alignment was assumed for the alternatives.

All alternative alignments are the same for approximately the first 3,500 ft. However, KYTC's alignment files only associated the first 3500 ft. of alignment with Alternative 1. As such, each alternative listed in Table 1 has a shorter length when compared to Alternative 1. The differences among alternative starting points and a visual representation of the eight alternative alignments is shown in Figure 1.
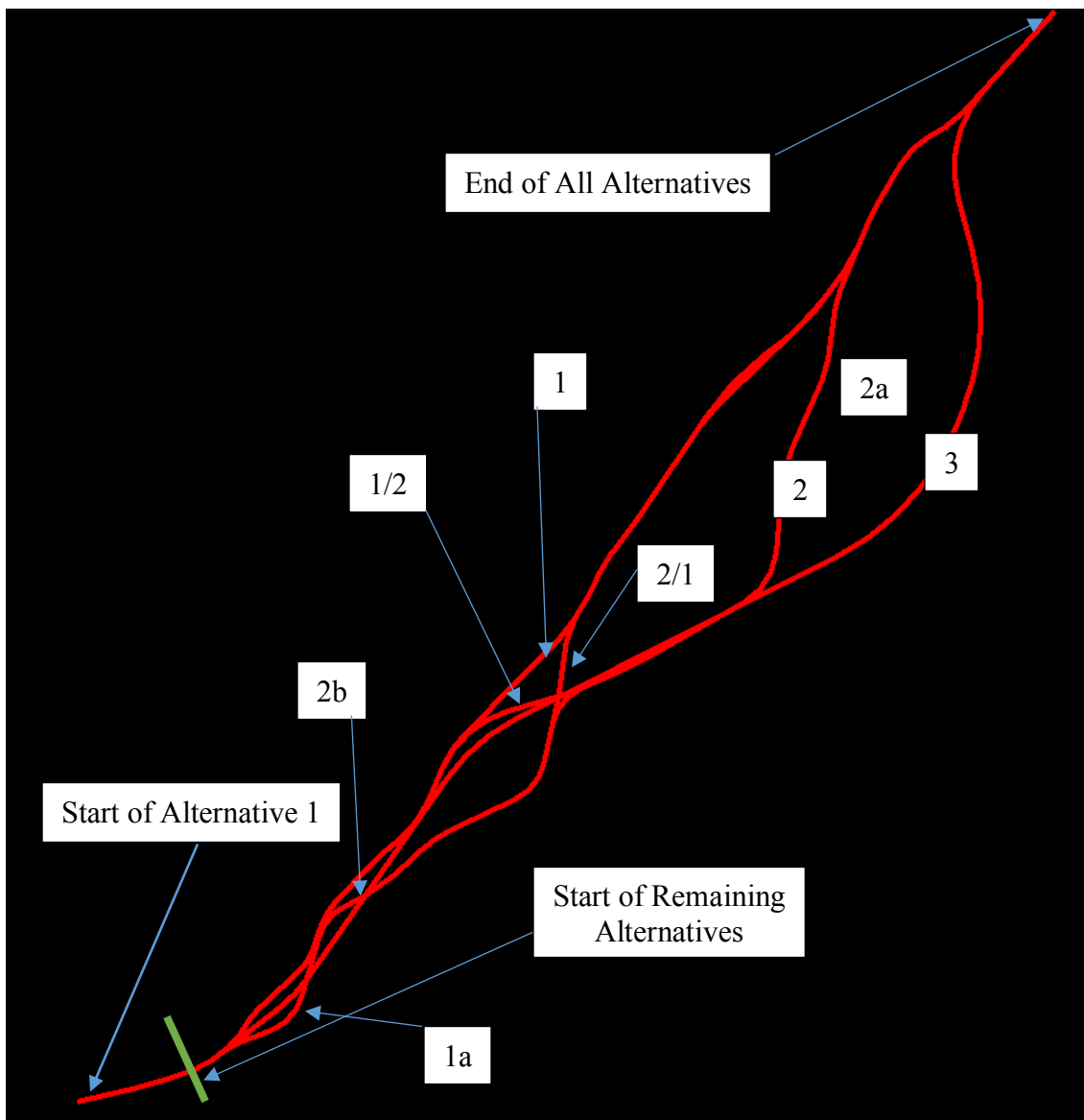

Figure 1 Alternative Alignment Comparison

In addition to the eight alignments provided by HMB, KTC created an alternative alignment based on the existing alignment of KY 30 in an attempt to provide a lower cost alternative that improves safety along

KY 30. Researchers used five years of historic crash data to identify curves along the existing alignment with high crash rates that could benefit from spot improvements. In addition to several spot improvements along the alignment, the beginning of the corridor was shifted south along US 421 to meet the KY 30 intersection for the recently renovated KY 30 corridor west of US 421. KTC's alignment is highlighted in blue in Figure 2. Alternative alignments are shaded red (same as in Figure 1); the existing alignment is in red with tick marks. The modified existing alignment uses the beginning of HMB's Alternative 1 to connect into the existing alignment near station 180+00. This connection of the existing alignment to the first section of Alternative 1 bypasses the intersection with US 421 and curves with high historical crash rates (Figure 4.) The curves nearest the connection between Alternative 1 and the existing alignment are smoothed to create a safer transition. The modified existing alignment deviates from the existing alignment in three additional locations: stations 365+00, 500+00, and 627+00. These three locations represent a series of horizontal and vertical curves that are difficult to traverse and show patterns of historical crashes. In addition to the realignments in the modified existing alignment, this proposed alternative also involves a widening of shoulders to 2 ft. along the entire length of the corridor.
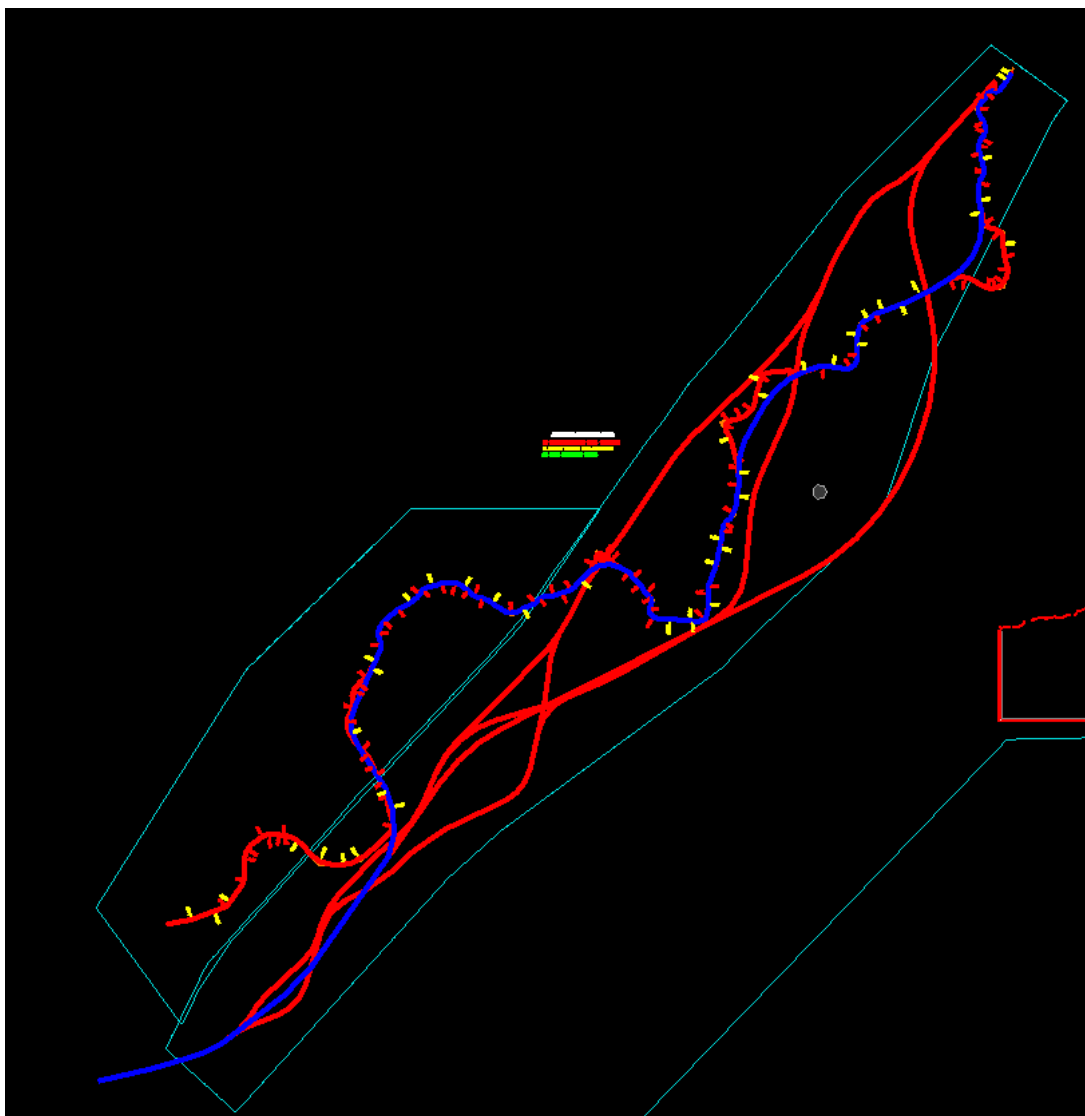

Figure 2 KTC Proposed Modified Existing Alignment (Blue Alignment)

Crash Prediction Module

The crash prediction module requires the selection of a superelevation policy, calibrated Safety Performance Function (SPF), Crash Modification Function (CMF) model, and crash distribution model as well as a set of years for analysis. IHSDM has preprogramed options for these requirements based on the HSM and AASHTO policies. In addition to these requirements, there is an option to include historical crash data to perform Empirical Bayes (EB) analysis if the alignment has known crash data.

The crash prediction module in IHSDM is programed with HSM SPFs and various CMFs for all highway types. IHSDM contains an option to adjust the default HSM SPFs with coefficients calibrated to state-specific crash data. KTC has a Kentucky-specific SPF for rural two-lane highways; however, the KTC SPF uses a different model format than what is programed into IHSDM. Therefore, the coefficients for the KTC SPF cannot be directly imported into the HSM SPF in IHSDM. The HSM SPF format for a rural two-lane highway is $SPF = AADT * L * 10^a * e^b$ while KTC uses $SPF = e^{a + b * \ln(AADT) + \ln(L)}$. Kentucky-specific data were used to calibrate a new SPF that fit the HSM model format. However, the Kentucky data produced an SPF with a lower goodness of fit than the HSM SPF because the HSM model format is not optimal for modeling rural, two-lane crashes. Accordingly, the default HSM SPF was used in the crash prediction modules for all KY 30 alignments.

