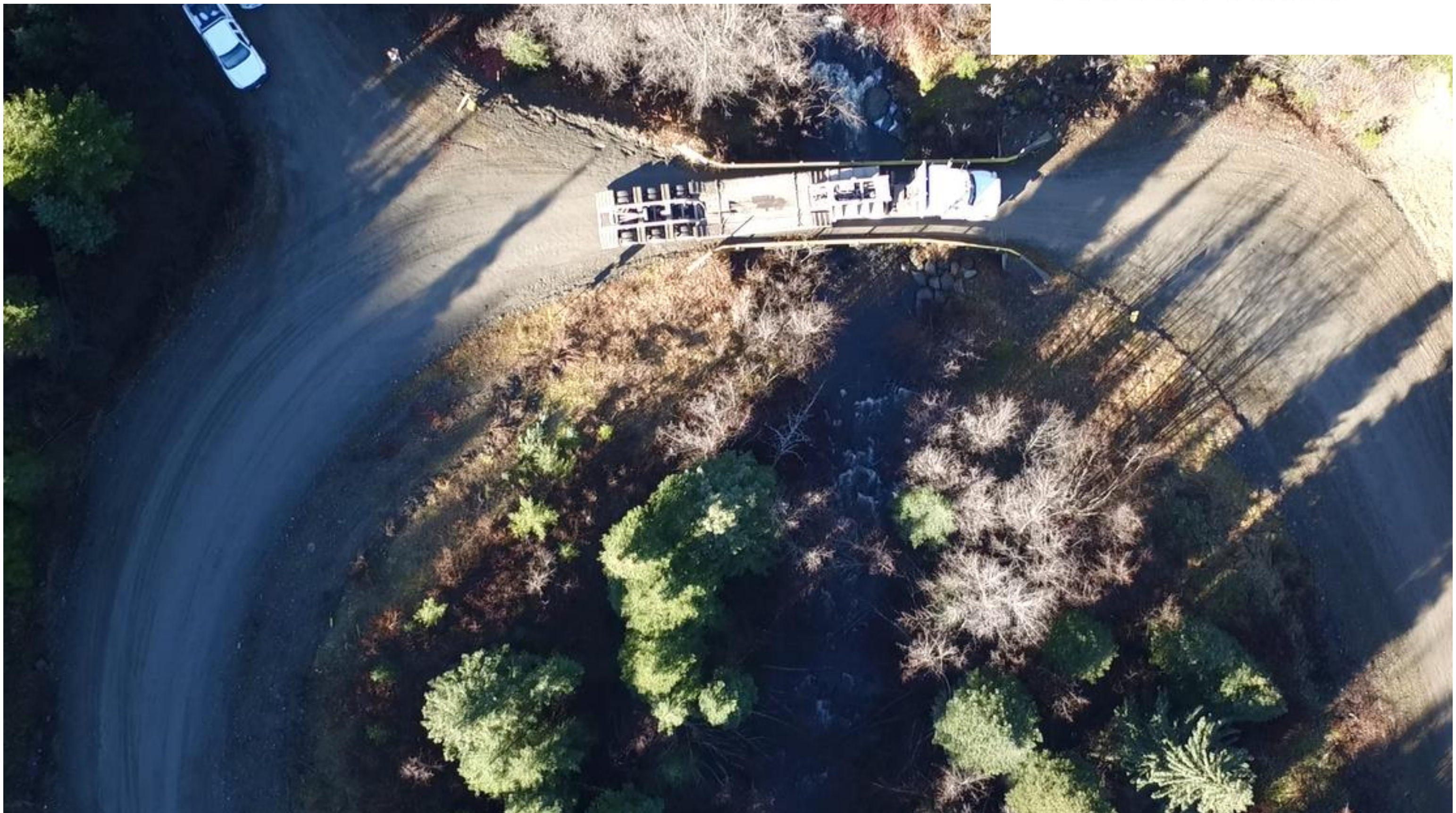

Field Testing to Validate Standardized Bridge Approach Curve Design Recommendations

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1. INTRODUCTION

In 2016, FPInnovations completed a report entitled *Standardizing the Design of Approach Alignment to Bridges on Forestry Roads in British Columbia: Review and Analysis* (Forrester, 2016). This report was undertaken at the request of the Engineering Branch of the B.C Ministry of Forests, Lands, and Natural Resource Operations (FLNRO). The objectives of this work were to determine the current state of practice for designing resource road bridge approach alignment and to make recommendations for standardizing this process. Recommendations in the Forrester (2016) report were based on a survey of engineers who are known to design bridges in BC, and based on computer simulations of vehicle turning. Results of the report indicate that current design methodologies are not standardized across the industry, leading to regional variation in how bridge approach alignment is designed.

To address the objective of the Forrester (2016) report, FPInnovations recommended use of a WB-19 design vehicle with a 500 mm clearance envelope for bridge approach alignment designs on mainline roads where travel speeds are greater than 30 km/h, and it is expected that low-beds or other large vehicles will be traveling. Because this recommendation is for roads with speeds greater than 30 km/h, it is assumed that designers will adhere to current minimum curve radius standards for roads as specified by the FLNRO Engineering Manual (2016), which specifies a minimum curve radius of 35 m for roads with travel speeds greater than 30 km/h. FPInnovations made recommendations for secondary roads beyond the reach of low-bed traffic also. For these types of roads, a highway configured log-hauling truck was recommended. A clearance buffer was not part of the recommendation for this vehicle, however, professional judgement by the designer and engineer of record is required. The decision to not specify a clearance envelope for this vehicle was to allow the professional to perform a risk assessment and determine suitable bridge approach alignment at bridge sites where topography constrains curve alignment.

