Optimizing Continuous Friction Testing on Low-Speed Roads and in Tight Curves

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16. Abstract		
ODOT proposed a research project to identify a Continuous Friction Measuring Equipment (CFME) device that could be used on Low-speed Roads and Tight curve scenarios, to assess the possibility of measuring available wet friction in areas of their roadway network where LWFT was not previously used. Finding a CFME device that uses the same tires at the LWFT was of great interest in hopes that this would assist in the translation of the device to the LWFT. A Literature Review was conducted. A test plan was developed and executed that evaluated three separate tasks. They were; contact patch study, force plate assessment, and dynamic testing of the CFME device and LWFT. This report documents findings of the literature review, and controlled environment testing of the selected device, with the goal to evaluate its fit for use for ODOT's application.		
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Table of Contents

List of Figures

List of Tables

1. Problem Statement

Ohio Department of Transportation's (ODOT) 2020-04 research program is titled "Optimizing continuous friction testing on low-speed roads and in tight curves". ODOT currently performs friction testing to determine whether a roadway has sufficient available wet friction to promote user safety during wet conditions. ODOTs Office of Technical Services currently performs friction testing using an ASTM E274 Locked Wheel Friction Tester (LWFT) at 40 mph in order to measure available friction on road surfaces in their network.

ODOT seeks to identify an appropriate Continuous Friction Measurement Equipment (CFME) Device to use at speeds of 20mph or when the roadway is curved. This research is targeted to identify and verify a device that meets ODOTs specific criteria. Such a method may be able to serve the needs of ODOT's stakeholders better, and ensure roadway safety across the state.

This report documents the research approach and key findings of the research program tailored to identify and validate of a process or a technology that can provide accurate, reliable, and repeatable friction testing at low speeds and in tight curves. The research also establishes testing parameters to evaluate the performance of such candidate technology solutions.

2. Research Background

A tailored research program was developed to identify alternative methods and technologies that can enable assessment of available friction in low speed and in-curve operational environments. The research plan included a strategically planned sequence of activities, each designed to meet a purpose. These activities produced interim deliverables, which allowed the ODOT Research and Technical Advisory Committee to review progress and guide research direction.

A brief summary of the overall research approach is presented here. First, the research team performed an assessment of ODOT's criteria for evaluation of available market solutions. The team then performed a market survey to identify candidate solutions that can meet outlined criteria. Next, one candidate solution was evaluated in Controlled Testing at the Transportation Research Center Proving Grounds. Then, the solution if deemed acceptable in Controlled Testing, was planned to be evaluated in Field Tests. Finally, the candidate solution was to be further evaluated in a Validation Testing activity.

The stage-gate design of the research program allowed ODOT to review performance of the candidate solution, at strategic checkpoints during and after the activities were complete. The research team developed test plans at the start of each activity to test the candidate solution and obtain relevant performance insights. Finally, the team pieced together the insights obtained from each activity to develop an overall picture of the candidate solution's performance. Table 1 outlines the research approach and stage-gates.

Table 1 - Research approach for ODOT 2020-04

Planned Activity	Deliverable	Purpose
Literature Review	Literature Review Report	Identify current practices and readily available technologies
	Evaluation Matrix	Evaluate technologies based on established criteria
Gate – Are there candidate solutions that can satisfy ODOT's needs? If no, STOP. If yes, pick candidate solution with highest rank in Evaluation Matrix for Controlled Testing.		
Controlled Testing	Test Report	Report findings during controlled testing of identified technology
Gate – Does the candidate solution satisfy evaluation criteria established in Controlled Testing? If no, STOP. If yes, proceed to conduct Field Testing.		
Field Testing	Test Comparison Matrix	Compare friction test data between identified technology and locked wheel friction test
	Translation Analysis	Develop translation between two datasets
Gate – Does the candidate solution satisfy evaluation criteria established in Field Testing? If no, STOP. If yes, proceed to conduct Validation Testing.		
Validation Testing	Test and Recommendations Report	Provide recommendations to assist in deployment of identified technology
Finish Research Program		

3. Research Approach

The following sections outline specific research approach used in activities of the research program.

3.1. Literature Review of Technical Solutions

The literature review activity kick-started the research program. This activity was designed to meet the following objectives:

- Perform a technical review of CFME and LWFT characteristics to determine feasibility that a CFME can meet ODOT's needs

- Design Evaluation Criteria tailored to be used for assessment of candidate solutions identified in Market Review
- Identify readily available candidate solutions via Market Review

The research team reviewed established literature sources to meet the technical review objective. This included an investigation of differences in operating principles of LWFTs and CFMEs. The team also investigated vehicle dynamics characteristics that are favorable for low speed roads and in-curve operation. All of this information was used to synthesize an Evaluation Criteria to rank order candidate CFME solutions. Candidate solutions were found by reviewing information available from CFME suppliers. Finally, the candidate solutions were rank ordered per the results of Evaluation Criteria to produce an evaluation matrix. This evaluations matrix details known technical specifications, data acquisition system information, water wetting system performance, and key operational conditions for each rank ordered candidate solution.

On completion of the literature review activity, the candidate solution that ranked highest in the evaluation matrix was proposed for Controlled Environment Testing.

3.2. Controlled Environment Testing

The candidate technical solution identified via literature review was subjected to tests in the Controlled Environment laboratory and facilities at the Transportation Research Center Proving Grounds in East Liberty, Ohio. Access to this independent testing facility offered ODOT an opportunity to evaluate the performance of the candidate solution, and hence its fit-for-use, on representative test surfaces in a repeatable and consistent manner.

First, evaluation procedures and criteria were designed to understand the efficacy of the candidate solution to meet objectives of the research program. Next, data collection plans were developed and the candidate solution was instrumented with sensors and data acquisition equipment (as applicable). Finally, the candidate solution was evaluated either in the laboratory or on controlled environment test facilities using the developed procedures.

3.2.1. Contact Patch Assessment

The contact patch assessment study was designed to evaluate the difference in contact area and contact patch shape observed on the test tire in select operating modes. Each operating mode was defined by a combination of set tire pressure and vertical load.

ODOT identified the ASTM E524 Standard Test Tire (Figure 1) as the desired test tire to be used for this research project. It is one of the test tires typically used on the LWFT, is a smooth tire and thus not as susceptible to influence of sideways mechanical bite if used on a side load device.

Figure 1 - ASTM E524 Standard Test Tire

It is believed that using the E524 Tire under an operating condition such that it bears a full-width contact patch will encourage uniform wear of the tire. Furthermore, having a tire contact patch similar to that observed on an ASTM E274 LWFT may aid in development of correlation. The TRC Force Plate was used to measure the load (Figure 2) on the tire as the contact patch was made with black ink on a steel plate painted white.

Figure 2 - Apparatus used for Contact Patch Assessment with the ASTM E524 Tire

Findings from this assessment provided recommendations towards the use of tire pressure and vertical load values to be used in operation for the candidate solution during Dynamic Testing.

3.2.2. Force Plate Assessment

Traditionally the force plate technique is used to calibrate load cells on the friction testing devices. The technique can also reveal a friction tester's propensity towards load shift during operation. This happens due to the moment created around the axle of the test wheel(s) by the friction forces at the road surface. This results in unloading the test wheel(s) and transferring weight forward in most cases to the hitch (if a trailer-type device).

In this research program, the force plate assessment technique was used to meet the following goals:

1. What is the load transfer observed from the test wheel(s) to another part of the device under normal operation?
2. Does the friction tester compensate for the load transfer when calculating the reported friction number?

The force calibration plates are a calibrated set of transducers that are placed on air bearings to produce a near frictionless interface with the floor surface. This allows the horizontal and vertical forces to be accurately measured when the test wheel is locked. CFME candidate solutions do not operate on a locked wheel principle. The research staff devised an alternate method to estimate the load transfer in case of CFMEs. The horizontal force was slowly applied to the test wheel(s) using the force plate apparatus, while the corresponding vertical load(s) was/were measured. Results obtained from the force plate may be corroborated by an alternate method using a load cell situated appropriately in such devices in the dynamic testing activity if so equipped.

In summary, the results from this assessment provide information about load shift expected in the vertical direction upon application of the horizontal force, which simulates friction load on the device, and whether the device accounts for the vertical load shift.

3.2.3. Dynamic Testing

Four specific criteria were identified to test the device's compliance to ODOTs needs. They were:

1. Does the device measure the same values whether traveling up or down a slope?
2. Does the device measure the same values in a curve regardless of direction of travel, Clockwise (CW or Right) vs. Counter Clockwise (CCW or Left)?
3. Does the device measure the same values in a curve as it does on a straight?
4. Does the device have the ability to measure differing friction levels of surfaces repeatedly?

A detailed test plan was developed (see Section 7.2) to evaluate the devices ability to meet the criteria listed above in order to comply with ODOTs needs for a device to operate at low speeds and in tight curves.

To evaluate slopes, the 10% and 23% slopes at TRC's Off Property facility were used. A 10% slope would be an upper limit of any road surface that would be tested in the field; however, by adding the 23% slope to the testing matrix, it was believed that if the device had any issues with slopes, it would be more easily identified. To satisfy the need to assure acceptable performance in a curve, both to test for left and right, and to compare curve results to straight-line results, curves were laid out on the Vehicle Dynamics Area (VDA). Two different surfaces were selected, Jennite (low-coefficient surface), and the asphalt surface (representing high mu surfaces). A radius of 150' was selected , as it was identified as being

ODOT's minimum design criteria for ramps and roundabouts[1]. This radius was laid-out with cones to identify the arc for the operator. For effective comparison of the device's performance, straight-line testing was performed on the same surface as the in-curve testing. This presented a significant advantage as it can be difficult to find test surfaces with enough area of homogeneous material that can be traversed in both a straight and a curve. The VDA offered this opportunity.

To measure repeatability, several passes on the same surfaces in a straight line were made on two different surfaces, Wet Jennite and Wet Asphalt. This allowed us to statistically evaluate both the repeatability of the RT3 Curve by reviewing the standard deviation of each data set, while also evaluating the averages of the data from each facility. A low value of standard deviation represents acceptable repeatability, as well as a distinctly different number for the averages represents the ability to discriminate between good friction and poor friction.

ODOT has extensive experience with the LWFT, thus it is important to understand the relationship between the new device being considered and the data generated from the LWFT. Measurements were taken with the LWFT of the surfaces used in the evaluation of the CFME. The data was used to document and compare capabilities of each device.