The default HSM CMFs were used in the crash prediction module because Kentucky currently lacks a set of rural two-lane CMFs. Figure 3 is a screenshot of the CMFs used in IHSDM for rural two-lane highways.
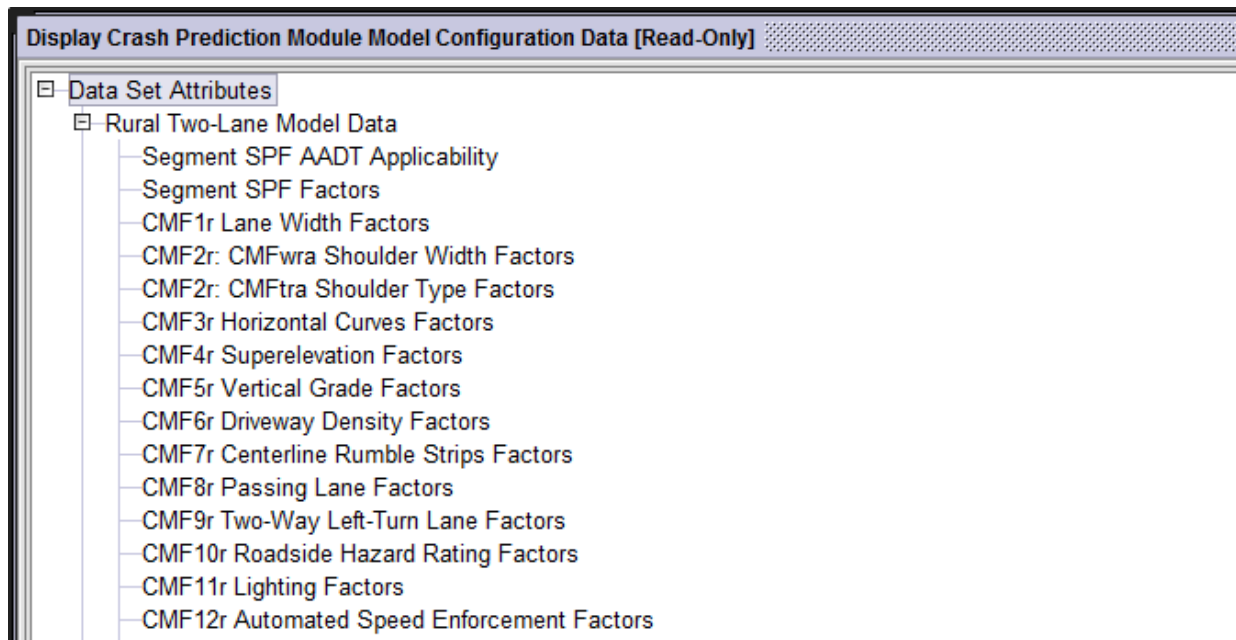

Display Crash Prediction Module Model Configuration Data [Read-Only]

- Data Set Attributes
  - Rural Two-Lane Model Data
    - Segment SPF AADT Applicability
    - Segment SPF Factors
    - CMF1r Lane Width Factors
    - CMF2r: CMFwra Shoulder Width Factors
    - CMF2r: CMFtra Shoulder Type Factors
    - CMF3r Horizontal Curves Factors
    - CMF4r Superelevation Factors
    - CMF5r Vertical Grade Factors
    - CMF6r Driveway Density Factors
    - CMF7r Centerline Rumble Strips Factors
    - CMF8r Passing Lane Factors
    - CMF9r Two-Way Left-Turn Lane Factors
    - CMF10r Roadside Hazard Rating Factors
    - CMF11r Lighting Factors
    - CMF12r Automated Speed Enforcement Factors

Figure 3 IHSDM Rural Two-lane CMFs

The default superelevation policy (AASHTO 2011) and crash distribution (HSM) were selected for all alignments. The modules were set for the years 2017 to 2038 in accordance with the AADTs provided in the DES.

In addition to the default HSM crash distribution, five years of crash data (2011–2015) were imported into IHSDM for the existing alignment. A query of crashes along KY 30 between 2011 and 2015 uncovered 35 crashes, nine of which were located at the intersection of KY 30 and US 421. Intersection crashes were excluded from the analysis because intersections were not programed into IHSDM for the existing or alternative alignments. The 26 remaining segment crashes had severities ranging from serious

injury to property damage only. Crash locations for the 2011–2015 interval are plotted in Figure 4, with higher crash segments circled in red.
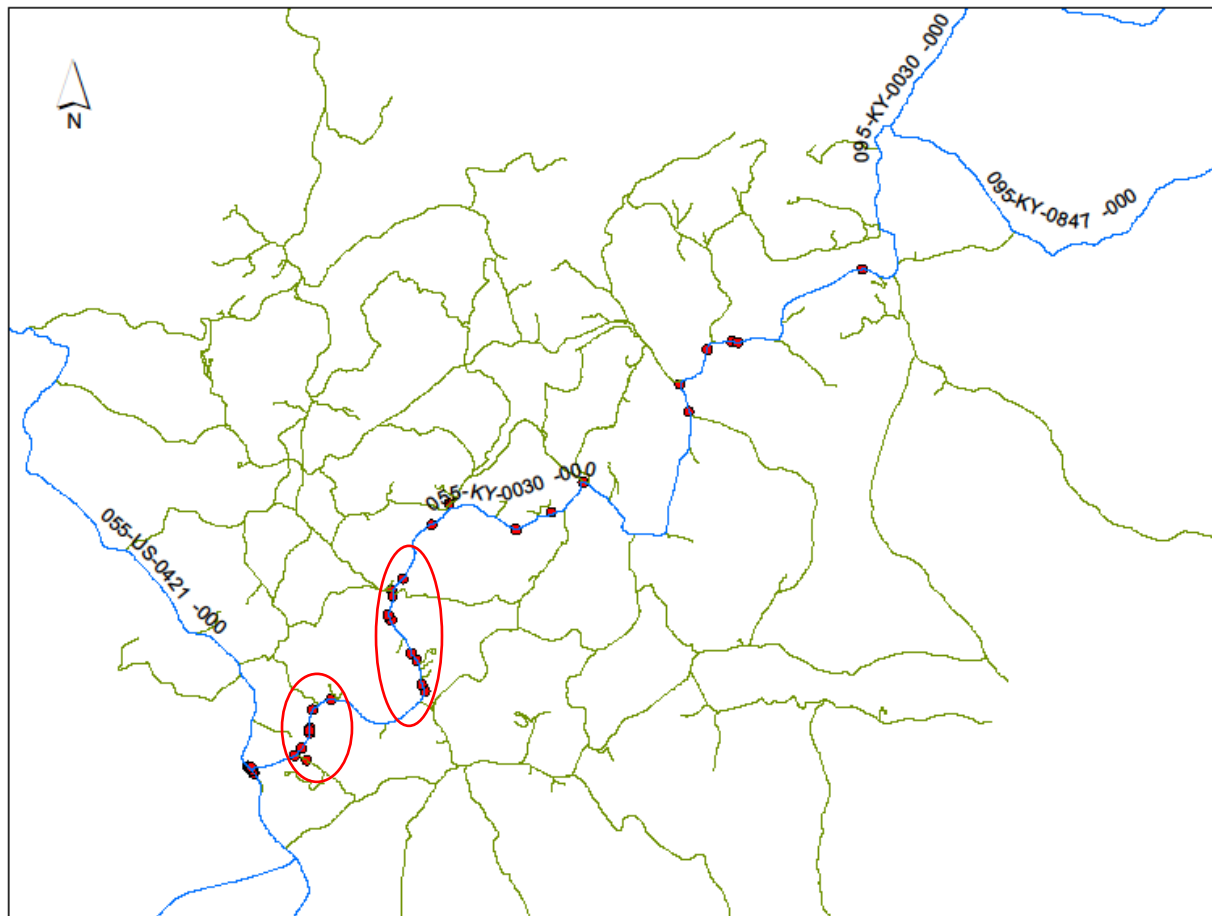

Figure 4 KY 30 2011-2015 Crashes

The crash data allowed researchers to perform EB analysis on the existing alignment. EB analysis more accurately models expected future crash rates and crash distributions by combining historical crash data with SPF crash predictions. With the added crash data, researchers executed two crash prediction models on the existing alignment, one using EB analysis and one using only SPFs. The two predictions for the existing alignment can be used to determine how the inclusion of historic crash data affects future crash prediction, and in turn, the identification of locations for spot improvements.

According to the HSM Part C Appendix A.2.1, the EB method is not applicable to corridor improvements that significantly modify an alignment from its existing state (and on which historical crashes occurred) (5). Historical crash data are not applicable to the alternative and modified existing alignments because they differ significantly from the existing alignment. As such, it cannot be said that these historical crashes would have occurred in the same location and manner on the alternative alignments. Accordingly, only a simple SPF estimate of crashes was used for the alternatives.

Comparison of Results
Table 1 summarizes the output of the crash prediction module for each alignment. This summary includes the time period for the crash prediction simulation, length of roadway, total expected crashes by severity (fatal and injury crashes combined (F/I), fatal and only severe injury crashes combined (F/S), and property damage only crashes (PDO)), and expected crash rates by severity. As intersections were

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excluded from analysis for all alignments, the expected crashes and crash rates in Table 1 are for segments only — not intersections. Alternatives 2, 2a and 2b were so geometrically similar that their IHSDM outputs were identical. Therefore, the crash prediction results for these three alternatives are displayed in a single column in Table 1. Due to the shorter length of the alternative alignments compared to Alternative 1 (shown in Figure 1), the lengths and total crashes for Alternatives 1a, 2, 2a, 2b, and 3 are lower than they would be if the additional 3,500 ft. were included in IHSDM analysis. However, the crashes on the additional 3,500 ft. were incorporated into the benefit-cost analysis (discussed later in the report) using the IHSDM-predicted crash rates for each alternative.