Objective. The objective of this research was to validate computer simulation of vehicle turning performed as part of the Forrester (2016) report. Validation of computer simulations is a prudent quality control check prior to standardizing on the bridge approach curve design vehicles recommended in Forrester (2016).

2. METHODOLOGY

Field validation of computer-simulated WB-19 turning performance was evaluated using a low-bed vehicle that had wheel-base dimensions and tracking characteristics similar to that of the WB-19 design vehicle. Prior to selection of the low-bed to be used for field validation, FLNRO Engineering Branch staff in Kamloops B.C., collected low-bed wheelbase date and provided this to FPInnovations. FPInnovations used the data to model the low-bed's off-turning performance using turning template software (AutoTurn 9.0) and compare this to turning simulations of the WB-19 design vehicle (Table 1). Differences between the simulated turning performance of the WB-19 and the low-bed vehicle were minor and not more than 3.5% for the six tight curves considered. Based on this the test low-bed vehicle was considered appropriate for use for the field validation of simulations of WB-19 turning through tight bridge approach curves.

Table 1. Simulated turning performance of test low-bed in six, tight radius, curves

Simulated vehicle/ curve radius	Maximum Swept Path Simulated with AutoTurn (m)					
	45° turn angle	% Difference from WB-19	90° turn angle	% Difference from WB-19	180° turn angle	% Difference from WB-19
WB-19 in 15 m-radius curve	5.64		7.80		8.65	
Test low-bed in 15 m-radius curve	5.70	1.1%	7.90	1.3%	8.75	1.2%
WB-19 in 24 m-radius curve	4.90		6.41		6.54	
Test low-bed in 24 m-radius curve	5.07	3.5%	6.53	1.9%	6.64	1.5%

The turning simulations of the WB-19 design vehicle were validated in two ways. First, a controlled course was established in a large gravel pit to determine whether the test low-bed actually turned in way that agreed with the simulations of turning for itself and for the WB-19. This was done by marking out two curves on the flat floor of the pit and then driving the test low-bed along the curve (steering the tractor so its centreline aligned with the curve). The curves had radii of 15 m and 24 m, a turn angle of 90°, and 10 m-long tangent sections at their beginnings and ends (Figure 1). As the low-bed drove through the curve, it was stopped every 5 to 10 m and the extents of the vehicle mapped using a Trimble TS3 robotic total station. Following the mapping of the vehicle swept path, the low-bed was again driven through the curves and filmed from above using FPInnovations DJI Inspire 1 unmanned aerial vehicle (UAV). The video footage was gathered to provide researchers with a visual understanding of how low-bed vehicles track through tight radius curves when driven naturally.

Figure 1. Low-bed following the 15 m-radius curve in the gravel pit trial. The second pink line denotes the 24 m-radius curve, and a robotic total station is positioned at the centre of the curves.

The second part of the validation comprised comparing simulated to actual turning performance of the test low-bed as it negotiated two forestry bridges with tight approach curves. Vehicle turning was monitored in two ways: mapping the extents of the low-bed swept path at 5 to 10 m increments as it travelled through the bridge sites, and filming the low-bed from above with a UAV to make a video record of actual low-bed turning and how driving decisions influenced turning. Two bridge sites were selected for the validation, with the first site being an example of a bridge with known approach alignment issues. Bridge Site #1 had been designed to accommodate a WB-15 design vehicle, which has a shorter wheelbase than the WB-19, and, thus, requires less road width to track through curves. Due to the tight approach alignment, which has led to guardrail damage and created a safety hazard, FLNRO is working with local licensees to redesign the approach alignment and bridge structure to accommodate a WB-19 with 500 mm of clearance buffer. At Bridge Site #1 (Figure 2), the low-bed negotiated the bridge in both directions three times. Of the three runs, the low-bed was filmed twice using the UAV, and had the vehicle path extents mapped on the third run.

The second trial location (Bridge Site #2), was an example of a bridge site that had been designed for a WB-19 with 500 mm of clearance buffer. Unfortunately, on the day of the field trial, there was extensive rain and researchers were unable to film the truck using the UAV. Researchers were able to map the extents of the low-bed as it navigated through the bridge site using the robotic total station.

Video of the low-bed negotiating the controlled course curves and Bridge Site #1 was reviewed to better understand and appreciate vehicle off-tracking in tight curves, while the mapped extents were used to quantify how well simulations agreed with real-world turning. To quantify the three trials, mapped extents of the swept path were imposed on as-built drawings. Data from the trials performed on the controlled curves was used to validate that the model and real-world tracking of the low-bed were in good agreement, and that the low-bed had similar tracking to computer simulated off-tracking of the WB-19 design vehicle. Data collected at the two bridge sites was used to create a visual representation of how the low-bed performed under actual field conditions, especially at a bridge site that had been designed to accommodate a WB-19 with a 500 mm clearance envelope (Bridge Site #2).