3.3. Field Testing

The original intention of this project was to use the selected candidate device in real-world applications to document its performance. An evaluation of the data collected at several locations would establish a set of criteria to determine if the surface had sufficient available friction. Due to the findings of the Dynamic Testing portion of the Controlled Testing, the Field Testing was not performed.

3.4. Validation Testing

The intention was to use the device at a few additional sites in the field to validate if the established criteria was satisfied in field testing. As Field Testing was not performed, Validation Testing was not needed.

4. Research Findings and Conclusions

The top candidate from the Literature Review was selected and tested per the approach outlined above. The findings and conclusions are detailed here.

4.1. Literature Review of Technical Solutions

An evaluation criteria was developed based on an understanding of ODOT's needs. The criteria built on the candidate device's; ability to operate at low speeds and in tight curves, choice of test tire, location of test tire(s) in regard to wheel-path, and the ability to maintain intended design parameters.

Information for nine (9) candidate devices was obtained during this Market Review. The research team evaluated the candidate devices using the established criteria. The results of the evaluation are summarized in Table 2 below. Each criteria was evaluated using the following scale:

[1] [1] ODOT Location and Design Volume 1 – Sec 503.2.2 Loop Ramp Design Speeds

- “1” – Meets Criteria
- “2” – Meets Criteria Conditionally
- “3” - Fails Criteria
- “N/A” – Not Applicable to the device

Table 2 - Evaluation of CFMEs per established criteria

	Evaluation Criteria				
Devices	Low Speed	Tight Curve	Tires	Test Tire Location	Parameter Design
Skidometer BV11	1	1	3	3	3
Dynatest HFT	1	1	3	2	1
Dynatest RFT	1	1	3	3	1
Halliday RT3 Flight	1	3	1	3	N/A
Halliday RT3 Curve	1	1	1	1	N/A
Griptester	1	1	3	1	3
PaveCFT	1	1	3	3	N/A
SCRIM Mini	1	1	3	1	N/A
NAC Dynamic Friction Tester	1	3	3	3	3

Based on this evaluation summary presented above, the research team made the following ranked order recommendations for consideration in this research project to ODOT:

1. Halliday RT3 Curve
2. SCRIM “mini” equipped with Dual Sided simultaneous capability
3. Dynatest Highway Friction Tester (HFT)

The research team in consultation with ODOT TAC chose the Halliday RT3 Curve device as a candidate solution fit for further evaluation in this research program.

4.2. Controlled Environment Testing

The Controlled Testing portion of the project comprised of 3 sections each providing data to build upon in the next. The Contact Patch of the Halliday RT3 Curve was evaluated; the reaction of the device to the longitudinal forces created by the road surface in the direction of travel was evaluated during the Force Plate Assessment; and Dynamic Testing provided valuable findings of how the device performed during simulated maneuvers.

4.2.1. Contact Patch Assessment

The LWFT has well-distributed loading on the tire at 1085 pounds and 24 psi. The RT3 Curve operates with a much lower load of 300 pounds per tire and had a tire pressure designation of 26 psi. A process was developed where various sets of tire pressures and loading conditions were simulated with the LWFT on the calibration force plate (see Section 7.3.1).

The contact patch of the RT3 Curve at 300 pounds and 26 psi was only 39% of the LWFT and the edges of the tire tread were not in contact with the road surface. It was believed that increasing the contact patch of the RT3 Curve could potentially assist in developing a better translation between the two devices. It was also believed that increasing the contact patch would provide a more consistent contact profile and improved tire wear. The 300 pounds and 26 psi causes the edges to not be in contact with the road surface. There is a line on the sidewall of the tire to indicate when the tire is worn out. At 1085 pounds and 24 psi, this works well as the tire is evenly worn. At the lighter load and higher pressure, the center would have to wear very thin. Also, the width of the contact patch would be increasing over time. Tire pressures of 15, 18, and 26 psi were evaluated at loading of 300 and 400 (the higher load was accomplished by adding metal plates to the device frame at each wheel). The results of each condition tested are shown in Section 7.3.1 below. A baseline tire pressure of 15 psi and loading of 300 was used throughout the testing. Although a loading of 400 may further improve the contact patch, this was considered an experimental weight and it was unclear if this would affect the durability of the device over time.

4.2.2. Force Plate Assessment

The RT3 Curve has a static weight of 300 pounds on each test wheel (unless additional weight is added). The device does not measure the vertical load dynamically while testing. This is common amongst CFME devices. Thus, an evaluation of vertical load shift (see Sec 3.2.1) as surface friction increased was desired to understand the potential effect on the computed Halliday Friction Number (HFN) (see Section 7.3.2).

The RT3 Curve presented a challenge in this portion of the study as there is no brake to lock the wheel from moving while the simulated surface friction was applied at the road surface. Wheel movement was restricted by placing a rod through a hole in the wheel and allowing it to stop against the swing arm, allowing the forces to be applied by the force plates and the resultant vertical load shift from the test wheels to the trailer tongue to be measured. No readings could be obtained from the RT3 Curve during this process, as the load cell was isolated from the forces.

It was found, with an initial load of 300 pounds, that a reduction of approximately 25 pounds will occur with the application of 50 pounds of force at the contact patch, in the direction of travel. The shape of the load transfer function is also believed to be linear. However, the magnitude of this force in normal testing is not clear as the data obtained by the method isolated the load cell, as discussed above. It is believed that with only 2 degrees of skew angle per wheel, that actual force applied by the road in the direction of travel is small in comparison to the loading used in this testing, which may render the resulting reduction in load to a level which is correspondingly small and potentially insignificant.

4.2.3. Dynamic Testing

Instrumentation and associated data acquisition system was added to the RT3 Curve to measure several parameters. They were:

- Raw voltages from RT3 Curve load cells (harness added to tie into signal in cab of truck)
- Steering wheel position from a string pot on the steering shaft (harness added to tie into signal in cab of truck)
- Wheel speeds at the wheels from the specifically designed and fabricated tone rings added to the test wheel along with associated sensors (only available for smooth tire)
- Ride height at the test wheels
- Displacement of the RT3 Curve "trailer" in relationship to the tow vehicle by placing string potentiometers from the stationary beam on the tow vehicle to the beam of the "trailer."
- Tire temperature on the tread surface
- Camera views of the device from the tailgate of the tow vehicle, sidewalls of both test tires, and inside the cab viewing the RT3 Curve's controls/display

More detailed information about the instrumentation is included in Section 8. After the instrumentation was installed, testing maneuvers were performed to confirm performance as detailed in the approach.

Due to the nature of this testing, multiple iterations of a specific parameter setup and test site were not practical in most cases from an efficiency standpoint. Therefore, the data generated was analyzed using engineering judgement. It is not expected that values will match exactly within one type of test (such as opposite direction). This is due to the variations in any test surface and/or the ability to test the exact same spot on a test pad. Therefore, a reasonable percent difference is expected. However, an occurrence of a large percent difference is flagged for further review, and performance is judged with due consideration to the surface type, location, nature of surface, and maneuver being evaluated. Low coefficient surfaces tend to have a higher percentage difference due to the actual values being smaller.

The initial settings were; tire pressure at 15 psi, weight on each tire at 300 lbs, skew angle of both wheels at 2 degrees, and the water thickness at 0.5 mm.

Testing the Device both up and down Slopes

The RT3 Curve appears to not be affected by slopes. The limited testing conducted showed similar values whether traversing up or down a slope (Table 3). A small amount of variation can be expected due to the fact that this a dynamic test and it is impossible to ensure that the exact section of road surface is retested in both directions. Also, these surfaces are typically used for durability testing and the condition of the surfaces was not as good as the other test surfaces used in the rest of the testing.

Table 3 - Summary of CFME Results: Testing on Slopes

Surface	Average Transducer Force (N)			Calculated HFN		
	Uphill	Downhill	% Diff.	Uphill	Downhill	Diff.
10% Slope (Wet)	219	218	0.5	67	67	0
10% Slope (Dry)	250	246	1.6	76	75	1
23% Slope (Wet)	201	206	2.5	62	63	1
23% Slope (Dry)	NA[1]	214	NA[1]	NA[1]	65	NA[1]

1-Data set was corrupted

The performance in a 23% Slope in the Uphill direction was not validated due to corruption in dataset. However, researchers do not believe there is a cause of concern with the device's performance in slopes.

Test of Device in both directions of the Curve

The RT3 Curve measured similar values regardless of direction of the curve (Table 4) as long as the radius of the curve was the same. Once again, a small amount of variation can be expected due to the fact that this a dynamic test and it is impossible to ensure that the exact section of road surface is retested in both directions.

Table 4 - Summary of CFME Results: Testing on Curves

Surface	Average Transducer Force (N)			Calculated HFN		
	CCW	CW	% Diff.	CCW	CW	Diff.
Jennite (Wet)	77	82	6.6	24	25	1
Asphalt (Wet)	191	183	4.5	59	56	3
Asphalt (Dry)	210	199	5.2	64	61	3

Test of device in Curve vs. Straight line

The RT3 Curve does not measure the same value in a curve as it does in a straight on the same surface (Table 5). Even taking into consideration the variation expected from dynamic testing on test surfaces, the amount of reduction in the value while in a curve was unexpected.

Table 5 - Summary of CFME Results: Testing in Curve vs. Straight Line

Surfaces	Average Transducer Force (N)	Calculated HFN

	Straight	Curve	Average Horizontal Force Reduction in Curve vs. Straight [%]	Straight	Curve	Diff.
Jennite (Wet)	115	77	32.9	35	24	11
Asphalt (Wet)	224	191	14.5	69	59	10
Asphalt (Dry)	246	210	14.4	75	64	11

Extensive testing was performed with a variety of parameters to gain a better understanding of the reduction of the "in-curve" values. Parameters such as tire pressure, vertical load, anti-roll bar setting, yaw dampers installed or removed, etc., were modified and tested to identify if any of these parameters could be significant in improving consistency between the two readings. Even a different type of tire was installed in this effort, ultimately no such condition was identified. Additionally, it was qualitatively observed by the research team that as the radius of the curve decreases, the difference in the measured friction number between straight and curve tends to increase. Results for testing of the device under these parameters are in Sec 7.3.3.