Table 1 Comparison of IHSDM Crash Prediction

	Existing EB	Existing SPF	Modified Existing SPF	Alt. 1 SPF	Alt. 1a SPF	Alt. 1 to 2 SPF	Alt. 2 to 1 SPF	Alt. 2, 2a, 2b SPF	Alt. 3 SPF
Time Period (yr)	22	22	22	22	22	22	22	22	22
Length (mi)	13.82	13.82	13.73	10.91	9.70	10.06	9.82	10.06	10.46
Total Crashes in Time Period	237	568	395	128	115	139	120	123	119
F/I Crashes	73	182	127	41	37	44	35	40	38
F/S Crashes	90	100	70	23	20	24	21	22	21
PDO Crashes	164	386	268	87	78	94	81	84	81
Crash Rate (crash/mi/yr)	0.78	1.87	1.31	0.53	0.54	0.63	0.55	0.56	0.52
F/I Rate (crash/mi/yr)	0.24	0.60	0.42	0.17	0.17	0.20	0.18	0.18	0.17
F/S Rate (crash/mi/yr)	0.30	0.33	0.23	0.10	0.10	0.11	0.10	0.10	0.09
PDO Rate (crash/mi/yr)	0.54	1.27	0.89	0.36	0.37	0.42	0.38	0.38	0.35

Querying five years of crash data (excluding intersection crashes) produced 26 segment crashes along the 13.82 miles of roadway — a crash rate of 0.38 crashes/mi/yr. The DES indicated that 52 crashes occurred along the corridor between 2010 and 2015. Compared to the data KTC used, this number includes an additional year of data as well as intersection and side road crashes close to KY 30. Because the HSM recommends three to five years of crash history for safety analysis, researchers chose the most recent five years of crash data as opposed to the six years presented in the DES. The segment crash rate predicted for the existing alignment using only SPFs is 1.87 crashes/mi/yr. This estimate is much higher than the current rate, 0.38 crashes/mi/yr. The EB analysis predicts a crash rate of 0.78 crashes/mi/yr. IHSDM does not account for driver familiarity in its crash prediction, which could explain the discrepancy between the current and expected crash rates. The crash prediction module also accounts for future growth of AADT, a factor expected to contribute to a higher crash rate.

As Table 1 shows, the modified existing alignment created by KTC has a crash rate of 1.31 crashes/mi/yr using SPF analysis, compared to the 1.87 crashes/mi/yr from the existing alignment's SPF analysis. This is a 30% reduction in crashes while still making use of the existing alignment.

The predicted crash rates for all HMB alternatives are relatively low, all lower than the expected crash rate on the existing alignment. This suggests that any of the alternative alignments would result in a corridor with fewer crashes than the existing alignment. Although IHSDM does not accurately represent the actual crashes on the existing alignment, the difference between the expected crashes/rates on the existing and proposed alignments is still meaningful in assessing relative performance.

The two sets of related alternatives, Alternatives 1 and 1a and Alternatives 2, 2a, and 2b, show little difference in expected crash rates along the proposed alignments. This is due to the alternatives' geometric similarities. Alternative 1 to 2 Crossover has the highest expected crash rate, 0.63 crashes/mi/yr, while Alt_3 has the lowest expected crash rate, 0.52 crashes/mi/yr. A difference of 0.11 crashes/mi/yr between the highest and lowest expected crash rates equates to roughly one crash/yr over the 10-mile length of the proposed alternatives, which is insignificant. Alternative 1a has the fewest total crashes; however, this is due to the alignment being shorter than the remaining alternatives. All alternative alignments share the same distribution of crashes across all severity levels, which is a function of the roadway type (rural, two-lane, undivided). PDO crashes account for 68% of total crashes, and fatal/injury crashes account for the remaining 32%. IHSDM also estimates 18% of crashes will be fatal or a serious injury crash.

IHSDM produces a graphical output for each alignment that shows the roadway's geometric features and expected crash rate plotted against alignment stationing. These plots serve as a simple method to visualize the expected crashes along the length of the alignment, allowing for the identification of high-crash locations. These plots also visualize the impact of proposed roadway geometry on crash rates. Appendix A contains a discussion of the crash plots for each alternative as well as a comparison between the SPF and EB plots for the existing alignment.

Benefit-Cost Analysis
From a safety perspective, the benefit derived from implementing a given alternative is fewer crashes. To estimate the expected safety benefit of a given alternative, the difference in expected crashes between the existing alignment and alternative alignments must be calculated and converted to a dollar amount. The estimated monetary benefits can be compared to the estimated cost of an alternative.

Selecting any of the new build alternatives would leave the existing KY 30 alignment in place for residents along the corridor. Over 120 households require the existing KY 30 for access to Kentucky's roadway network. Adding a new alignment will not remove all traffic from existing KY 30; therefore, the roadway will still be a source for potential future crashes. To model the expected future crashes on existing KY 30 if an alternate alignment were selected, the existing AADT was halved (as a conservative effort to represent travel by the people who can access their homes only through the existing KY 30 alignment) and an SPF analysis performed. Reducing the AADT on the existing KY 30 results in 198 crashes over the 22-year study period (2017 to 2038). By adding these crashes to the predicted number crashes for each new build alternative we can anticipate total expected SPF crashes on both the existing KY 30 corridor and the new KY 30 corridor.

For the modified existing alignment, the new segment of alignment connecting the existing KY 30 alignment to US 421 south of its current intersection with US 421 would bypass 35 homes, leaving those residents to use the existing, unimproved KY 30. Conservatively, assuming these households generate 10 trips per day, an AADT of 350 could be expected on the 2.4-mile stretch of unmodified KY 30 that would result in crashes on top of those occurring on the modified KY 30 alignment. SPF analysis of the 2.4-mile stretch of KY 30 with 350 AADT predicts 14 crashes over the 22-year study period. Adding these crashes

to the crashes predicted for the modified existing alignment results in the total expected crashes if the modified existing alignment were implemented.

Although EB analysis of the existing alignment more accurately represents the crashes along the corridor, to more accurately compare the existing alignment and alternative alignments, SPF analysis of each alignment must be used. It would not be reasonable to compare the EB analysis of the existing alignment to the SPF analysis of the alternative alignments because the EB analysis provides an additional layer of data that cannot be incorporated into the evaluation of the alternatives. In the case of KY 30, the use of historical crashes reduces the total number of crashes predicted through IHSDM. Comparing EB crash estimates for the existing alignment to an SPF crash prediction for an alternative alignment would increase the gap between the two crash estimates. More crashes would be predicted on the alternative alignment because these alignments would not benefit from a more accurate crash prediction, as they lack historical crash data. Therefore, the SPF crashes on the alternatives must be compared to the SPF crashes on the existing alignment — not the EB crashes — to provide a consistent method of crash prediction between the alignments.

Comparing the SPF, EB, and historical crash analysis for the existing alignment shows the SPF analysis predicts more crashes than the EB and historical crash analyses. If the reduction in crashes were derived from the difference between IHSDM SPF crash predictions of the existing and alternative alignments, the reduction in crashes would be higher than the expected future crashes on KY 30 based on the historical crash analysis. The HSM stresses the use of engineering judgement for all safety decisions; therefore, to avoid overinflating the benefit of any proposed alternative, the ratio of the alternative alignment SPF crashes to the SPF crashes for the existing alignment was applied to the annual historic corridor crash rate to estimate the safety benefit of a given alternative. This approach provides a conservative estimate of the actual crash reduction potential of each alternative. Table 2 shows the SPF-predicted crashes from IHSDM for each alignment as well as the reduction in crash rate compared to the existing alignment.

Table 2 SPF Crash Rate Summary

Alignment	SPF Predicted Crashes	Additional Crashes for Existing KY 30	Total Predicted Crashes	Expected Percent Crash Reduction
Existing	568	n.a	568	0.00
Modified Existing	395	14	409	27.99
Alternative 1	128	198	326	42.61
Alternative 1a	123	198	321	43.49
Alternative 1 to 2	148	198	346	39.08
Alternative 2 to 1	128	198	326	42.61
Alternative 2	131	198	329	42.08
Alternative 2a	131	198	329	42.08
Alternative 2b	131	198	329	42.08
Alternative 3	127	198	325	42.78

As noted, Alternatives 1a through 3 share an alignment with Alternative 1 over their first 3,500 ft. However, the design files did not associate that segment of alignment with each alternative. As such, it was omitted from IHSDM analysis for those alternatives. To account for the additional crashes that would occur along that segment for the alternatives using it, the overall crash rate of each alternative as predicted by IHSDM (Table 1) was multiplied by 0.66 miles (3,500 ft.), then by the 22-year study period used in the DES. Additional crashes were combined with the total predicted crashes for each alternative (see Table 1), which resulted in the SPF-predicted crashes displayed in Table 2.

Kentucky crash records distribute the injury severity of the 26 historical crashes on KY 30 into five categories: fatal, incapacitating, non-incapacitating, possible injury, and property damage only. The SPFs from the HSM distribute injury severity among three categories: fatal and serious injuries, injuries, and property damage only. To facilitate direct comparisons between the two distributions, historic crashes were aggregated to adapt to the SPF severity distribution. Crash distributions are displayed in Table 3. The historical crash frequency percentages are based on the crashes that occurred on KY 30 in the past five years. SPF crash frequencies are based on rural, two-lane data in the HSM. In addition to the frequency of each severity type, the National Safety Council (NSC) comprehensive cost per crash is provided in the table. The HSM severity distribution does not distinguish fatal from incapacitating injuries or non-incapacitating injuries from possible injuries. Therefore, a weighted average cost was calculated for these combined injury types using the NSC comprehensive costs and the 2015 annual distribution of crashes in Kentucky obtained from the 2015 Traffic Collison Facts. NSC reported a dramatic increase in comprehensive crash costs between 2014 and 2015. The 2015 crash costs were applied to all crashes in the study period.

Table 3 2011-2015 KY-30 Historic Crash Distribution and Costs

Injury Type	Comp. Cost per Crash ($) (6)	Weighted Cost ($) (7)	5-Year Historic Frequency	Historic Weighted Comp. Cost ($)	SPF Predicted Frequency	SPF Weighted Comp. Cost ($)
Fatal	9,900,000	2,678,496	4%	1,071,340	18%	482,129
Incapacitating	1,100,000					
Non-Incapacitating	298,000	196,440	23%	45,181	14%	27,502
Possible Injury	138,000					
Property Damage Only	8,400	8,400	73%	6,132	68%	5,712
Comp. Cost per crash ($)				158,453		515,343

Understanding the significance of the two crash severity distributions is critical for grasping the process used to calculate the safety benefit of each alternative. The proposed alternatives, except for KTC's modified existing alignment, differ significantly from the existing KY 30 corridor. The proposed alignments are corridors with higher speeds and less curvature. The existing corridor has lower speeds and greater curvature compared proposed alternatives. As such, different crash types are anticipated on the alternatives. The differing crash types correspond to a difference in crash severity, hence the use of two different severity distribution. The historical distribution correlates with injuries expected on existing KY 30 and the modified existing alignment. The SPF severity distribution correlates with injuries expected on the alternative alignments.