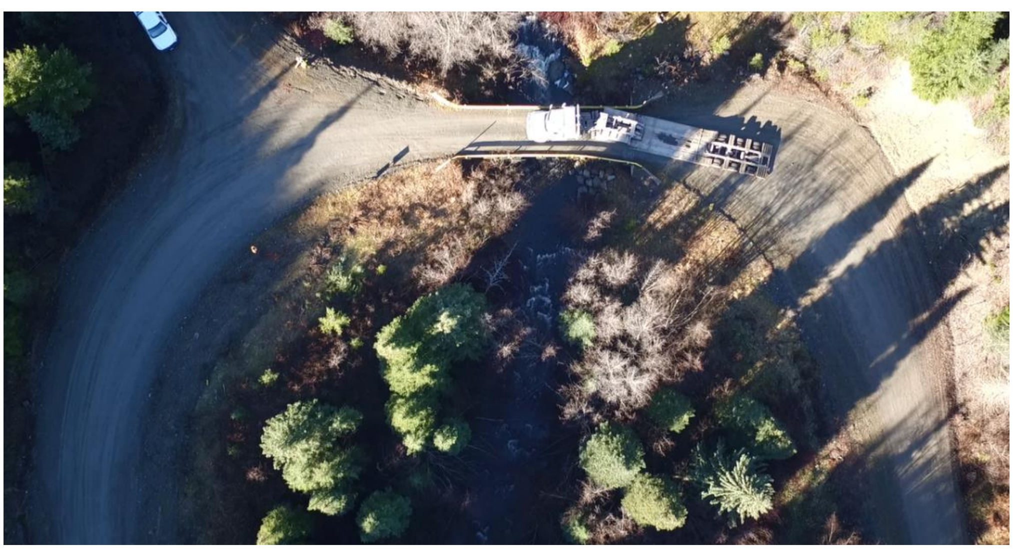

Figure 2. Low-bed negotiating the tight approach curves of Bridge Site #1. Travel direction is up the road (towards the woods).

3. RESULTS AND DISCUSSION

Forrester (2016) recommended adopting a WB-19 design vehicle with a 500 mm clearance buffer for designing bridge approach curves on mainline resource roads where travel speeds are greater than 30 km/h and the minimum curve radius is 35 m. On secondary roads, or roads beyond the reach of low-beds, a highway configured log hauling truck was recommended to allow design engineers to meet operational realities that are often encountered in steep ground where tight bridge approach alignment is necessary. Field trial results have provided confidence in the recommendations made in the Forrester (2016) report. It appears, based on a small sample size, that turning simulations are able to accurately predict low-bed turning, and that low-beds being used on BC resource roads can fit within the tracking path of a WB-19 design vehicle with a 500 mm clearance envelope. Further, field trails demonstrated that a low-bed, with tracking characteristics comparable to a WB-19, successfully negotiated bridge approach curves that were tighter than recommended in the Forrester (2016) report (e.g., curves with less than 35 m-radius)(Figure 3).