As mentioned in Section 4.2.1, the tire pressure of 15 psi and 300 lbs of vertical load was established as the baseline condition for all testing. When it was first learned that the device seemed to measure a lower average friction value (designated as Halliday Friction Number or HFN) in a curve than in a straight-line testing, other combinations of tire pressure and loading were tested. Table 6 is a comparison of testing with 15 psi and 26 psi tire pressure at 300 lbs of vertical load. Because it is clear that the direction of curve does not matter, only CCW direction was tested for efficiency:

Table 6 - Summary of CFME Results: Testing with different tire pressures

Surface	Maneuver	Average HFN Value at Designated Tire Pressures	
		15PSI	26PSI
Jennite (Wet)	Straight	40	42
	Curve CCW	30	30
Asphalt (Wet)	Straight	79	77
	Curve CCW	67	63

From this table it is clear that increasing the tire pressure from 15 psi to 26 psi, approximately 75%, did not have a significant effect on the HFN values when tested in a particular maneuver (straight or in-curve), even though the contact patch would have changed dramatically. It is believed this also indicates that any tire pressure buildup due to heat in the tire is insignificant. As is also evident from the table, an increase in tire pressure does not impact the device's ability to read the same friction value in a straight line, as in a curved road.

Transition Testing

Testing was performed to better understand the dynamics of this condition. In this testing, the vehicle was accelerated in a straight line and recording was initiated. After allowing the vehicle to stabilize at speed, a steering input was initiated to transition to a 500' radius curve. After approximately 2 seconds, a steering input was initiated to transition to a 150' radius curve. Figure 3 shows the tape placed on the steering wheel for straight-line, 500' radius curve, and 150' radius curve.

Figure 3 - Steering wheel of RT3 Curve truck taped with curve radius markers.

From this testing, it was found that a 500' radius curve had minimal effect on the HFN; however, once the steering wheel was turned to reduce the radius, the HFN began to be affected and was reduced. On the vehicle tested, the steering angle should not exceed 30 degrees or the average HFN will be affected. The graphs (Figure 4, Figure 5, and Figure 6) show that as the steering angle increases, as would happen when traversing through a curve, the HFN decreases. Additionally, corresponding graphs (Figure 4, Figure 5, and Figure 6) with each load cell data are included to show that the inside wheel drops in value while the outside wheel stays nearly the same or increases slightly.

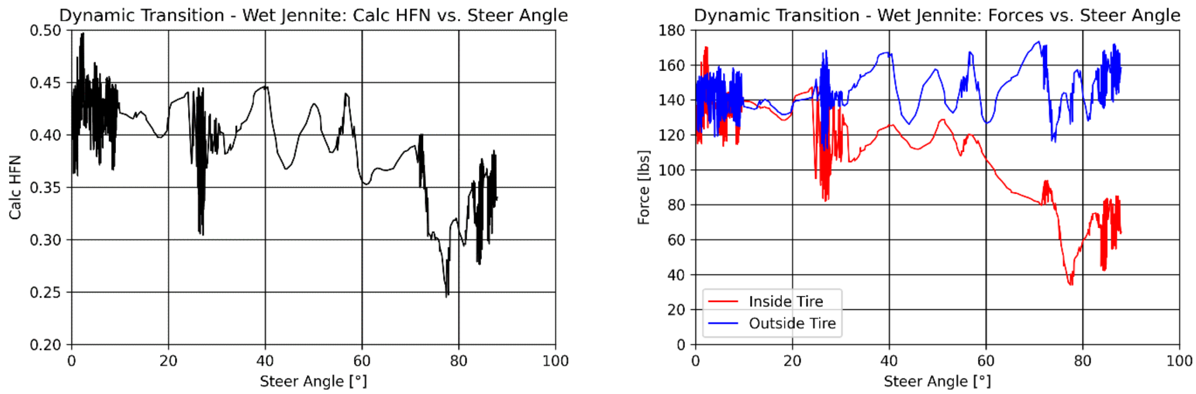

Figure 4 - Summary of Results of Dynamic Testing on Wet Jennite.

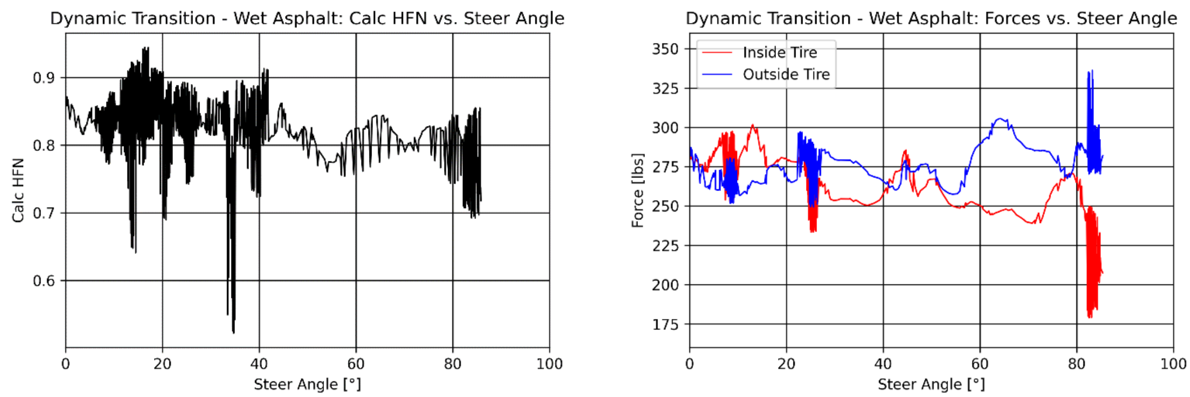

Figure 5 - Summary of Results of Dynamic Testing on Wet Asphalt.

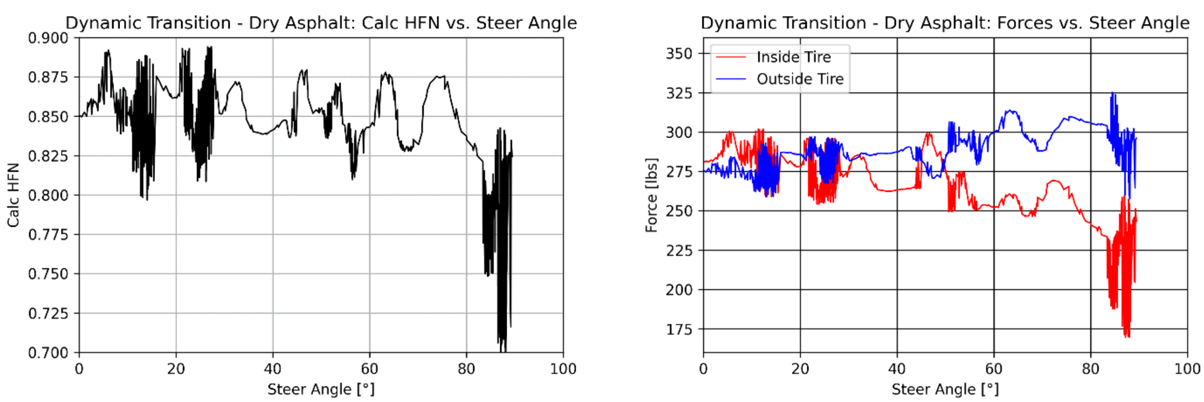

Figure 6 - Summary of Results of Dynamic Testing on Dry Asphalt.

It was found that as the device transitions from straight to a curve, the inside wheel friction value decreases at a faster rate than the outside wheel increases, thus the average value decreases. It seems this indicates that the inside wheel is seeing less friction due to the tire becoming more in line with the direction of travel and thus the effective skew angle decreases. A review of the data collected suggests that the arc travelled by the outside tire is not causing the effective skew angle to increase much over the straight-line condition.

The following sketch illustrates (Figure 7) that when traveling straight, both tires are equally skewed to the direction of travel and the average of the two force values will represent the corresponding HFN value expected for a particular surface. However, according to the values recorded, it is estimated that when traveling in a curve, the inside wheel (left in this case), has less force on the wheel because it is lining up with the direction that wheel is traveling.

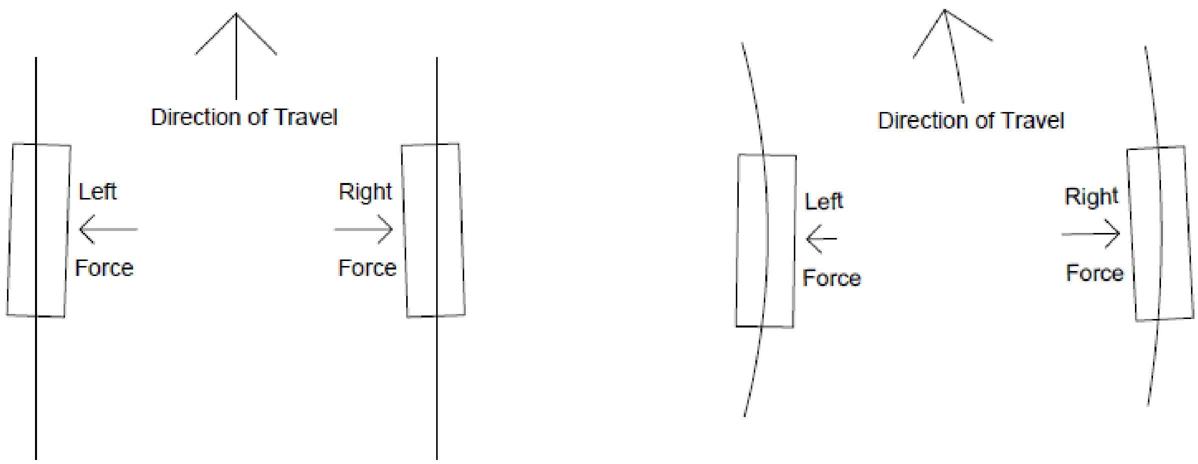

Figure 7 - Sketch to illustrate tire forces observed on RT3 Curve CFME device in a curved road

Differentiation and Repeatability

The RT3 Curve was tested 5 times in a straight line on both Wet Jennite and Wet Asphalt. Table 7 shows a summary from the data collected.

Table 7 - RT3 Curve Baseline Test: Performance in straight-line across various surfaces.