To calculate the safety benefit of each alignment over the study period, first the annual historical crash rate was calculated by dividing the number historical crashes along the KY 30 corridor (26) by the five-year study period. This equals 5.2 crashes/yr. The annual crash rate was then multiplied by 22 years (length of the study period) and the comprehensive cost per crash from the historical severity distribution. This yielded the cost of crashes had no alterations to the alignment been made. Next, the annual crash rate for each alternative was reduced in accordance with the "Expected Percent Crash Reduction" column in Table 2. The reduced crash rate for each alternative was multiplied by the 22-year study period and the SPF-weighted comprehensive cost per crash to derive expected crash cost, assuming an alternative was implemented (except for the modified existing alignment which used the historical weighted comprehensive cost). The difference between the two crash costs for a given alternative was calculated to

determine the expected safety benefit for each alternative. The results of these calculations are summarized in Table 4.

Table 4 Expected Safety Costs of KY 30 Alternatives for 22-year Study Period

Alignment	Crash Cost from No Implementation (Million $)	Crash Cost from Alternative Implementation (Million $)	Safety Benefit (Million $)	Project Cost (Million $)	B/C Ratio
Existing	18.13	18.13	0	0	N/A
Modified Existing	18.13	13.05	5.08	35.1	0.14
Alternative 1	18.13	33.84	-15.71	72.5	-0.22
Alternative 1a	18.13	33.32	-15.19	72.5	-0.21
Alternative 1 to 2	18.13	35.91	-17.78	72.3	-0.25
Alternative 2 to 1	18.13	33.84	-15.71	80.4	-0.20
Alternative 2	18.13	34.15	-16.02	77.9	-0.21
Alternative 2a	18.13	34.15	-16.02	77.9	-0.21
Alternative 2b	18.13	34.15	-16.02	77.9	-0.21
Alternative 3	18.13	33.73	-15.6	N/A	N/A

Table 4 also contains the cost estimate of HMB's alternatives from the DES. Alternative 3 does not have a cost estimate because it was not covered in the DES. For the modified existing alignment proposed by KTC, the cost estimate assumed $2.6 million for the shouldering and an additional $5 million per mile of alignment where curves were smoothed or new alignment was added (6.5 miles total). Benefit-cost (B/C) ratios were calculated by dividing the expected safety benefit of an alternative by its expected cost. B/C ratios are also displayed in Table 4.

The modified existing alignment is the only alternative with a positive B/C ratio. However, the B/C ratio is less than one (0.14), meaning the project cost outweighs the expected safety benefits. The remaining new build alternatives have negative B/C ratios, meaning the cost of crashes is expected to increase following their implementation. Increased crash costs are logical because although the number of crashes is expected to decrease for new build alternatives, their geometry will increase speed and crash severity, leading to a higher cost per crash. Additionally, if a new build alternative were selected, the existing KY 30 alignment will remain in place to facilitate access for residents living along it. It would be an additional source of crashes for the corridor. Crashes on the existing corridor lessen a new build alternatives' potential for crash reduction, reducing their expected safety benefit.

A low or even negative safety B/C ratio would suggest that this project's justification and priority are based on more than just the goal of reducing crashes. Comparing KY 30's existing geometries to AASHTO's Green Book design standards indicates the roadway does not reflect traditional engineering values viewed as desirable, although this philosophy is now viewed as "nominal safety." These design alternatives will provide benefits other than safety — they will increase corridor efficiency (by reducing travel times through the corridor) and promote economic activity through infrastructure improvements. Additionally, a project's purpose and need, per the Federal Highway Administration, can stem from "Legislation" (i.e., a federal, state, or local governmental mandate for the action). As such, the project could be justified if all its potential benefits are taken into account. IHSDM analysis is limited because it only captures safety benefits.

Summary of Findings
IHSDM, with its built-in crash prediction module, is a convenient tool for implementing HSM Part C methodologies on any classification of roadway or intersection. The tool is preprogrammed with SPFs

and CMFs published in the HSM, but users can input locally calibrated SPF and CMF regression coefficients. IHSDM can be used to evaluate existing alignments or slight alterations to existing alignments by combining SPFs and historical crash data and performing EB analysis. IHSDM lets users evaluate alignments significantly different from the existing alignment using only SPFs. The output of IHSDM's crash prediction module includes several tables summarizing the frequency and severity of expected crashes as well as a graphical output that plots expected crash rates against geometric features of the roadway.

Performing EB analysis with historical crash data is critical for identifying the correct locations to implement spot improvements, if the goal of a project is to install safety countermeasures on an existing alignment. Relying solely on SPF crash predictions along existing alignments can result in incorrectly identifying high-crash locations.

Applying IHSDM to KY 30 indicated that all alternative alignments have an expected B/C ratio less than one, which means they offer no economic safety benefits. In fact, the new build alternatives have negative B/C ratios, indicating the cost of crashes is expected to increase, most likely due to increases in crash severity. Therefore, any alternative or treatment that can reduce the project cost, such as the modified existing alignment proposed, would be the most cost-effective in terms of safety. IHSDM analysis was only capable of capturing the expected safety benefit. As stated in the DES, the goal of the KY 30 project is to provide a safer and more efficient corridor, and to make transportation infrastructure improvements needed to support economic activity in Eastern Kentucky. The selected alternative may be economically justifiable when viewed holistically based all the potential benefits it may provide regardless of the expected safety benefits. The potential non-safety benefits of each project alternative should be analyzed to inform and improve the decision-making process for the KY 30 redesign.

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Appendix A: IHSDM Crash Plot Comparison
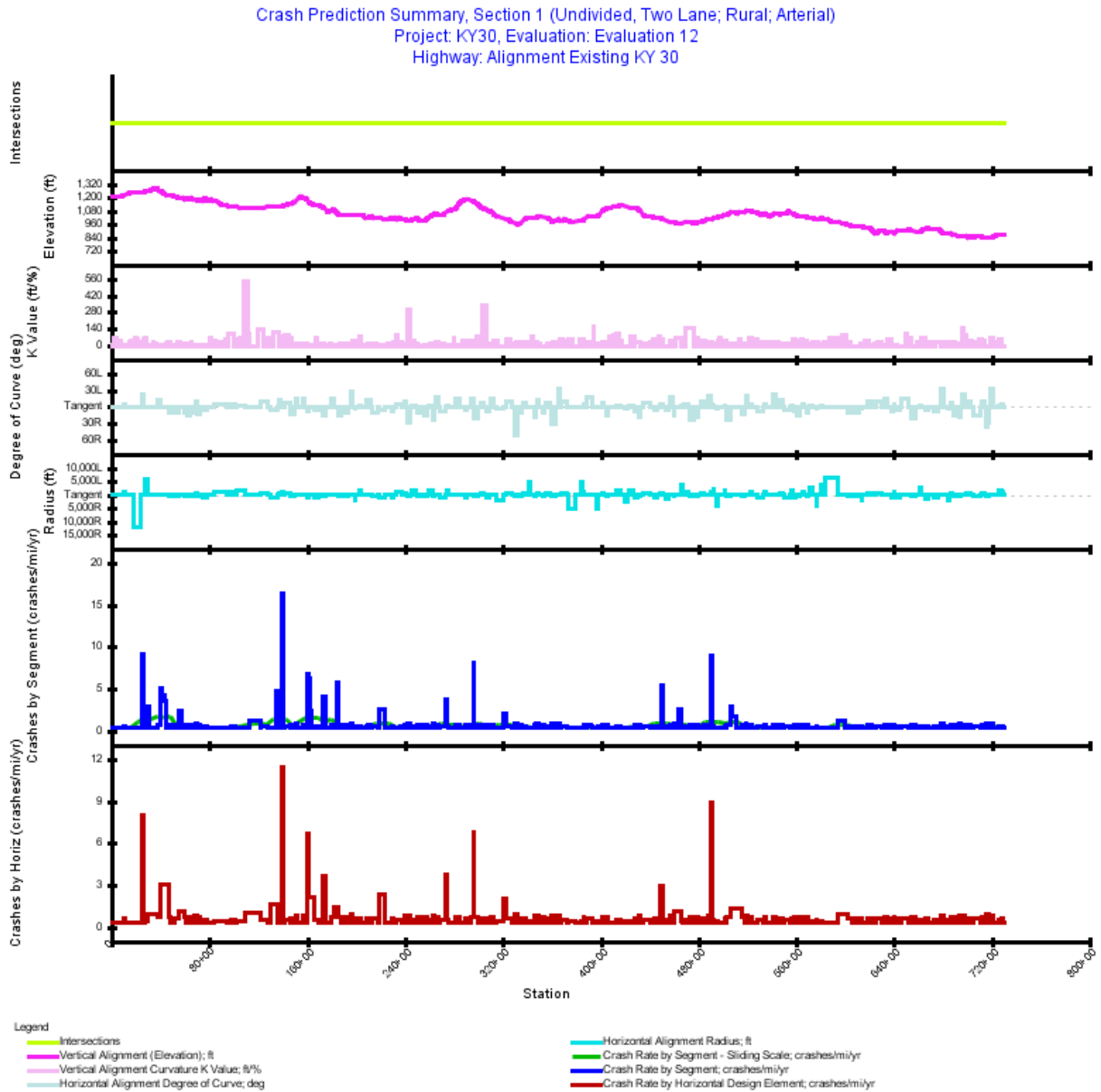
Figure 5 Existing Alignment EB Crash Prediction Summary
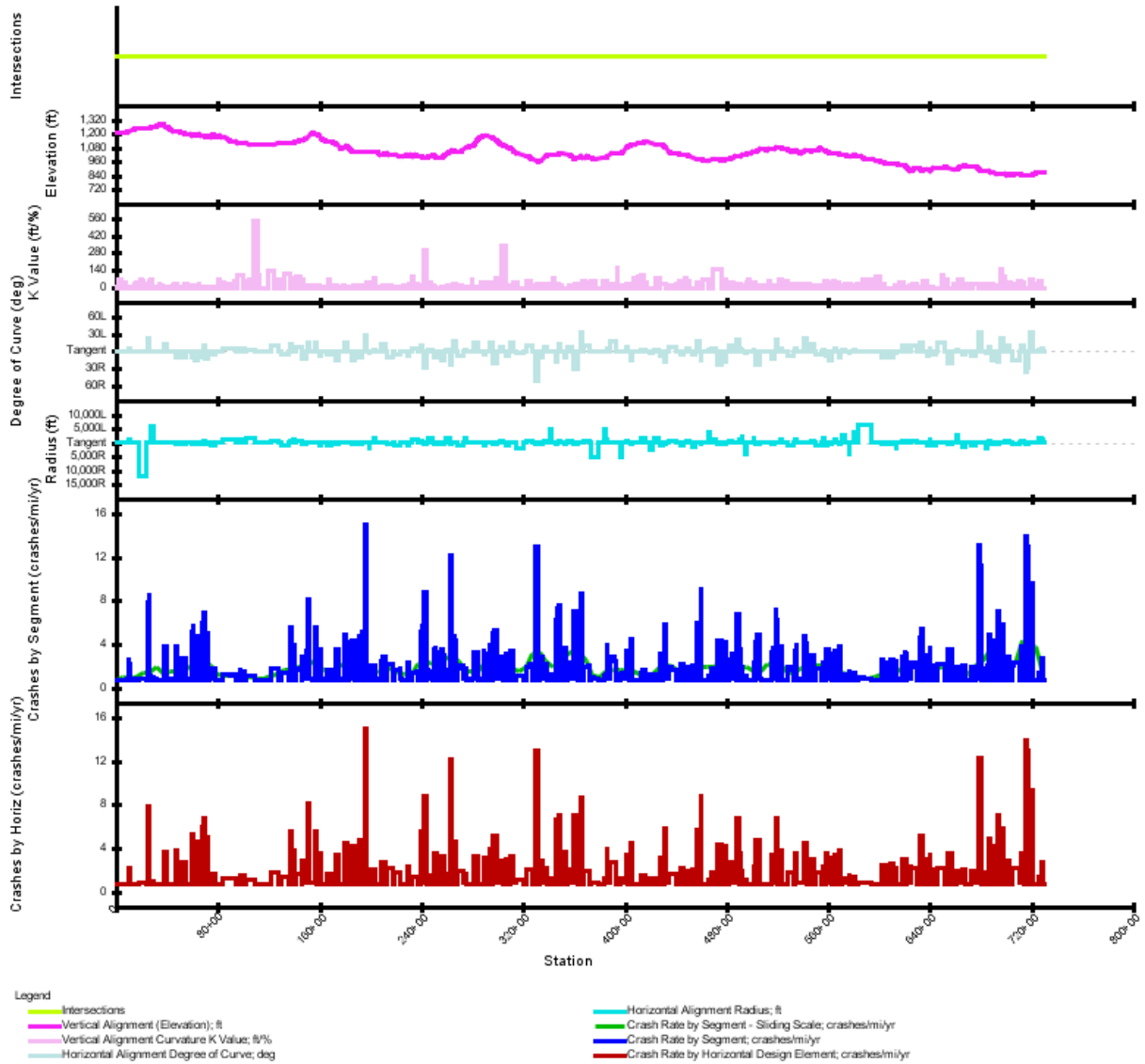
Figure 6 Existing Alignment SPF Crash Prediction Summary