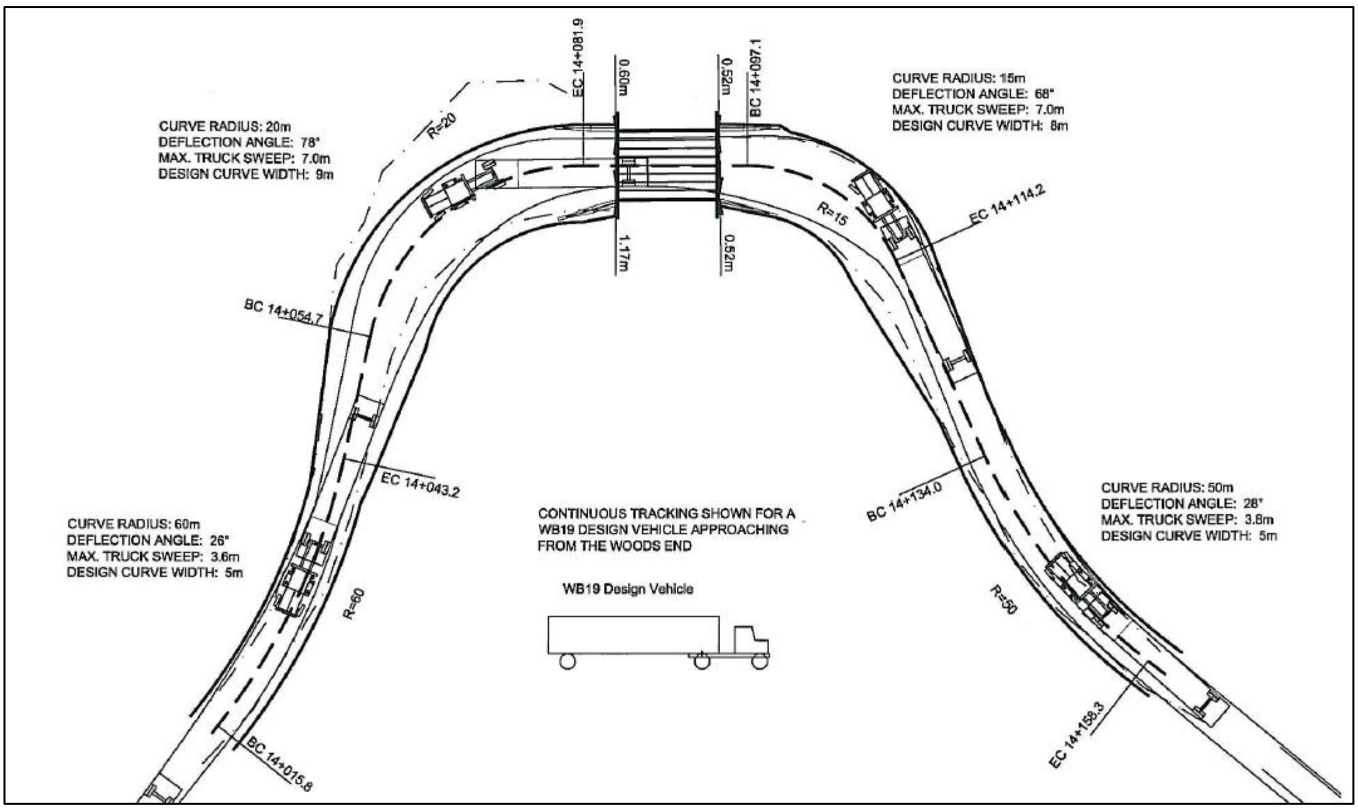

Figure 3. Design tracking analysis completed for Bridge Site #2 where both bridge approach curves had less than a 35 m-radius (BCTS, 2014).

Gravel Pit Trial

Results of the gravel pit trial confirmed that the low-bed selected for field validation had similar tracking characteristics to a WB-19 design vehicle when negotiating 90° turns with 15 m- and 24 m-radii (Appendix A). The mapped extents of the actual low-bed swept path through the 15 m-radius curve deviated by no more than 0.12 m from the inside edge of the simulated WB-19 swept path width and by no more than 0.11 m from the outside edge of the simulated WB-19 swept path width (Figure 4). For the 24 m-radius curve, a maximum deviation of 0.12 m from the inside of the curve of the swept path was recorded, with no recorded deviation from the outside. These results are considered representative of low-bed turning through tight curves, under ideal driving conditions.

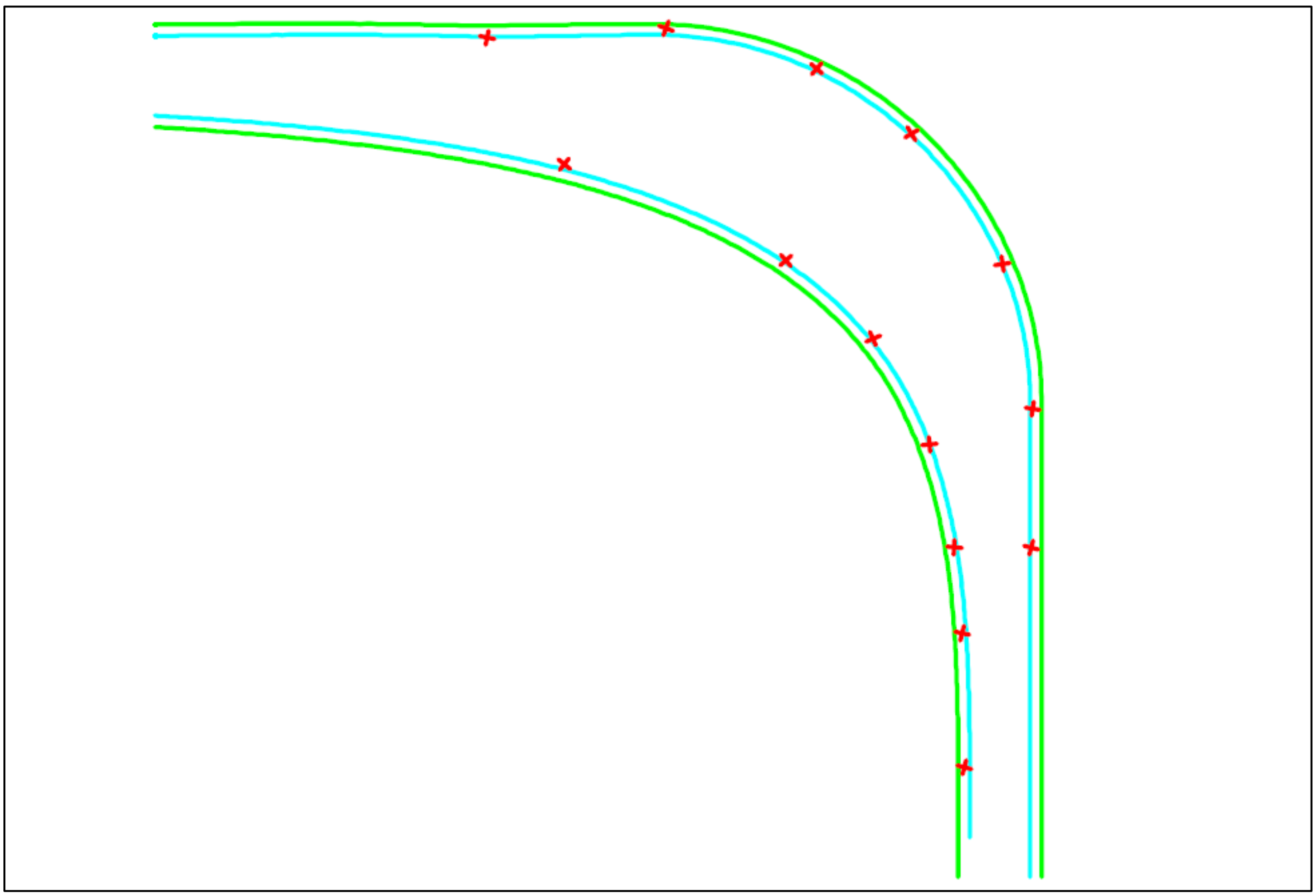

Figure 4. Measured extents of test low-bed's swept path through a 90° turn angle at the gravel pit (red crosses) compared to the simulated swept path of the WB-19 design vehicle tracking (blue line), and to the simulated swept path of the WB-19 plus a 500 mm-wide buffer envelope.