Surfaces	Force (N)		Calculated HFN	
	Average[1]	Standard Deviation	Average[1]	Standard Deviation
Jennite (Wet)	139.27	2.64	42.4	0.5
Asphalt (Wet)	237.17	4.54	72.2	1.5

As the average values from the two surfaces show, the RT3 Curve appears capable of differentiating between different surfaces, and the low standard deviations reflect on the device's repeatability.

Characterization of the Surfaces with the LWFT

The LWFT has been the device that ODOT has used for decades to measure available friction of their road surfaces. The original design speed for the LWFT was 40 mph. It has long been known that surfaces inherently have a speed gradient, thus the friction value measured increases as the travel speed decreases. Since the speed gradient varies on different surfaces, ODOT has strictly used 40 mph as their test speed with the LWFT.

The original intention was to measure the test surfaces used for this research with the TRC Inc. LWFT shown in Figure 8.

Figure 8 - TRC Inc. LWFT used for surface characterization.

The LWFT was used straight-line at 40 mph to document the surface friction characteristics with both the ASTM E524 Smooth tire (used by the RT3 Curve in this research project), and the E501 Ribbed Tire. Additionally, it was decided to test the LWFT on the same test surfaces at 20 mph and in curves to document the capabilities of the device. The testing parameters follows:

- Smooth Tire and Rib Tire – Both tires are typically used by ODOT on the LWFT and provides different information about texture.
- 40 mph and 20 mph Straight-line Testing – To better understand the speed gradient on all surfaces with both tires.
- 150' radius at 20 mph, and 300' radius at 40 mph – Although the 150' radius at 20 mph has been the test parameter used for evaluation of the proposed CFME, the 300' radius is a fair representation of testing that has been performed by ODOT on ramps at 40 mph. This will help validate any previous testing conducted with the LWFT device.
- Wet Jennite, Wet Asphalt VDA, Wet Asphalt VDA2 - These three surfaces have been used for the Dynamic Testing performed at TRC.

The full data sets are included in Section 7.3.3.

The combined data collected on all three surfaces by the LWFT with both the smooth and rib tire is shown in Table 8.

Table 8 - Summary of Results: Speed and Curve Gradients of LWFT with Smooth and Ribbed Tires.

Tires	Speed Gradient (Straight) 40 to 20	Curve Gradient from Straight vs. 300' radius @ 40 mph		Curve Gradient from Straight vs. 150' radius @ 20 mph	
		Left	Right	Left	Right
Smooth	13.2	2.6	-2.1	2.1	-0.7
Rib	6.6	2.2	-1.8	2.7	-0.5
Overall	9.9	2.4	-1.9	2.4	-0.6

The same data calculated as percentages are as follows (Table 9):

Table 9 - Summary of Results: Speed and Curve Gradients of LWFT with Smooth and Ribbed Tires, in percentages.

Tires	Speed Gradient (Straight) 40 to 20 [%]	Curve Gradient from Straight vs. 300' radius @ 40 mph [%]		Curve Gradient from Straight vs. 150' radius @ 20 mph [%]	
		Left	Right	Left	Right
Smooth	26%	4	-4	5	-1
Rib	14%	5	-4	4	0
Overall	20%	4	-4	5	-1

It appears from a review of data in (Table 8 and Table 9) that the ASTM E501 ribbed tire may be used with the LWFT without any concern for the effect of the ribs influencing the data since the ribs are in line with the direction of travel. However, additional data collection efforts may need to be conducted to confirm these findings.

In an attempt to compare the curve gradients obtained by both the RT3 Curve and the LWFT, the following table (Table 10) was created from data collected with the smooth tire at 20 mph on the 150’ radius:

Table 10 - Comparative test results between RT3 Curve and LWFT

Surfaces	Curve Gradient from Straight vs. 150' radius @ 20 mph [%]			
	RT3 Curve		LWFT	
	Left	Right	Left	Right
Jennite	-33	-29	12	-3
Asphalt	-25	-19	1	0
VDA2	-11	NA	2	-1

4.3. Overall Conclusion

The RT3 Curve establishes suitable friction values at 20 mph as long as steering input is less than a 500’ radius curve. This makes the device suitable for low speed testing. However, if used in curves where the radius is less than 500’ the data should be adjusted to compensate for the reduction in HFN.

Based on the findings in this research project, it may be of interest to the pavement friction community if other CFME devices were evaluated for their response to measuring in a curve versus a straight, especially side force devices.

Through comparison testing with the LWFT, it was found that the LWFT can be used at 20 mph both on straight-line testing and in curves as small as 150’ radius. However, there may also need to be consideration of an adjustment to the data in regard to the speed gradient from 40 to 20 mph, and perhaps a slight consideration for the left turns increasing the value and right turns decreasing the value, with regards to the curve gradient. It would seem from the data that the adjustment for curve data is much less a concern than the speed gradient issue in regard to current in-house practices.

5. Recommendations for Implementation

The RT3 Curve CFME device did not meet the expectations of the research project. The performance in-curve appeared to be significantly different from those in a straight line. The device however, meets expectations of repeatedly measuring surfaces in a straight line, and at low-speeds.

Testing of the Locked-wheel Friction Tester showed that it can be used in a curve. Some consideration may need to be given for curve gradient on low-coefficient surfaces. It is recommended that more work be done to understand the speed gradient on various surfaces, and confirm that the curve gradient is minimal for a spectrum of surfaces. This would allow more confidence in data collected at speeds other than 40 mph with the LWFT. This would also allow for better interpretation of the results from data collected at speeds other than 40 mph. Additional data collection efforts with the ASTM E501 ribbed tire on the LWFT are also proposed in future work to confirm its ability to be used in low-speed and in-curve environments.

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7. Appendix - A

7.1. Summary of Literature Review of Technical Solutions

As a first task of this research program, the TRC Team performed a market survey of the state of pavement friction assessment techniques available circa 2020. While the field of pavement friction assessment is fairly established, new technologies which claim to provide a better coverage of assets have emerged.

The goal of this section is to summarize the readily available technical solutions, via market survey, and review of existing literature, which improve ODOT's existing approach towards pavement friction management. This section delivers the researchers' technical and market review findings.

7.1.1. Background research

First, the TRC Team reviewed the state of regulation in the field of Pavement Friction Management. The need for establishing a data-based asset management program that ensure safe public roads has led to the emergence of pavement friction management techniques adopted by DOTs nationwide.

Next, the TRC Team reviewed the current state of technical approach. The technical offerings in the domain of pavement friction are designed with the intent to satisfy friction measurement needs in two domains: public roads, and airport runways. The solutions developed rely on either the locked wheel friction testing using an E274 Locked Wheel Friction Tester (LWFT), primarily supplied by one of two manufacturers, or continuous friction measurement using one of several Continuous Friction Measuring Equipment (CFME) devices on the market.

The TRC Team embarked on establishing evaluation criteria to identify candidate CFME solutions that satisfy ODOT's unique operational domain needs.

7.1.2. Evaluation Criteria for CFMEs to satisfy ODOT's requirements

Unlike the LWFT that has its design regulated by an ASTM standard (E274), CFME's characteristics vary widely. Each identified CFME will be evaluated to the criteria below:

Low-speed operation

It is assumed that all CFMEs will be able to operate at lower speeds (defined as low as 20 mph.).

Tight Curve operation

- Stability in curve

Since one of the goals of this study is to identify suitable CFMEs that can be used in tight curves, the width and height of the devices will need to be evaluated. These parameters are an indication of the Center of Gravity of the device. Any tall and narrow devices will not be considered as viable options due to their increased rollover tendency.

- Ability to operate in both LH and RH curves

The geometry of the CFME must be balanced so that the direction and radius of the curve will not have an effect on the data collected.

Tires

There are approximately 4 different types/sizes of test tires used on CFMEs. Since ODOT has so much history with the LWFT using the ASTM E501 and E524 tires, it is strongly desired to consider the use of these tires on a CFME. It is believed that doing so may aid in the translation or identification of sufficient or insufficient available wet friction of a given surface and requisite friction demand. Either the E501 ribbed tire or the E524 smooth tire could be used on a fixed slip device; however, it is believed that only the E524 tire should be considered on a side force device. This is due to the possibility of the data being affected by the action of the edge of the ribs "catching on" aggregate of surface treatments, such as longitudinal grooving (Kummer, 1966).

Test Tire Location

The test tire(s) must be oriented so it/they will be in the wheelpath while the vehicle travels within the lane.

Ability of device to retain desired parameters

Evaluation of whether the CFME percent slip varies based on method as friction level increases.

7.1.3. Results of Market Survey

The TRC Team performed a market survey of various CFME alternatives with the goal to obtain the following information:

- Supplier
- Product Name
- Operation Principle – The verbiage included comes primarily from the supplier's website, thus it will have a strong marketing tone and is not to be interpreted as part of the research team's evaluation.
- Salient Features – Description of device's features such as data acquisition, water delivery etc. are also taken from the supplier's website.
- Photo of the Device
- Product Website – A link is provided for further review by the reader.
- Assessment – The research team's responses based on the Evaluation Criteria in Sec 7.1.2.

Information for nine (9) candidate devices was obtained during this market review. Based on the information available at the time of this Literature Review, the research team has developed the following summary (Table 11) per the specific Evaluation Criteria of Sec 7.1.2. Legend used to evaluate CFMEs follows:

- "1" – Meets Criteria
- "2" – Meets Criteria Conditionally
- "3" – Fails Criteria
- "N/A" – Not Applicable to the device

Table 11 - Evaluation of CFMEs per established criteria during the Literature Review phase

	Evaluation Criteria				
Devices	**Low Speed**	**Tight Curve**	**Tires**	**Test Tire Location**	**Parameter Design**
Skidometer BV11	1	1	3	3	3
Dynatest HFT	1	1	3	2	1
Dynatest RFT	1	1	3	3	1
Halliday RT3 Flight	1	3	1	3	N/A
Halliday RT3 Curve	1	1	1	1	N/A
Griptester	1	1	3	1	3
PaveCFT	1	1	3	3	N/A
SCRIM Mini	1	1	3	1	N/A
NAC Dynamic Friction Tester	1	3	3	3	3

Based on this summary above, the research team makes the following ranked order recommendations for consideration in this research project to ODOT:

1. Halliday RT3 Curve

The RT3 Curve utilizes the ASTM E524 tire and appears to have the ability to operate in a LH and RH curve. This makes the RT3 Curve a top candidate for the challenges identified in testing at low speeds and in tight curves.