Figures 5 and 6 serve as examples showing the impact of adding historical crash data to a corridor analysis. In both figures, the horizontal and vertical curve features of the existing alignment are detailed with the light blue and pink lines, respectively. The dark blue line shows crash rate by roadway segments based on horizontal and vertical curve features, and the red line shows crash rate by segments based solely on horizontal curve features. The high peaks of dark blue and red lines are locations where crash rates are expected to be highest and could be targeted for spot improvements. There is a stark difference in the location of the crash rate peaks between the EB analysis in Figure 5 and the SPF analysis in Figure 6. The peak crash rates in the EB analysis more accurately reflect the locations where crashes are occurring. The SPF analysis identifies locations with undesirable geometric design such as sharp horizontal or vertical curves and difficult curve transitions (i.e., reverse curves). In reality, the locations with worse geometry are not always high crash locations, and KY 30 serves as an example of this.

Stations 30+00 to 60+00 and 150+00 to 200+00 in Figure 3 correspond to two segments on KY 30 with the highest numbers of historical crashes. These segments are circled in red in Figure 4. The EB method identified these locations through peak crash rates. Some of the major peaks from the SPF method correspond to locations with one or two crashes, but all the major peaks from the EB method corresponded to at least one crash.

Without incorporating historical crash data, locations for spot improvements based on peak SPF crash predictions would have been selected where their crash reduction potential would be limited to a single crash. Using the historical data and EB analysis, spot improvement selection based on peak crash rates calls attention to locations where the crash reduction potential is much higher.
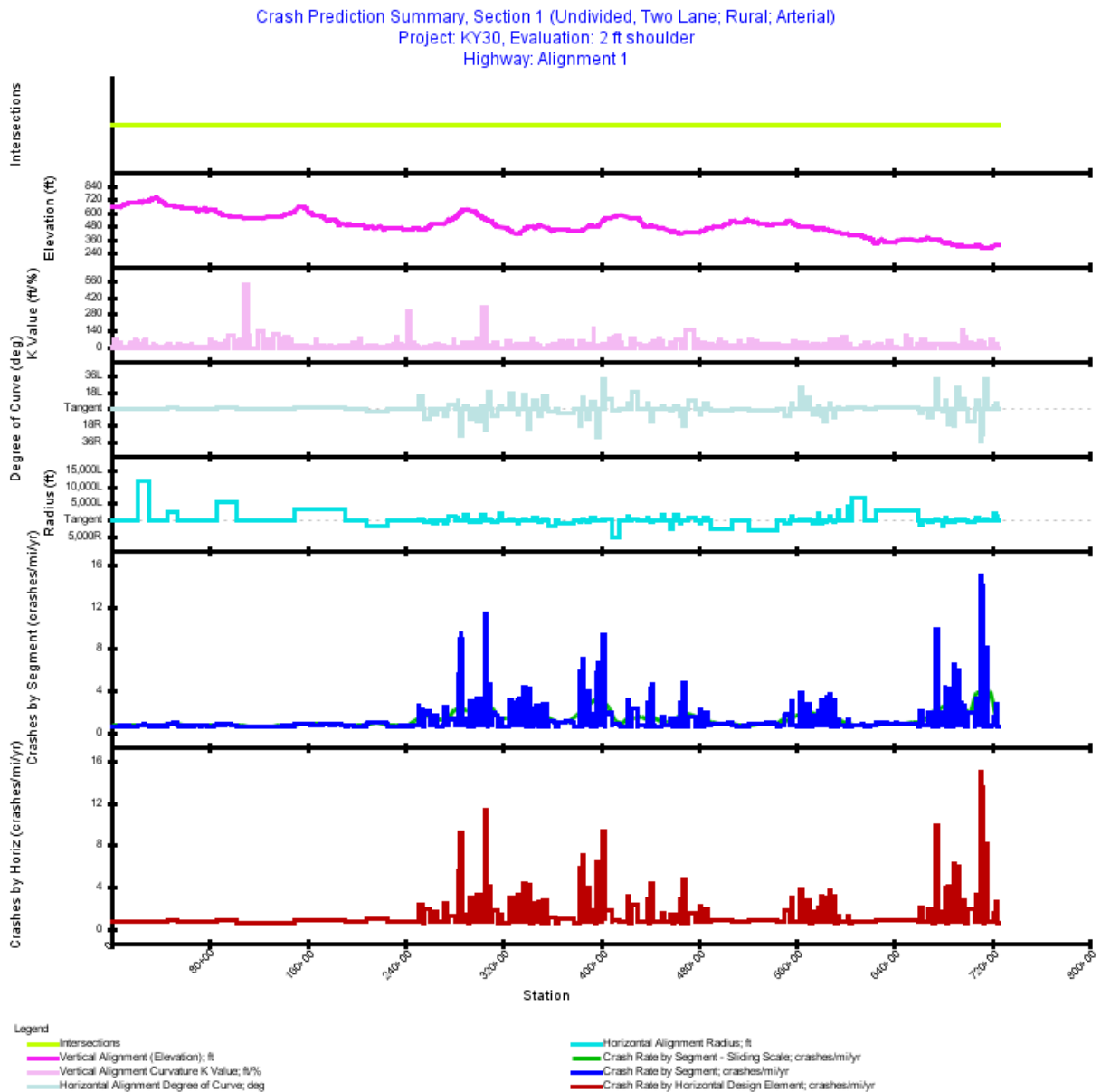
Figure 7 Modified Existing Alignment SPF Crash Prediction Summary

The crash rates are predicted to be lowest along the sections of the modified existing alignment where the beginning section of Alternative 1 leads into the existing alignment and where the existing curves were smoothed. Crash rates are still predicted to be high at locations where the horizontal and vertical alignments of the existing alignment were not modified, however, the peak crash rates are slightly lower at these locations compared to the peak crash rates on the existing alignment due to the addition of 2 ft. shoulders.
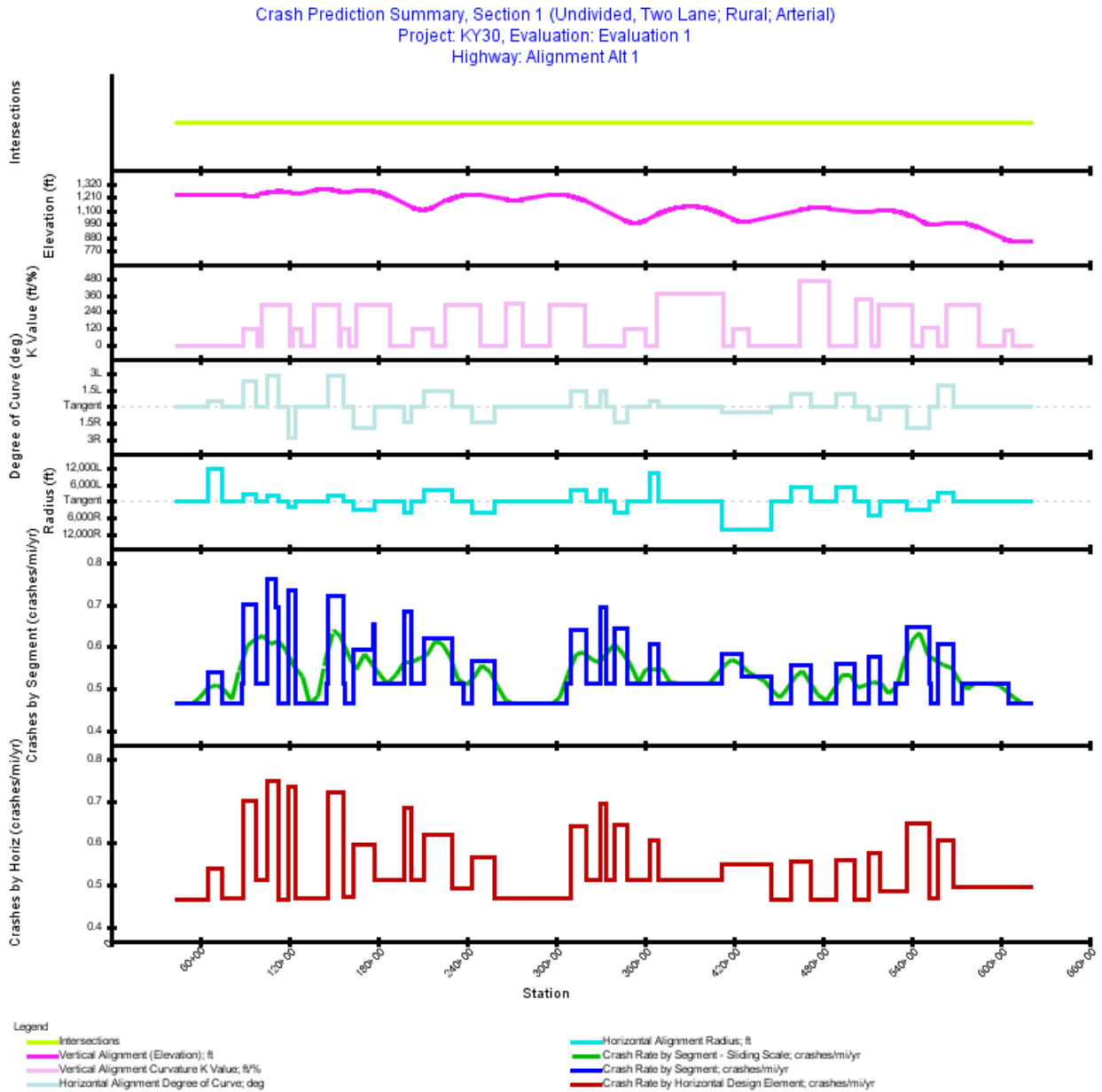
Figure 8 Alternative 1 Crash Prediction Summary