For the comparison of actual low-bed tracking to turning simulations of itself, results confirmed that the actual low-bed turning agreed well with simulated turning (Figure 5). For both the 15 m and 24 m-radius curves tested in the gravel pit, deviation from the simulated swept path was less than 0.05 m.

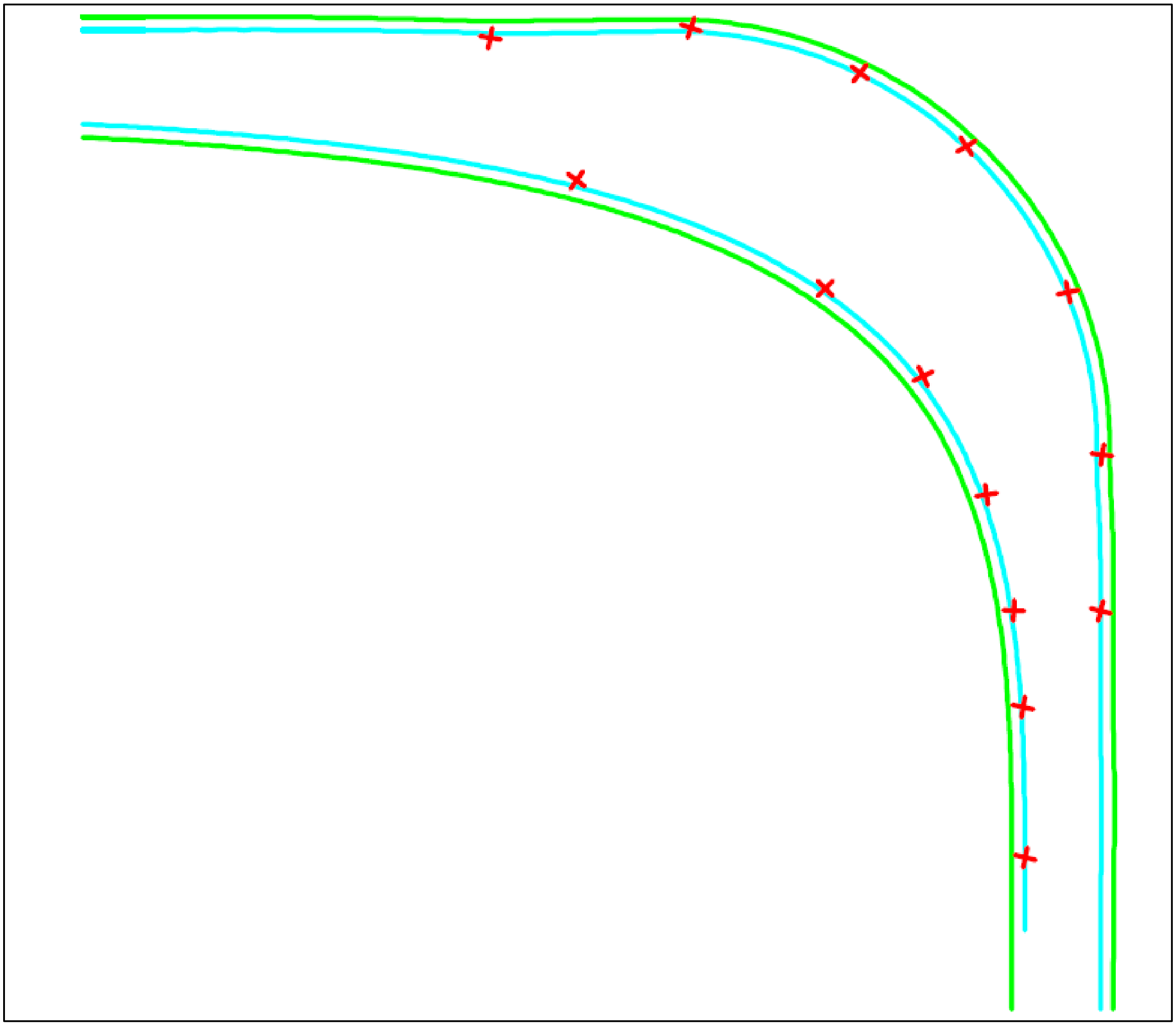

Figure 5. Measured extents of test low-bed's swept path through a 90° turn angle at the gravel pit (red crosses) compared to the simulated swept path of the test low-bed (blue line), and to the simulated swept path of the test low-bed plus a 500 mm-wide buffer envelope.

Bridge Site #1

Results from the testing at Bridge Site #1 showed that when a bridge with tight approach alignment is not designed to accommodate a WB-19 design vehicle with 500 mm clearance buffer there is very little margin for error for a low-bed crossing the bridge. Video of the low-bed traveling in both directions showed that the driver must swing the tractor wide to the outside of the curve to allow the trailer to track onto the bridge without striking the guardrails, barricades or delineator signs. Damage to the guardrails was evident at Bridge Site #1, and it appeared that the guardrails had been bent outwards due to vehicle impacts (Figure 6). Further, delineator signs at either end of the bridge appeared to have been struck by vehicles. It should be understood that the driver who participated in these field trials was one of the most experienced operators with the company hired for the project. A less experienced driver may have had more difficulty driving the low-bed through Bridge Site #1.