2. SCRIM "mini" equipped with Dual Sided simultaneous capability

Although the SCRIM uses a proprietary tire, like the Halliday, it appears to have the ability to operate in a LH and RH Curve, when equipped with test wheels in both wheelpaths and operated simultaneously.

3. Dynatest Highway Friction Tester (HFT)

Although the HFT does not use either the ASTM E501 or E524 tire, it is deemed a good alternative to the Halliday RT3 Curve. Awareness of vehicle in lane is necessary for validity of data (capturing wheelpath) and lane safety.

In similarity to the LWFT, the HFT uses the same two-axis force transducer and has a similar operating interface.

7.1.4. Supplementary Information about the Halliday RT3 Curve

Supplier	Halliday Technologies Inc.
Product Name	Halliday RT3 Curve
Product Technical Summary	
Operation Principle*	The RT3 Curve is a CFME based on the side force measurement principle. The device measures lateral force applied to a load sensor, experienced by the measuring wheel offset at a small toe-in angle. Due to the setup low toe-in angle, the device can run without water year round without concern for tire degradation. Halliday Technologies claims that the measuring tire can last up to 3,000 miles without replacement. Measuring wheels align with wheel tracks for average vehicle and an offset can be introduced if needed. The design of the device has low number of moving parts enhancing its reliability. The proprietary DAQ software can present data on a graph or present it with overlay from in-built GPS information.
Salient Features*	• RT3 is a CFME based on the side-force principle. • The load sensor captures axial force on measuring wheels experiencing lateral force under constant vertical load. • There are two measuring wheels, which lie on the outside of trailer, collecting data in the wheel tracks. • Design appears to allow for measurement in curves and on straight roads. • The toe-in (skew) angle is typically small (2°) and is adjustable. • Low skew angle allows for RT3 measuring tire to run without a water system, and last for 3000 miles. • When not testing, the measuring wheels retract to minimize wear and tear, improving unit life. • The DAQ software can present data in graph and GPS mode. • GPS mode allows for testing at different locations, over extended distances. • Graph mode allows for testing a single location to capture temporal variation. Each data point contains, data time stamp, friction value, speed, distance, steering, GPS LAT, LON and Heading.

Product Website	https://www.hallidaytech.com/roadway-rt3-curve-friction-tester/
Assessment	Evaluation per Sec 7.1.2: There are two skewed test tires opposing each other and it is anticipated they will compensate for changes in a curve since the decrease in skew angle on one side should be compensated by an increase in skew angle on the other side Evaluation per Sec 7.1.2: ASTM E524 tire is recommended tire for this device Evaluation per Sec 7.1.2:Test tires are located in the wheelpaths Observation(s) • Device suitable for testing at low speeds and likely in curves on public roads. • Water delivery nozzle has laminar flow like LWFT.

7.2. Controlled Environment Test Plan

The research team in consultation with ODOT's TAC chose the Halliday RT3 Curve CFME device for further assessment in a Controlled Environment based on the findings of the Literature Review. The RT3 Curve uses full size tires (typically 15" and 16" rim size) for assessment of pavement friction, one of which is the smooth ASTM E524 Standard Reference Test Tire (SRTT). The RT3 Curve collects friction data in a continuous fashion using the side-force principle. A friction value is generated by the two test tires being skewed at an angle relative to the direction of travel. The forces measured by the load cells at the two test tires are averaged and is referred to as the Halliday Friction Number (HFN).

The research evaluates the RT3 Curve's performance in a laboratory and test-track settings using the custom TRC Inc. designed Controlled Environment Test Plan as a guide. The goal of this assessment is to first establish the RT3 Curve's baseline performance, then determine the effect of changing some key parameters on the device's performance.

The research team determined there were three areas that needed to be investigated to gain a better understanding of the RT3 Curve to assure it was compliant to meet the needs of the ODOT TAC. The three areas were:

1. Tire Contact Patch
2. Horizontal Force vs. Vertical Load Force Assessment
3. Dynamic Testing

The goals of each area were as follows:

<u>Tire Contact Patch</u>

Contact patch of a tire depends on its tire pressure and vertical load. The RT3 Curve uses the E524 smooth test tire under a nominal load of 300 lbs per tire, and at 26 psi tire pressure. The ASTM E274 LWFT uses the E524 smooth test tire under a nominal load of 1,085 lbs per tire, and at 24 psi tire pressure. The contact patch assessment study was designed to evaluate the difference in contact area and contact patch shape observed on the E524 Tire in different operating modes observed. The goal was to define the best tire pressure and vertical load based on results of the contact patch assessment and RT3 Curve's capabilities.

<u>Horizontal Force vs. Vertical Load Force Assessment</u>

As the horizontal force increases due to increased friction of the road surface, it is common for the vertical load to be reduced due to the moment created around the spindle, thus transferring vertical load from the test wheel to the hitch of the device. Therefore, it is important to understand the relationship between the horizontal force and the vertical load as both are used to compute the relative Friction Number. If the vertical force reduces significantly and is not measured dynamically, the calculated Friction Number will have error as the available friction of the road surface increases. The research team designed a test method to capture this variation of vertical load under applied horizontal force setting. This test documented the reduction in vertical load created by the increasing horizontal force.

<u>Dynamic Testing</u>

The intended use of the RT3 Curve is to measure friction in tight curves and at low speeds. The typical roads that meet this type of requirement are Interstate ramps, low speed intersections, and roundabouts. Therefore, this test was designed and executed to evaluate the ability of the RT3 Curve to comply with the following requirements:

1. Does the RT3 Curve measure the same values whether traveling up or down a slope?

2. Does the RT3 Curve measure the same values in a curve regardless of direction of travel (CW vs. CCW)?
3. Does the RT3 Curve measure the same values in a curve as it does on a straight?
4. Does the RT3 Curve have the ability to measure differing friction levels of surfaces repeatedly?

An initial test matrix was developed to confirm the characteristics of the RT3 Curve on controlled surfaces for each set of machine's key parameters. This test matrix (Figure 9) was executed in a controlled environment on TRC Proving Ground facilities.

	Straight		CCW	CW	CCW	CW	Transition (Straight)		Slopes		Water		
Test #	Jennite	Asphalt	Jennite	Jennite	Asphalt	Asphalt	Lo to Hi	Hi to Lo	10%	23%	Onboard	Offboard	Dry
1	X										X		
2			X								X		
3				X							X		
4		X											X
5					X								X
6						X							X
7		X									X		
8					X						X		
9						X					X		
10							X					Jennite	Asphalt
11								X				Jennite	Asphalt
12									Up				X
13									Down				X
14									Up		X		
15									Down		X		
16										Up			X
17										Down			X
18										Up	X		
19										Down	X		

Figure 9 - Image of CFME Test Matrix for Controlled Environment Testing

The following plan (Figure 10) was developed to create a systematic approach to confirming the effect of changing various parameters to see the effect on the results and compliance with the four goals set above:

		Variable Changed												
Tentative Plan		TP	Load	TP	Skew	TP	Load	TP	Water	TP	Skew	TP	Skew Water	TP
Test #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Tire Pressure (psi)	15	18	18	15	15	18	18	15	15	18	18	15	15	18
Weight (pounds)	300	300	400	400	400	400	300	300	300	300	300	300	300	400
Skew Angle (degrees)	2	2	2	2	4	4	4	4	4	4	2	2	Max	Max
Water (mm)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1	0.5	0.5

Figure 10 - Variation of RT3 Curve machine parameters during Controlled Environment Testing

7.3. Controlled Environment Testing Detail and Results

7.3.1. Contact Patch Assessment

This research used the observed tire's contact patch to assess the tire pressure to use for the ASTM E524 tire under RT3 Curve's vertical load conditions. Tire pressure and vertical load were two variables for the study.

Goal

The Contact Path Assessment was designed to achieve the following goals of the research program.

1. Document static contact patch of ASTM E524 tire under RT3 Curve and ASTM E274 LWFT operating conditions.
2. Evaluate effect of two parameters; tire pressure, and vertical load on tire contact patch.
3. Determine values of tire pressure and vertical load parameters, to be used for the CFME during controlled environment performance evaluation.

Apparatus

TRC Inc.'s Force Calibration Plate was used to conduct the contact patch assessment. The figures below demonstrate the apparatus used for contact patch assessment.

Figure 11 – Apparatus used for Contact Patch Testing of the ASTM E524 Tire.

Figure 11, on the left displays the ink applicator device (small paint roller with foam roller cover) used to coat the ASTM E524 tire. Black water-based ink was used for the assessment. An air control valve was used to carefully regulate the air pressure supplied to the axle jack. The jack was slowly lowered to load the tire on the white painted steel plate. Cold tire pressures were set within 1/10th of a psi measured at room temperature, using the Procomp pressure gauge.

Figure 12 – ASTM E524 Tire over Force Plate A) No contact patch, B) With contact patch.

Figure 12 demonstrates the process of developing a tire contact patch. The axle jack placed under the ASTM E274 LWFT is used to raise and lower the axle height and manipulate load through the tire. The steel plate used for contact patch imprint is also shown in the figure.

Method

Table 12 - Data points for ASTM E524 Contact Patch Evaluation

Use Case	Tire Pressure (psi)	Vertical Load per Tire (lbs)
A (LWFT setting)	24	1085
B (Baseline RT3 Curve setting)	26	300
C	26	400
D	15	300
E	15	400
F	18	300
G	18	400

Contact patch for the ASTM E524 tire was captured for various combinations of tire pressure and vertical load as shown in Table 12. The following paragraphs document the methods used for load adjustment, capturing contact patch prints, and measuring area of contact patch.

Method for Load Adjustment and Making Contact Patch Prints

- Setup the ASTM E274 skid system on the force plate.
- Adjust the tire pressure to the desired setting
- Apply ink on the tire using a roller for even application.
- Using an air jack under the trailer axle, lower the tire onto the steel plate until the desired load is achieved and then raise the tire off the plate.

Method to measure area of contact patch imprints

- Mylar graphing paper was used to trace the outline of each contact patch. Each square inch has 100 boxes. The total boxes were counted to measure the area in square inches.

Test Results

The contact patch test results were assessed both subjectively and objectively. In the subjective assessment, the shape of the contact patch was taken into consideration, as it is believed to show the pressure of the tire on the surface across the width of the tread. The objective assessment is designed to document the estimated tire contact patch area for these use cases. Use case A (LWFT) was chosen as a baseline for reference.