Alternative 1 shows highest expected crash rates (approximately 0.75 crashes/mi/yr) between stations 60+00 and 180+00. These higher crash rates correspond to the presence of a series of closely spaced horizontal and vertical curves. However, the highest crash rates for this alternative are significantly lower

than peak crash rates on the existing alignment. Accordingly, the reduction in crash rates suggests Alternative 1 is a safer option than the existing alignment.
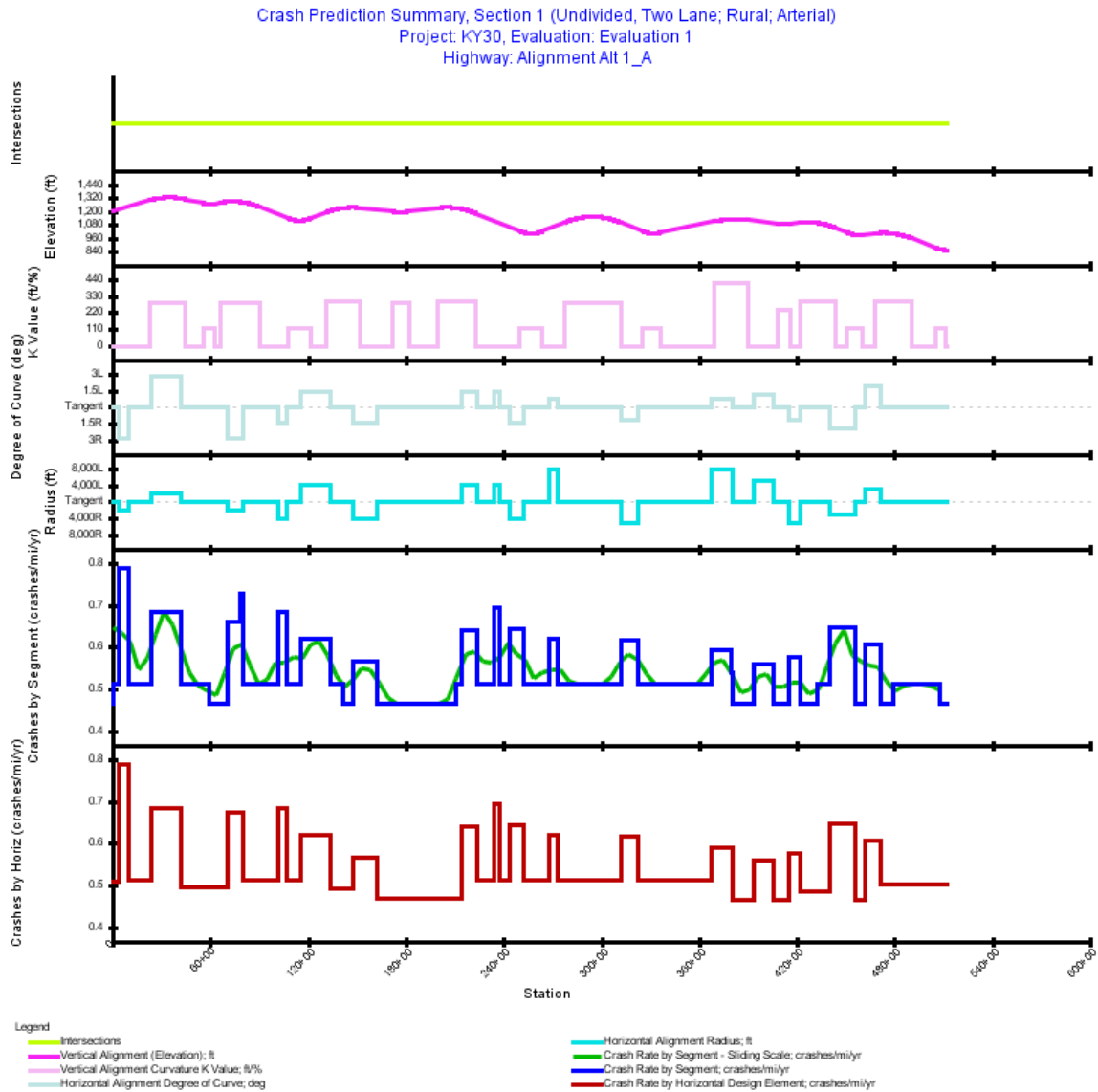
Figure 9 Alternative 1a Crash Prediction Summary

Again, as with Alternative 1, Alternative 1a shows a higher crash rate near the beginning of the alignment due to the presence of more curvature. Accounting for the fact that the start of Alternative 1a is roughly 4,000 ft. after the start of Alternative 1. The peak crash rate here is just under 0.8 crashes/mi/yr, slightly higher than Alternative 1. Overall, the minor changes between Alternatives 1 and 1a have little impact on the expected crash rates along the alignment.
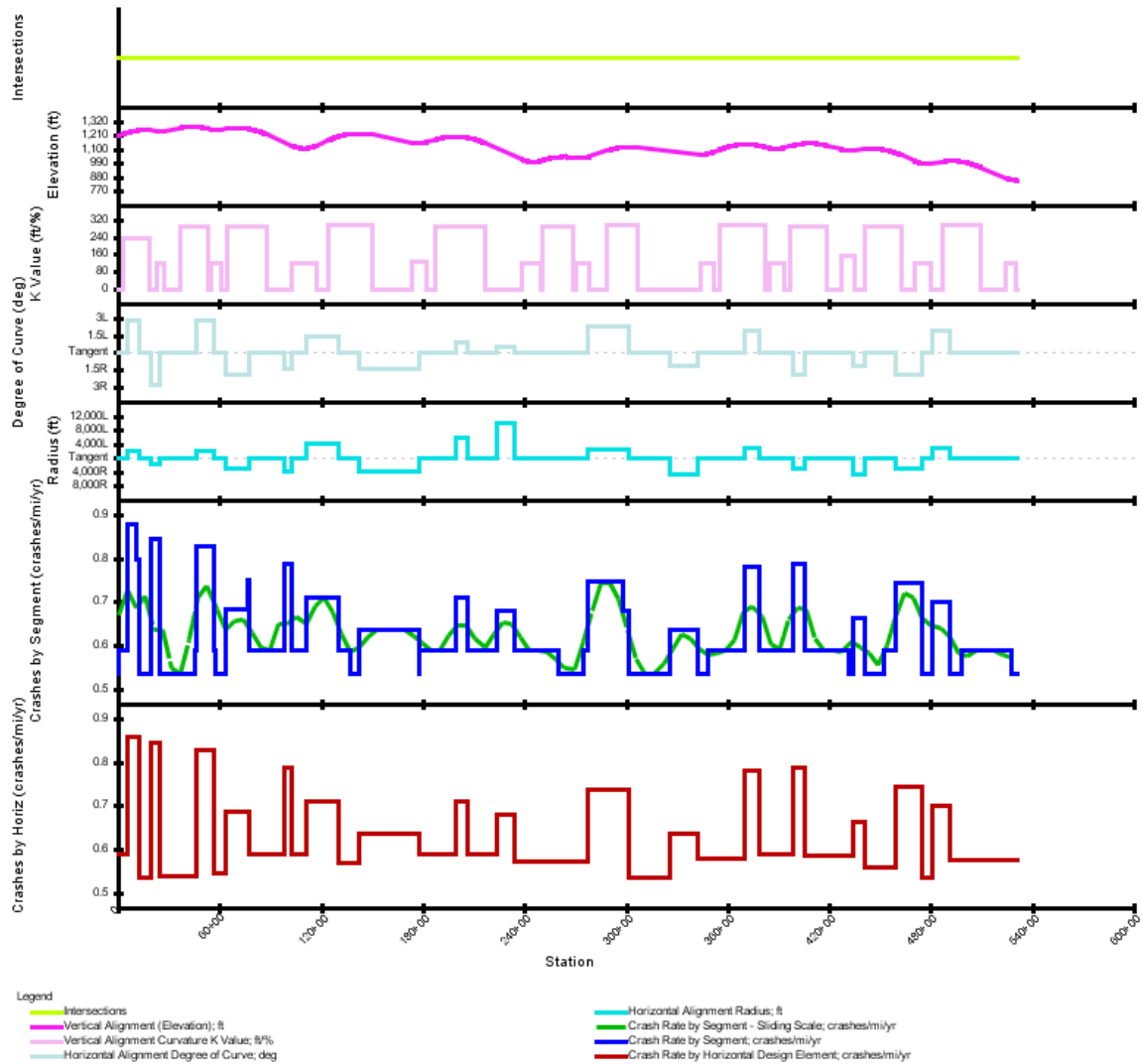
Figure 10 Alternative 1 to 2 Crash Prediction Summary