Figure 6. Looking towards town at Bridge Site #1. Evidence of vehicle impacts include guard rail scrapes, bent over left side delineator, and missing right side delineator at the far end of the bridge.

Mapping of the low-bed extents as it negotiated Bridge Site #1, in conjunction with physical measurements of clearance, showed that the low-bed passed within 250 to 300 mm of the bridge guardrails (Figure 7). On the inside edge of the swept path, the rear of the low-bed trailer came to within 300 mm of the guardrail, and on the outside edge of the swept path the low-bed came to within 250 mm of the guardrail, when travelling up the road (from the town side approach). Marginally better results were recorded when the low-bed traveled down the road (from the woods side approach).

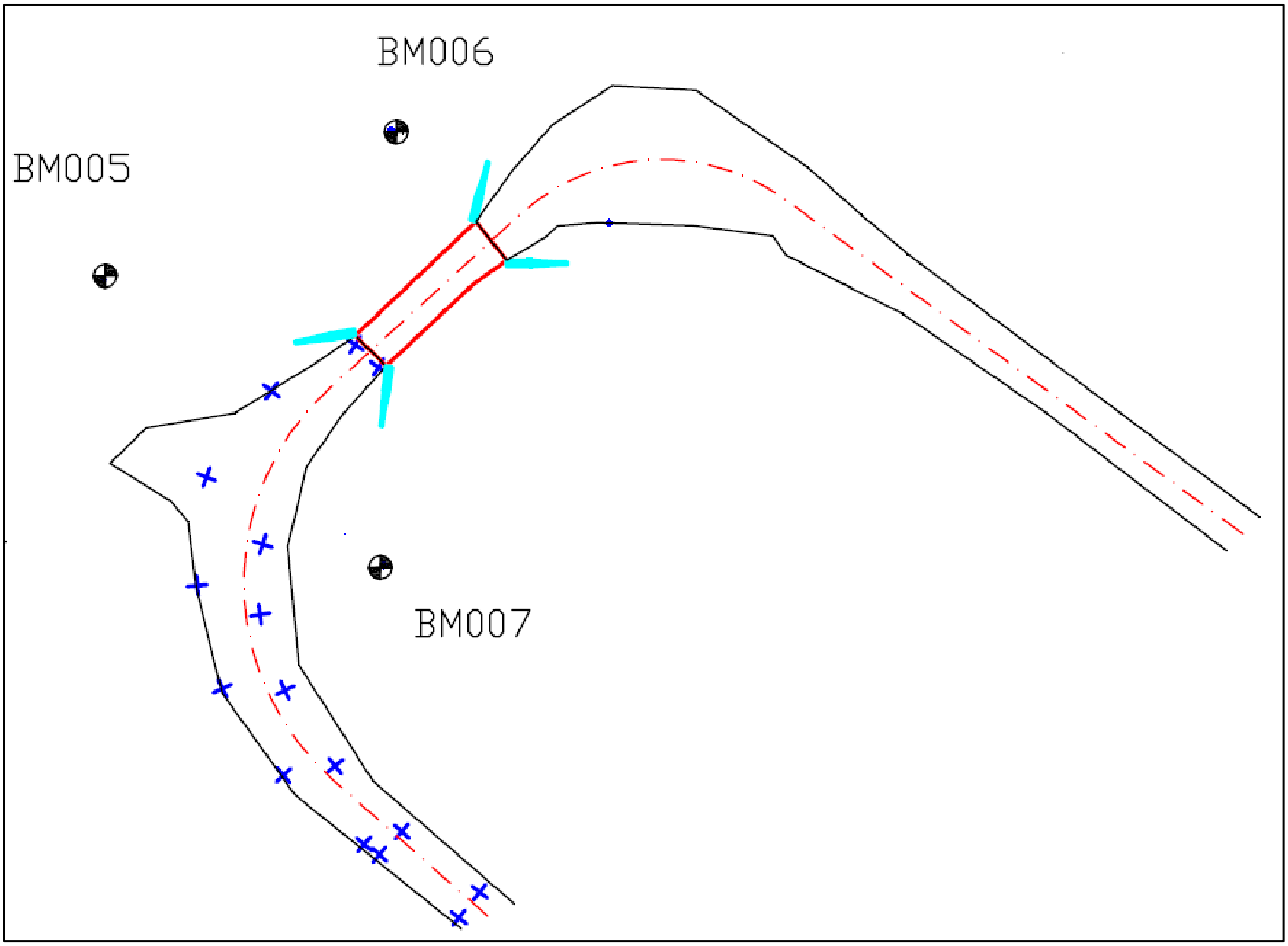

Figure 7. Measured extents of the low-bed's swept path at Bridge Site #1 (blue crosses).

Bridge Site #2

The structure and approach alignment at Bridge Site #2 were designed to accommodate a WB-19 design vehicle with a 500 mm clearance envelope. The town-side bridge approach curve had a 20 m-radius, and lacked a straight tangent onto the bridge. The woods-side bridge approach curve had a 15 m-radius, and also lacked a straight tangent leading onto the bridge. Field observation and mapping of the vehicle extents as it negotiated the tight bridge alignment showed that the low-bed was able to safely navigate the bridge site and maintain a 500 mm buffer throughout (Figure 8).