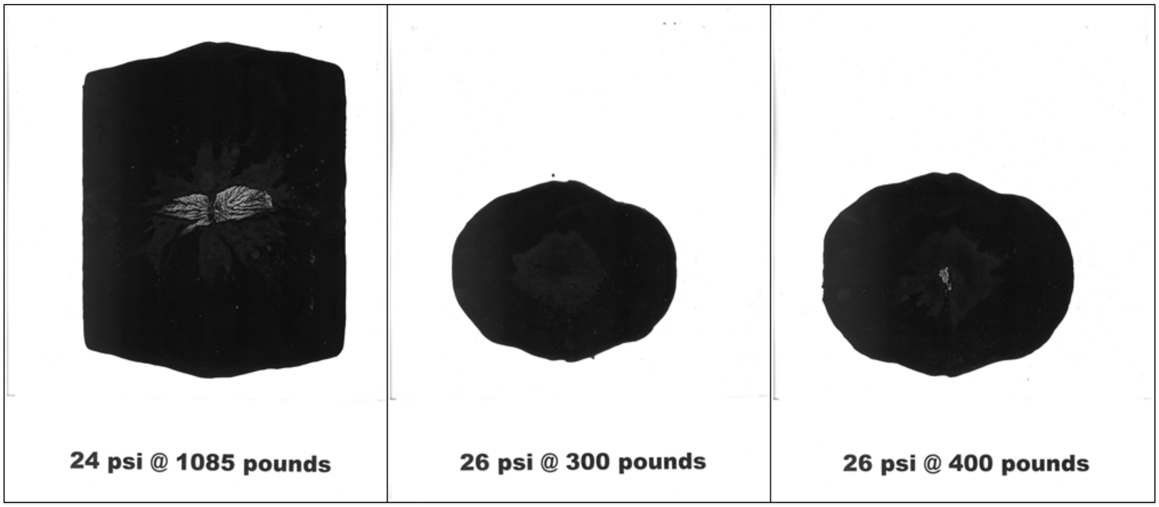

Figure 13 –Contact Patch Imprint of ASTM E524 Tire on Steel Plate at various Tire Pressures and Vertical Loads. Results are for use cases: A) 24psi, 1085lbs, B) 26psi, 300lbs, C) 26psi, 400lbs.

Figure 13 documents the contact patch observed by the ASTM E524 tire under use cases A, B and C. In use case A, a boxed shape of contact patch is observed. This implies that full width of tire is in contact with the steel plate with 24psi tire pressure and 1085lbs load. In use case B and C, the observed shape of contact patch resembles an oval. This implies that full width of the tire is not in contact with the steel plate, with the given tire pressure and vertical load setting.

Figure 14 documents the contact patch imprint for use cases D through G. Contact patch for the two use cases for tire pressure 15 psi and 18 psi are documented. The oval shape of contact patch is dominant when a vertical load of 300 lbs is applied on the tire. The boxed shape of contact patch is observed when the vertical load is increased to 400 lbs, with both tire pressures.

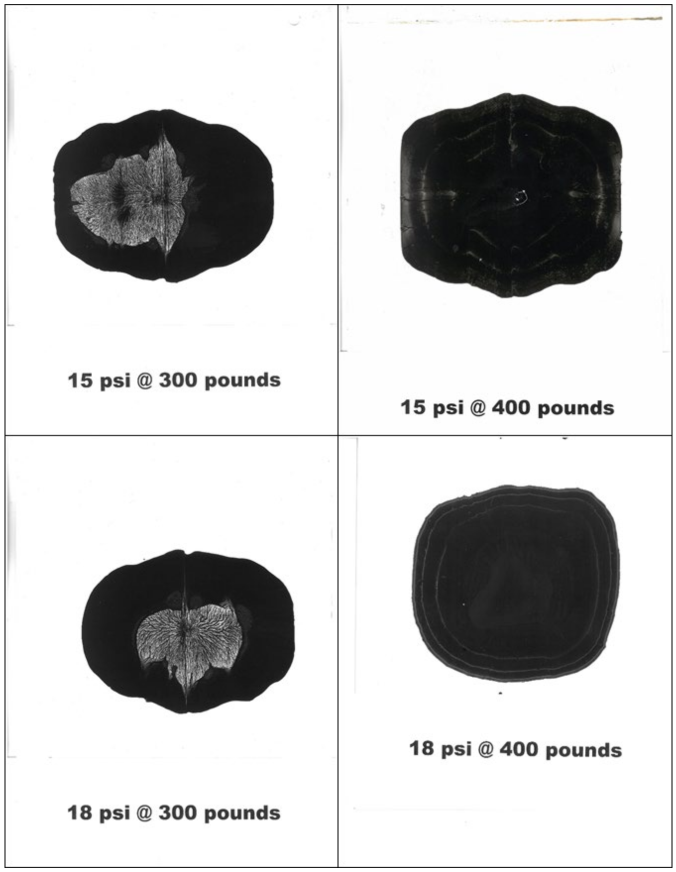

Figure 14 - Contact Patch Imprint of ASTM E524 Tire on Steel Plate at various operating conditions indicated by parameters Tire Pressure and Vertical Load. Results are for use cases: D) 15psi, 300lbs, E) 15psi, 400lbs, F) 18psi, 300lbs, and G) 18psi, 400lbs

It is important to note that the contact patch prints were produced in a static condition with no distortion caused by skew angle. During the dynamic operation, the skew angle of the RT3 Curve will cause the actual contact patch to distort causing the outside edge to lengthen and the inside edge to shorten. It is unknown if the actual area stays the same. In the objective assessment shown in Table 13, the contact patch area measured in use case A is used as a reference, and is normalized to 100%.

Table 13 - Contact Patch Area of ASTM E524 Tire under a variety of load and tire-pressure use-cases

	ASTM E524 Tire Use Case and Contact Patch Performance						
Use Case	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Tire [psi]	24	26	26	15	15	18	18
Load [lbs/tire]	1085	300	400	300	400	300	400
Relative Contact Patch Area [%]	100	39	49	49	62	45	57

Table 14 - Impact of increase in load on change in Contact Patch Area at three tire pressures.

Contact Patch differential performance [% Change]	Constant Tire Pressure @ 15psi	Constant Tire Pressure @ 18psi	Constant Tire Pressure @ 26psi
Increase load by 100lbs [300lbs – 400lbs]	26	27	25

Table 15 - Impact of increase in tire pressure on change in Contact Patch Area at two tire load conditions.

Contact Patch differential performance [% Change]	Tire Load @ 300 lbs/tire	Tire Load @ 400 lbs/tire
Increase tire pressure [15psi to 18psi]	-12	-11
Increase tire pressure [18psi to 26psi]	-14	-16

The ASTM E524 tire is used by the RT3 Curve device with a tire pressure of 26 psi and vertical load of 300 lbs per tire (use-case B). The contact patch observed under this use-case bears an oval shape.

Results indicate that a reduction of tire pressure and an increment in vertical load on the tire, leads to a more uniform contact patch between the tire and pavement. The contact patch appears to have a boxed shape at 18 psi and 400 lbs of vertical load.

A reduction in system tire pressure from 26psi to 15psi at a tire load rating of 300 lbs/tire leads to an increase in contact patch area by 26%. Therefore, initial tire pressure for controlled testing was 15psi and load per tire was 300lbs.

Operation of the device may lead to an increase in tire temperature and hence the tire pressure (set at room temperature). However, this increase may be minimal due to low skew angle of the current RT3 device. Although increasing the tire pressure reduces the contact patch, the dynamic testing showed minimal impact on friction data collected (Table 6).

7.3.2. Horizontal Force vs. Vertical Load Force Assessment

The Force Calibration Plates are a calibrated set of transducers that set on air bearings to produce a near frictionless interface with the floor surface. This allows the horizontal and vertical forces to be accurately measured when the test wheel is locked. They were set up to pull rearward on both test wheels of the RT3 Curve simultaneously. Since the device is not equipped with brakes on the test wheels, the rotation was stopped by inserting a rod though a hole in each wheel and contacting the frame of the device. The horizontal force was slowly applied to both wheels while the corresponding vertical load was measured.

Goal

As the horizontal force increases due to increased friction of the road surface, it is common for the vertical load to be reduced due to the moment created around the spindle, thus transferring vertical load from the test wheel to the hitch of the device. Therefore, it is important to understand the relationship between the horizontal force and the vertical load as both should be used to compute the relative Friction Number. If the vertical force reduces significantly and is not measured dynamically, the calculated Friction Number will have error as the available friction of the road surface increases.

$$Friction\ Number\ (FN) = \frac{F_{horizontal}}{F_{vertical}}$$

This process documented the reduction in vertical load created by the increasing horizontal force.

Apparatus

TRC Inc.'s Force Calibration Plates were used to conduct the force plate assessment. The figure below (Figure 15) demonstrate the apparatus used for force plate assessment.

Figure 15 - Apparatus used for Force Plate Assessment of the RT3 Curve.

Figure 15 shows the RT3 Curve positioned on the Force Plates as described above. The horizontal forces simulating the forces created by the road friction were applied slowly and evenly to each wheel. The corresponding vertical load forces were documented. This process was completed twice, once with 300 pounds of vertical load, and again with 400 pounds of vertical load.

Method for Horizontal Force Adjustment and Vertical Load Assessment

- Each force plate was "floated" (air was supplied to the air bearings and the plates were leveled by adjusting the flow to each of the three air bearing located under each force plate.

- With no horizontal force applied to either test tire, the vertical load was recorded for both test wheels (initial vertical load was nominally 300 pounds for each wheel).
- The steel rod was placed through the test wheel on each side to limit rotation of the test wheel when the horizontal force was applied to the force plate
- The horizontal force was slowly applied to each force plate until five pounds was achieved on each side. The corresponding vertical loads were documented for each test wheel.
- The horizontal forces were slowly increased by five pound increments up to 50 pounds and the corresponding vertical loads were documented.
- The vertical load was increased to a nominal 400 pounds for each test wheel and the process was repeated.

Test Results

The results from the force pull assessment were plotted and are in Figure 16 and Figure 17.