The combination of Alternatives 1 and 2 shows a series of higher crash rates at the beginning of the alignment that mirror the expected crash rates of Alternative 1 (starting at station 100+00 of Figure 1), except the peak crash rates have increased. Along the middle and end of the alignment, where this alignment matches Alternative 2, the crash rate peaks increase in magnitude but decrease in frequency when compared to Alternatives 1 and 1a. This phenomenon is a function of a decrease in horizontal and vertical curve features. However, the remaining horizontal curves have smaller radii, resulting in higher crash rates. The combination of the Alternative 2 crossover with the beginning section of Alternative 1 increases expected crash rates.
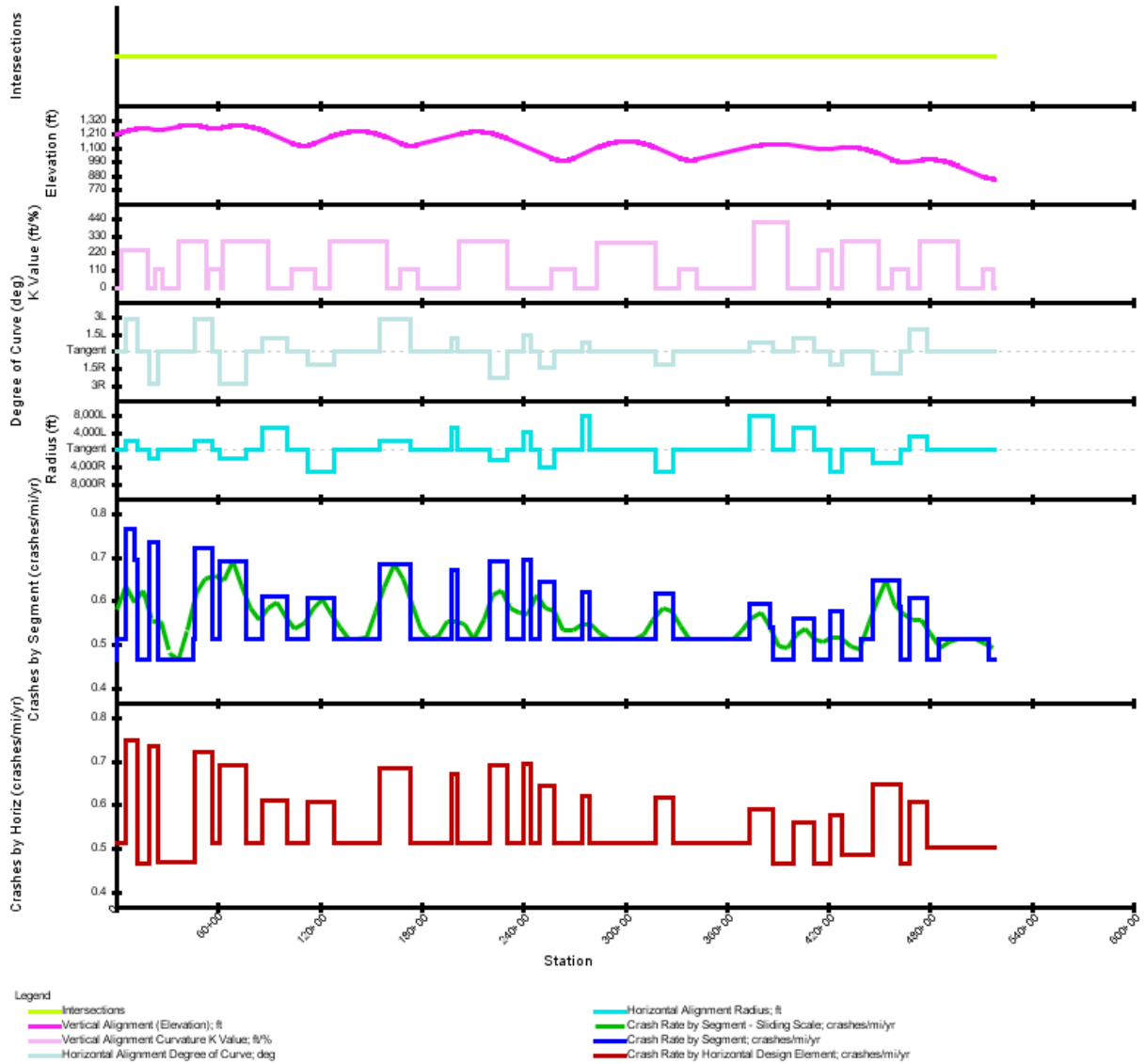
Figure 11 Alternative 2 to 1 Crash Prediction Summary

This alternative combines the first part of Alternative 2 with the second part of Alternative 1, the opposite of the previous alternative. The combination results in lower expected crash rates than the previous combination. Crash rates peak more frequently in the middle of this alignment compared to the previous combination of Alternatives 1 and 2. Overall, this combination of alternatives has a lower crash rate than the alternate combination, which is seen in both the crash summary graphs and Table 1.
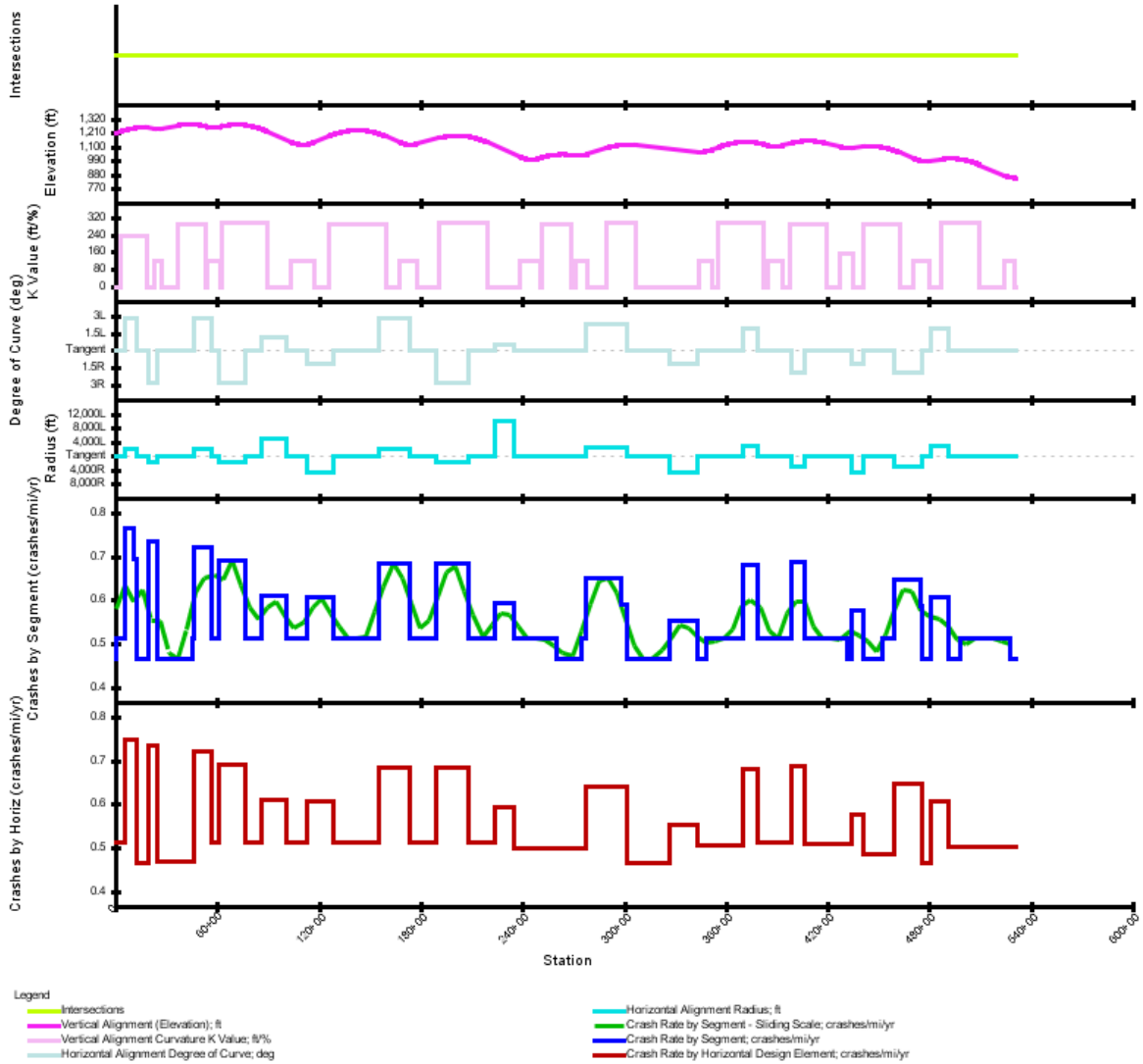
Figure 12 Alternative 2 Crash Prediction Summary

A comparison of Alternative 2 to Alternative 1 shows fewer crash rate peaks, but peaks lasting for longer distances in the middle of the alignment, corresponding to longer horizontal curves with smaller radii. Apart from this difference, the beginning and end of the two alignments show little difference in the magnitude and distribution of crash rate peaks. From Table 1, the overall crash rates between the two alternatives are similar in magnitude, which is reflected in the similarities between their summary plots.
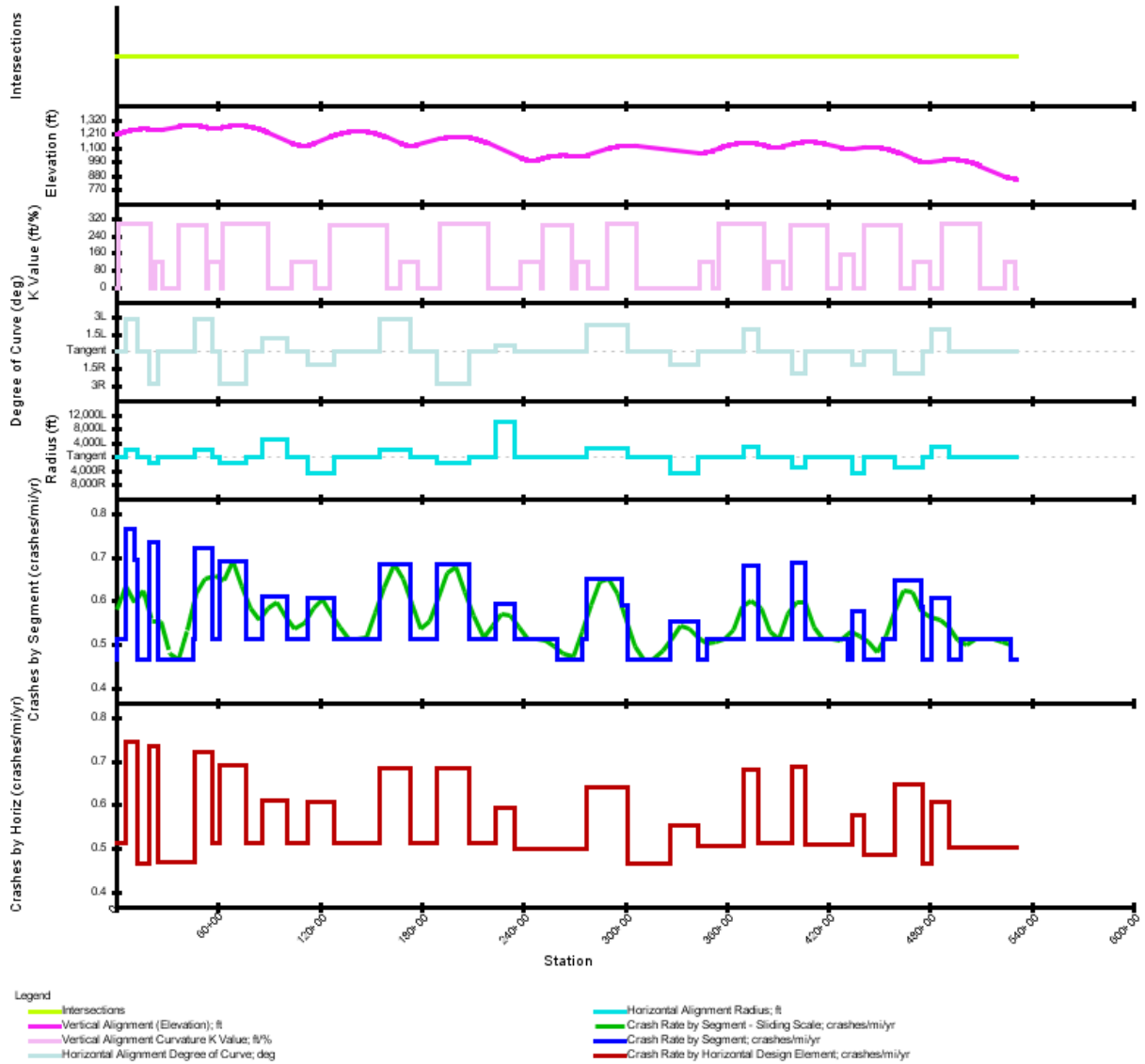
Figure 13 Alternative 2a Crash Prediction Summary