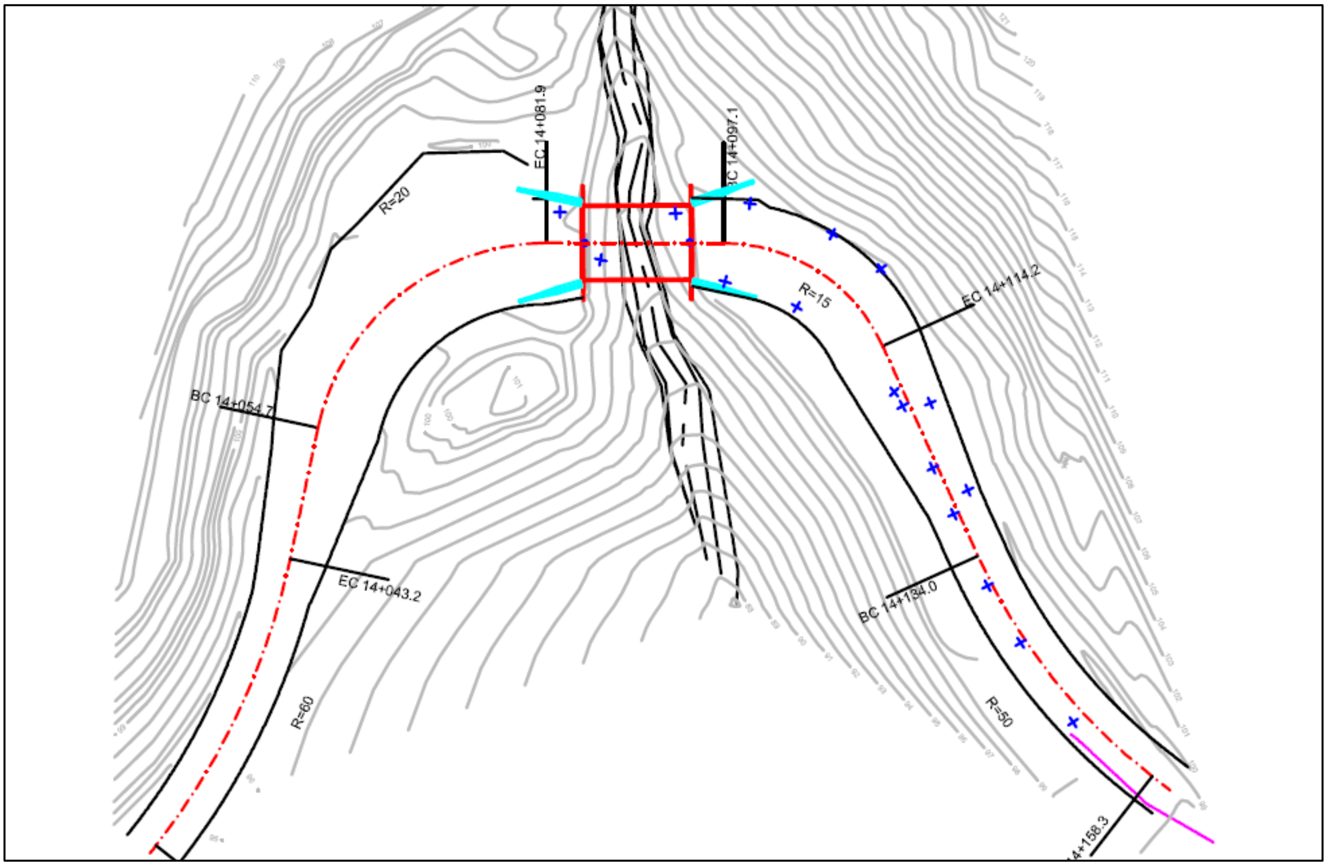

Figure 8. Measured extents of the low-bed's swept path at Bridge Site #2 (blue crosses).

Bridge Site #2 was designed with approach curve radii less than those recommended in the Forrester (2016) report for a WB-19 with 500 mm clearance buffer. The town-side approach had a curve radius of 20 m, and the woods-side approach a radius of 15 m. As a result, field observations and measurements indicated that the 500 mm buffer was maintained on the outside and inside of the vehicle swept path by only a small margin. If the driver had been less experienced, or had not taken the time to assess the bridge approach and plan how to drive the site, the buffer distance may have been less. This was substantiated by field observations of delineator sign impact damage, confirming the theory that the margin for error on this site was small even with a design clearance buffer of 500 mm (Figure 9). In general, the clearance buffer exists to account for variability in driver skill, road conditions, driver error, and to accommodate a range of vehicle configurations. This field trial validated the reasoning behind the recommendation from Forrester (2016) that a WB-19 with a 500 mm buffer be used on mainlines with travel speeds greater than 30 km/h and a minimum approach curve radius of 35 m. When these criteria are not met, professional judgement must take into consideration site specific conditions and select a design vehicle or clearance buffer that will maintain road user safety. Measures such as flaring the bridge ends, utilizing flexible-mount delineators, and accepting a higher risk of damage to the bridge structure may be viable options for road designs in which 35 m-radius bridge approach curves are not economically feasible. The design professional should document why they deviated from the recommended design standard, and what measures they incorporated to ensure road user safety.

Figure 9. Delineator sign on the woods side of Bridge Site #2 shows signs of impact damage, potentially from being struck by a low-bed.