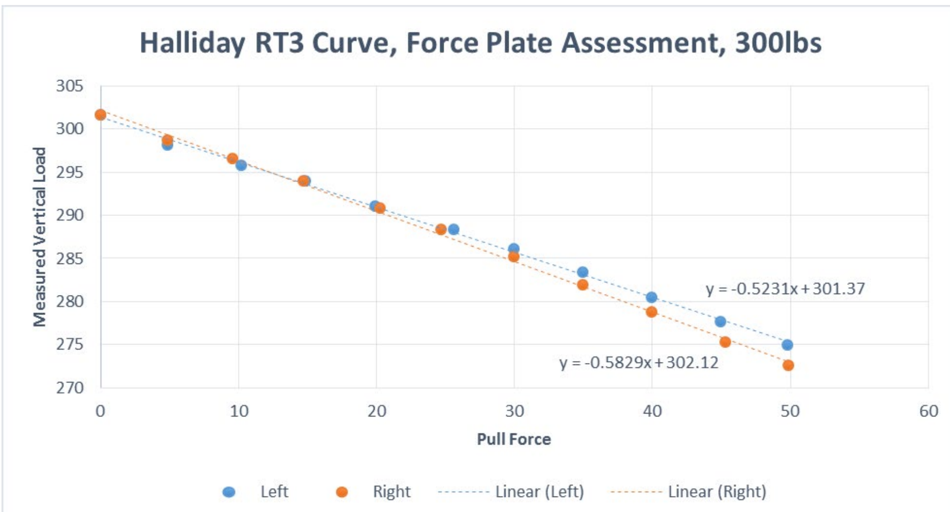

Figure 16 - Impact of change in horizontal force on vertical load for 300lbs of load.

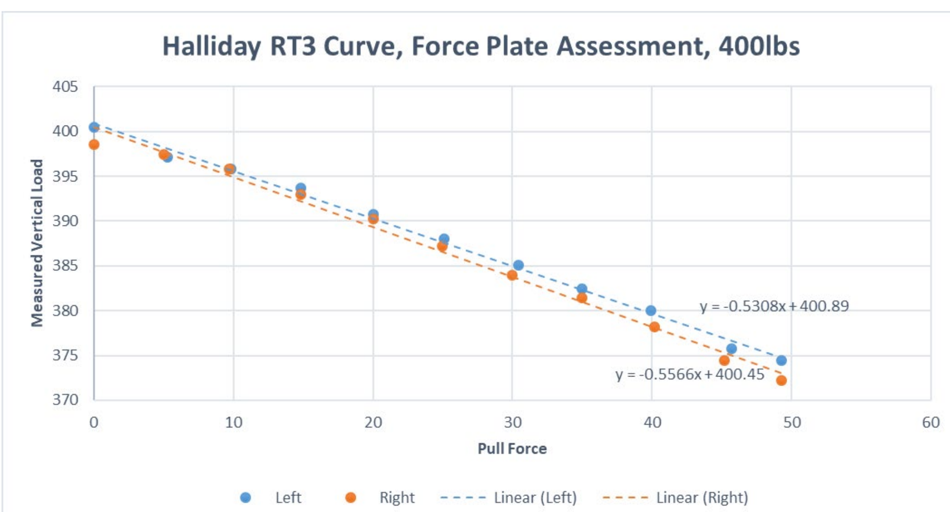

Figure 17 - Impact of change in horizontal force on vertical for 400lbs of load.

The reduction in vertical load is a linear function of the horizontal force applied.

Even though the RT3 Curve does not measure the vertical load at the test wheels, it is not deemed to be an issue due to the nature of how the device measured the force in the horizontal direction.

It is believed that the actual horizontal force in the direction of travel is always relatively low due to the low skew angle; therefore, the reduction in the vertical load is potentially not an issue. However, with a better understanding of the correlation between horizontal force in the direction of travel and the measured, force by the load cell, an adjustment to the vertical load used for the HFN calculation could be made.

7.3.3. Dynamic Testing

The RT3 Curve is a CFME device with a unique design. It is believed to be the only CFME device that uses a full-size tire (15", 16" wheel) as used on the LWFT. The RT3 Curve uses the skew angle to develop a side load corresponding to the available friction of the road surface. The performance of the RT3 Curve was evaluated in controlled environment under a variety of test scenarios and machine parameters. The test plan was developed with due regard to satisfy a DOT's needs and fine-tuned to meet ODOT's needs.

Goal

The intention of the Dynamic Testing was to answer these questions:

1. Does the RT3 Curve measure the same values whether traveling up or down a slope?
2. Does the RT3 Curve measure the same values in a curve regardless of direction of travel (CW vs. CCW)?
3. Does the RT3 Curve measure the same values in a curve as it does on a straight?
4. Does the RT3 Curve have the ability to measure differing friction levels of surfaces repeatedly?

The following parameters are adjustable; skew angle of each test wheel relative to the direction of travel, tire pressure in each tire, wheel load at each wheel, and water thickness. It was unclear the effect varying each of these parameters would have on the results, so each one was considered in the test matrix. A variety of surface friction values will be experienced in the application ODOT has designated. Thus the RT3 Curve was evaluated on a select set of surfaces to facilitate comparison based testing and evaluation that represented the range expected.

Test Approach

A sequence of testing was developed to create scenarios to collect data and gain a better understanding of the effect of each parameter on the 4 primary goals stated above. All testing on the RT3 Curve included in this report was performed at 20 mph, which was the requirement from ODOT. The testing was performed by operating the device as follows:

- Straight Testing
- 150' Radius Curve – Both CW and CCW (150' radius is the minimum design criteria for ODOT ramps, roundabouts[2], etc.)
- Testing on 10% and 23% Slopes – Both Uphill and Downhill

[2] ODOT Location and Design Volume 1 – Sec 503.2.2 Loop Ramp Design Speeds

Testing was performed on three separate surfaces:

1. Jennite – A sealed surface designed to be used with water applied to create a low-mu surface.
2. Wet Asphalt – An unsealed surface with water applied to create the possibility for the test tire to hydroplane and possibly a mid-mu surface.
3. Dry Asphalt – An unsealed surface without water applied to create a high-mu surface.

Four parameters were identified that could be varied to potentially influence the measurements of the device. These parameters were:

1. Tire Pressure – 15 psi, 18 psi, and 26 psi
2. Weight on Test Wheel – Either 300 pounds or 400 pounds on each wheel
3. Skew Angle of the Test Wheels (relative to the direction of travel)– 2°to 8° on each side
4. Water thickness – 0.5 mm or 1.0 mm

The sequence of parametric variation was introduced in Figure 10.

Figure 18 – RT3 Curve being tested on Jennite surface with instrumentation installed.

Test Results

RT3 Curve Baseline Testing

The full test sequence was performed with the following baseline parameter set:

Table 16 - RT3 Curve Parameters: Baseline Testing

Tire Pressure	Vertical Load	Skew Angle	Water Thickness
15 psi	300 pounds	2 degrees	0.5 mm

Testing on Slopes

Table 17 - RT3 Curve Baseline Parameters Test: Performance on Slopes.

Surface	Average Transducer Force (N)			Calculated HFN		
	Uphill	Downhill	% Diff.	Uphill	Downhill	Diff.
10% Slope (Wet)	219	218	0.5	67	67	0
10% Slope (Dry)	250	246	1.6	76	75	1
23% Slope (Wet)	201	206	2.5	62	63	1
23% Slope (Dry)	NA[1]	214	NA[1]	25	65	NA

1 – Data set was corrupted.

The performance in a 23% Slope in the Uphill direction was not validated due to corruption in dataset. However, researchers do not believe there is a cause of concern with the device's performance in slopes.

From this testing (Table 17), it appears that slopes do not affect the device as the values measured from traveling uphill and downhill were very similar. However, more testing should be performed to verify on additional surfaces.

Testing in CW and CCW directions

All testing for this section was conducted on the main VDA surface.

Table 18 – RT3 Curve Baseline Parameters Test: Performance in CW and CCW directions

Surface	Average Transducer Force (N)			Calculated HFN		
	CCW	CW	% Diff.[1]	CCW	CW	Diff.
Jennite (Wet)	77	82	6.6	24	25	1
Asphalt (Wet)	191	183	4.5	59	56	3
Asphalt (Dry)	210	199	5.2	64	61	3

1 – Difference between CW and CCW, with CCW value as baseline.

From this testing (Table 18), it appears the device is not affected by direction of travel through a curve as the values measured from traveling CW and CCW were very similar. However, the relatively high center of gravity of the vehicle coupled with the lateral acceleration created by the speed on this tight radius made it difficult for the driver to maintain the circle comfortably.

Testing in Straight-line vs. Curve for the VDA1 surface.

Table 19 - RT3 Curve Baseline Test: Performance in straight-line vs. in-curve on VDA1 surface

Surfaces	Average Transducer Force (N)			Calculated HFN		
	Straight	Curve	Average Horizontal Force Reduction in Curve vs. Straight [%]	Straight	Curve	Diff.
Jennite (Wet)	115	77	32.9	35	24	11
Asphalt (Wet)	224	191	14.5	69	59	10
Asphalt (Dry)	246	210	14.4	75	64	11

The values measured while testing in a curve (Table 19), regardless of direction of travel (CW or CCW), do not match the values measured while testing on the same surface in a straight. The values in a curve were less than the values from testing in a straight.

Straight-line values on Low Mu surface (Wet Jennite) were on average 33% higher than the values on a 150' radius curve. Straight-line values on High Mu surface (Wet asphalt) were 15% higher than the values on a 150' radius curve.

Ability to Measure Differing Friction Level Surfaces Repeatedly

The RT3 Curve was tested 5 times in a straight line on both Wet Jennite and Wet Asphalt. Table 20 shows results of testing conducted on Wet Jennite using the device.

Table 20 - Repeatability Testing of RT3 Curve on Wet Jennite

Run #	Average Left Force	Average Right Force	Calculated HFN
1	138.54	136.25	42
2	138.5	137.58	42
3	137.45	135.94	42
4	142.59	141.45	43
5	142.74	141.66	43

The following table (Table 21) shows results of testing conducted on Wet Asphalt on VDA1 using the device.

Table 21 - Repeatability Testing of RT3 Curve on Wet Asphalt

Run #	Average Left Force	Average Right Force	Calculated HFN
1	244.31	234.99	73
2	241.25	232.56	72
3	246.86	237.94	74
4	240.15	233.31	72
5	232.29	228.07	70

The average values and standard deviations for each surface are shown in the following table

Table 22 - RT3 Curve Baseline Test: Performance in straight-line across various surfaces.