Alternative 2a has the same geometry as Alternative 2, but with a minor change in the alignment on the first two vertical curves. This minor change does not impact on the crash rates; therefore, Alternative 2a is identical to Alternative 2 in terms of expected safety performance.
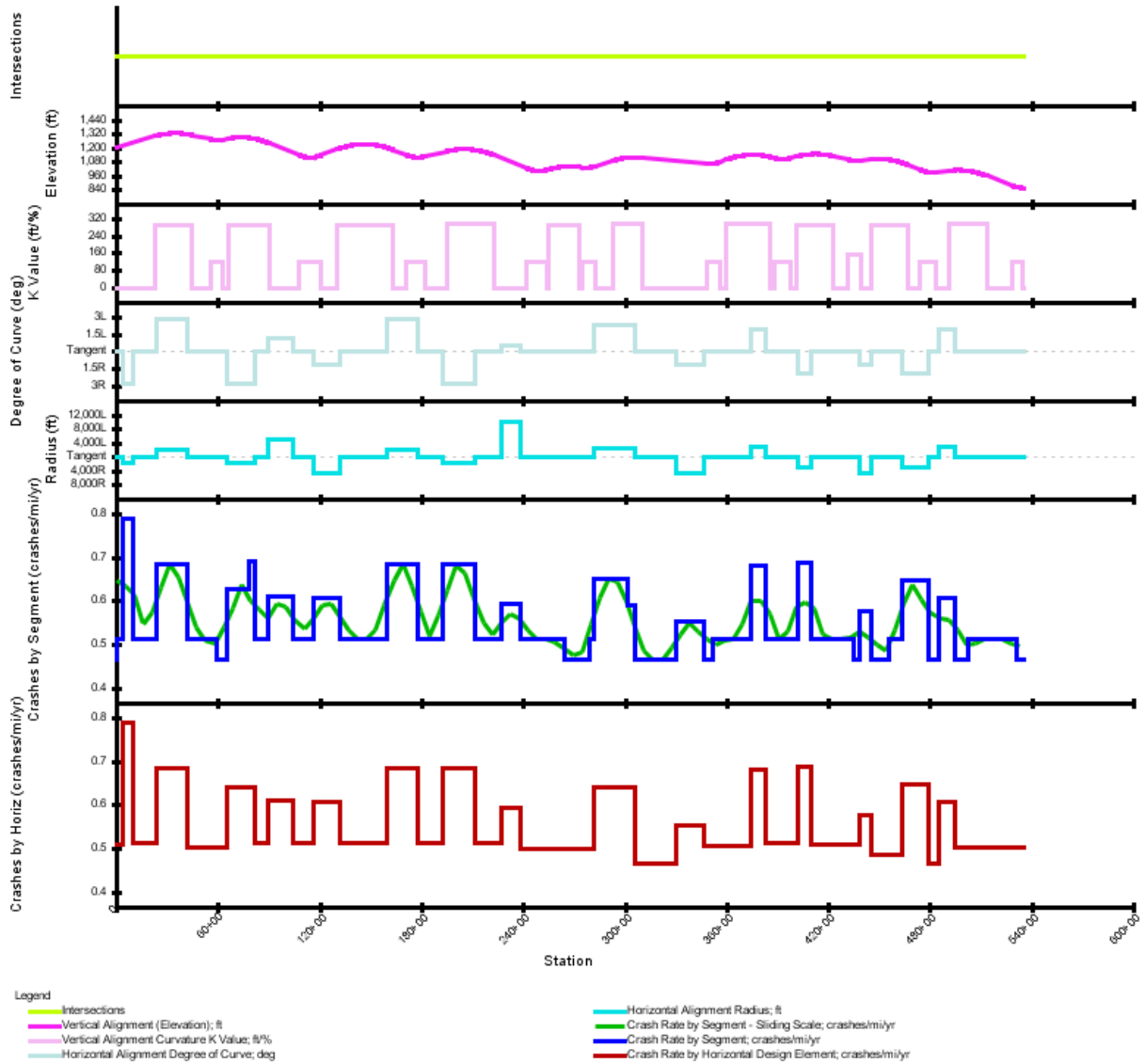
Figure 14 Alternative 2b Crash Prediction Summary

Alternative 2b is nearly identical to Alternative 2 in terms of expected crash rates along the alignment; the only difference being within the first 6,000 ft. of the alignment. The beginning of Alternative 2b replaces three high-magnitude, but short, peak crash rates with one short peak higher than Alternative 2's peaks and one longer peak with a lower crash rate. These changes in crash rates do significantly impact on the overall crash rate for Alternative 2b, as is evident by the nearly identical crash rates for Alternatives 2 and 2b presented in Table 1.
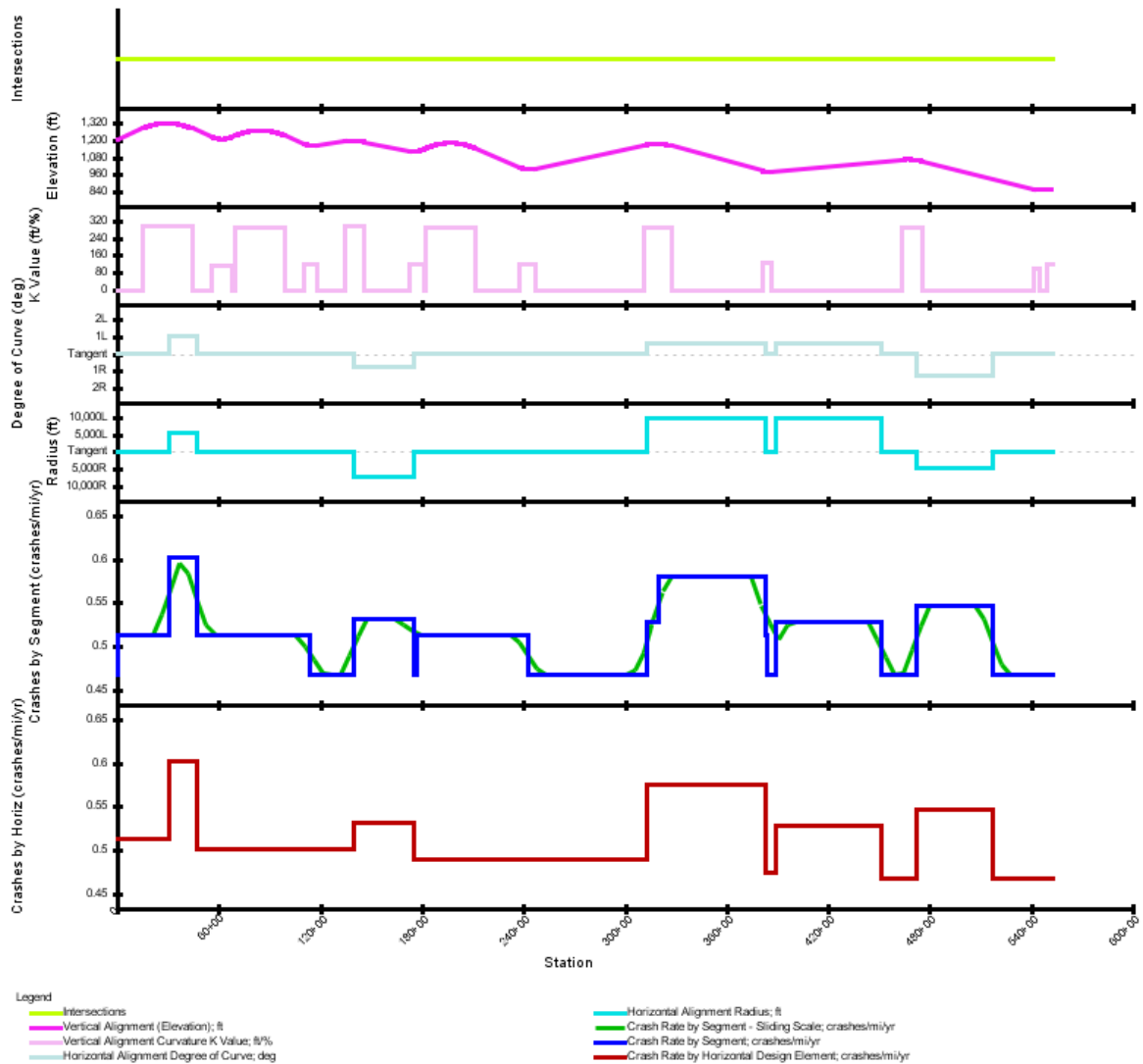
Figure 15 Alternative 3 Crash Prediction Summary

Alternative 3 has the lowest magnitude and fewest crash rate peaks of all the alternatives. This alternative also has the fewest horizontal and vertical curve features. The curves of this alignment are longer and have larger radii than all other alternatives, hence the crash rate peaks are lower in magnitude, but extend over longer distances. Due to the lack of curves on Alternative 3 compared to the opposing alternatives, IHSDM estimates this alignment will have the lowest crash rate.