4. CONCLUSIONS

Standardizing the design methodology for bridge approach alignment on BC resource roads is important to maintain road user safety, and protect valuable bridge assets that provide vital access for the BC forest industry. Due to the diverse nature of terrain in BC a one size fits all methodology to approach alignment design is not realistic, as some roads are constrained by topography or other site conditions. However, where roads meet specific criteria it is possible to standardize design methodology. Findings from field validation trials have provided confidence in simulation software to accurately reflect actual vehicle tracking characteristics, and that low-bed tracking can be represented by a WB-19 design vehicle.

Based on field trial results, FPInnovations has confidence in the Forrester (2016) report recommendation for design engineers to adopt a WB-19 with 500 mm clearance envelope on roads where travel speeds are greater than 30 km/h, and approach curve radii reflect curve radius specification in the FLNRO Engineering Manual (2016). Where alignment does not meet this criterion, and low-bed traffic is expected, additional professional judgement is required to ensure road user safety. Alternative measures can be implemented to mitigate some of the risk associated with tighter bridge approach alignments; however, the design professional should document why they deviated from the recommended design standard, and what measures they incorporated to ensure road user safety.

On secondary roads beyond the reach of low-beds, recommendations made in the Forrester (2016) report can still be adopted. However, as discussed in the report there is reliance on the professional to ensure all vehicles travelling the secondary road networks are able to safely negotiate bridges. Selection of this design envelope vehicle was intended to allow designers flexibility with bridge approach alignments when faced with topographical or other constraints.

5. REFERENCES

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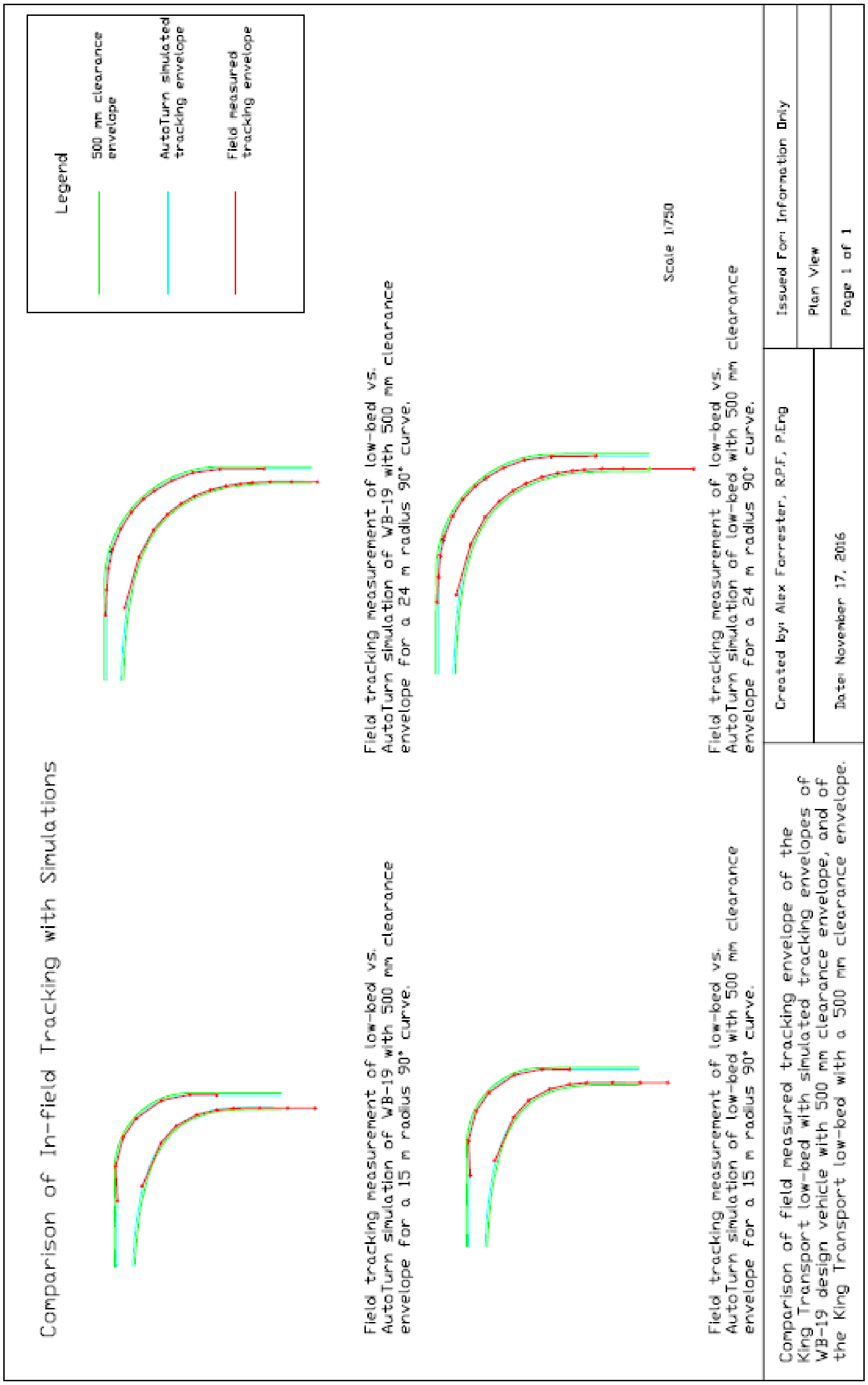
6. APPENDIX A. COMPARISON OF MAPPED TRACKING WITH TURNING SIMULATIONS



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