Surfaces	Force (N)		Calculated HFN	
	Average[1]	Standard Deviation	Average[1]	Standard Deviation
Jennite (Wet)	139.27	2.64	42.4	0.5
Asphalt (Wet)	237.17	4.54	72.2	1.5

As the average values from the two surfaces show, the RT3 Curve appears capable of differentiating between different surfaces, and the low standard deviations reflect on the devices repeatability.

Shift in Test Program Focus

Analysis of performance of the RT3 Curve suggests that the friction values measured in curve vs. straight-line tests conducted on the same surface do not match. The TRC team in consultation with the ODOT TAC staff shifted the focus of the research program to understand the behavior in a curve. The initial adaptation was to utilize the concentric circles on the VDA surface. This allowed for testing in curves much greater than the originally specified 150' radius to better understand the impact of the curve on the data. Because the circles on the original VDA have been used to varying degrees over the years, there was some concern that conditioning of the pavement may be different than the section used to measure the straight-line data used for comparison. Fortunately, there was a new test facility (VDA2) that had recently been completed that assured uniform pavement texture and homogeneous surface. Corresponding radii were established with safety cones and testing was repeated there to confirm the results.

The concentric test circles on the VDA and VDA-2 bear the radii documented in Table 23.

Table 23 - List of concentric circle radii available for testing at TRC Proving Grounds

Location: Surface	Concentric Test Circle Radii
VDA: Asphalt	[500’, 400’, 300’, 230’, 200’, 150’]
VDA-2: Asphalt	[300’, 250’, 200’, 150’]

Figure 19 - Testing on Concentric Circles on VDA-1: Asphalt

The test scenario was run under a variety of strategically chosen machine conditions, listed below:

1. Dry and wet condition
2. Change in Vertical Load on Tire (from 300 lbs/tire to 400 lbs/tire)
3. Change in Tire Pressure (15psi to 18psi)

The intent of testing different conditions was to see if aby of these variables affected the phenomena of decreasing HFN values in a curve verses a straight.

The following sections outline performance of the device under the decreasing radii circles.

Concentric Circles Testing

Baseline Testing in Dry and Wet Condition

The focused test sequence was performed with the following baseline parameter set:

Table 24 - RT3 Curve Baseline Parameters: Concentric circles test

Tire Pressure	Vertical Load	Skew Angle	Water Thickness
15 psi	300 pounds	2 degrees	0.5 mm

The RT3 Curve was positioned on the 500’ radius circle on the VDA. The vehicle was accelerated to 20 mph and traveled just outside the line for the remainder of the lap. The driver increased the input on the steering wheel to travel to the 400’ radius circle and maintained for the remainder of the lap. This was repeated until all the remaining circles were tested including the 150’ radius circle. The straight-line data was collected on the same surface.

The physical dimensions of VDA2 are smaller and did not allow for full circles, thus half circles were marked out with safety cones for the radii shown in the tables. Data was collected at 20 mph for each pass. The straight-line data was collected on the same surface.

Table 25 - Testing on VDA1: Asphalt with Baseline Parameters

Machine Parameter - Water Condition	Curve Radius (CCW direction) on VDA: Asphalt	Average Horizontal Force Reduction in Curve vs. Straight [%]	Difference from Straight Average [%]	
			Left Wheel	Right Wheel
DRY	500’	-2	-5	0
	400’	-4	-8	0
	300’	-6	-13	1
	230’	-10	-23	3
	200’	-10	-23	3
	150’	-15	-32	2
WET	500’	-8	-11	-4
	400’	-10	-15	-5
	300’	-10	-18	-2
	230’	-12	-23	-1
	200’	-14	-29	0
	150’	-25	-45	-5

Testing the VDA (Table 25) on circles up to a 500’ still showed a reduction in the values compared to the straight-line data. Wet testing condition had a greater disparity. The table above shows the difference from straight-line for both the left and right wheel. It should be noted that regardless of the radii, the right wheel (outside for CCW direction / Left Turn) showed marginal change relative to the straight-line value. However, the left wheel (inside for CCW direction / Left Turn) shows a significant drop in the forces and increases as the radius decreases.

Table 26 - Testing on VDA-2: Asphalt with Baseline Parameters

Machine Parameter - Water Condition	Curve Radius (CCW direction) on VDA-2: Asphalt	Average Horizontal Force Reduction in Curve vs. Straight [%]	Difference from Straight Average [%]	
			Left Wheel	Right Wheel
DRY	300’	-9	-18	0
	250’	-8	-20	4
	200’	-11	-26	5
	150’	-16	-35	4
WET	300’	-7	-15	2
	250’	-6	-16	4
	200’	-6	-18	6
	150’	-11	-27	5

The testing on VDA2 (Table 26) confirmed the reduction in force on the inside wheel, although not to the same extent overall. This seems to be because the outside wheel did a better job of compensating for the loss of friction on the inside wheel. It was interesting to see that the dry testing yielded a slightly higher difference than the wet testing this time. The pavement was very new and a different mix than the VDA.

This testing confirmed that there is a reduction in the average force value form the RT3 Curve in a curve relative to a straight. This reduction is present on a 500’ radius curve although the condition increases as the radius decreases. In all cases, the inside wheel loses force and the outside wheel does not increase enough to compensate.

<u>Testing w/ Increased Load on Tire</u>

The focused test sequence was performed with the following parameter set (Table 27)

Table 27 – RT3 Curve Increased Load on Tire: Concentric circles test

Tire Pressure	Vertical Load	Skew Angle	Water Thickness
15 psi	400 lbs	2 degrees	0.5 mm

Table 28 - Testing on VDA: Asphalt with increased load to 400 lbs/tire.

Machine Parameter	Curve Radius (CCW direction) on VDA: Asphalt	Average Horizontal Force Reduction in Curve vs. Straight [%]	Difference from Straight Average [%]	
			Left Wheel	Right Wheel
DRY	500’	-1	-3	1
	400’	-2	-7	2
	300’	-4	-11	3
	230’	-6	-16	4
	200’	-8	-21	6
	150’	-12	-31	6
WET	500’	-5	-8	-2
	400’	-6	-11	-1
	300’	-8	-17	1
	230’	-10	-23	3
	200’	-11	-26	4
	150’	-19	-40	2

Adding 100 pounds to each wheel did not appear to have an appreciable effect on the results as the values in the table above a similar to the values in the Table 25.

Testing w/ Increased Tire Pressure

The focused test sequence was performed with the following parameter set:

Table 29 - RT3 Curve w/ Increased Tire Pressure: Concentric circles test

Tire Pressure	Vertical Load	Skew Angle	Water Thickness
18 psi	400 lbs	2 degrees	0.5 mm

Table 30 - Testing on VDA: Asphalt with Increased Tire Pressure 18 psi.

Machine Parameter	Curve Radius (CCW direction) on VDA: Asphalt	Average Horizontal Force Reduction in Curve vs. Straight [%]	Difference from Straight Average [%]	
			Left Wheel	Right Wheel
DRY	500’	-3	-5	0
	400’	-4	-9	1
	300’	-6	-14	2
	230’	-9	-20	3
	200’	-9	-22	4
	150’	-15	-33	4
WET	500’	-6	-10	-2
	400’	-9	-15	-2
	300’	-9	-19	0
	230’	-11	-24	2
	200’	-13	-28	3
	150’	-19	-39	1

Adding 3 psi to each tire did not appear to have an appreciable effect on the results as the values in the table above a similar to the values in the Table 25 and Table 28.

Further Approach and Results

Upon learning that the friction values measured by the RT3 Curve on a 150’ radius were lower than when testing on the same surface in a straight, and the concentric circles verified the trend, all further testing focused on how various parameters affected this characteristic. Thus, parameters were either extended or added to see if any of them affected this phenomena. The rest of the testing was only performed on 150’ radius circle and straight, and only with water. Following are descriptions of the testing performed and the corresponding results.

Tire Pressure Range Extended

Although previous testing had compared results between 15 psi and 18 psi with no apparent change in the results between testing in a curve and straight line values, further testing was performed comparing results at both 15 psi and 26 psi. It is known that the contact patch shape and area are significantly different at these two pressures; however, this testing was to confirm that reducing the tire pressure from 26 psi (RT3 Curves recommended tire pressure) to 15 psi had not caused this issue to occur. Following is the comparison:

Table 31 – Baseline Performance of RT3 Curve with the device at 15psi, 2deg skew, with yaw dampers on.

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	128.71	130.71	40
	CCW	56.36	141.83	30
	CW	143.56	29.36	26
Asphalt (Wet)	Straight	268.99	247.99	79
	CCW	185.67	253.62	67
	CW	241.35	132.05	57

Table 32 - Performance of RT3 Curve with the device at 26psi tire pressure.

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	136.34	137.08	0.42
	CCW	54.16	143.43	0.30
	CW	142.50	38.13	0.28
Asphalt (Wet)	Straight	259.18	242.93	0.77
	CCW	162.11	247.57	0.63
	CW	240.23	131.82	0.57

From this data, it is clear that even with an increase in tire pressure from 15 psi to 26 psi (73% increase) the HFN values measured in a curve were still less than those measured in a straight. This also should remove any concern about the potential increase in tire pressure as a result of heat buildup having an effect on the HFN values.

Effect of Yaw Dampers

The RT3 Curve is equipped with adjustable dampers that mount from the tongue to the front beam at the pivot point to control sway, especially on surfaces that have varying friction values. Testing was performed with and without the dampers to confirm if they had any effect on the difference in values between a curve and a straight. Following is the data comparing the two configurations:

The following tables outline performance of the RT3 Curve device with and without the yaw dampers. Both tables are with the device at 2deg skew angle, using an E-524 tire over both Jennite and Asphalt surfaces.

Table 33 - Performance of the RT3 Curve with yaw dampers connected.

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	128.71	130.71	40
	CCW	56.36	141.83	30
	CW	143.56	29.36	26
Asphalt (Wet)	Straight	268.99	247.99	79
	CCW	185.67	253.62	67
	CW	241.35	132.05	57

Table 34 - Performance of the RT3 Curve with yaw dampers removed.

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	138.02	138.69	42
	CCW	49.77	143.24	29
	CW	145.47	38.66	28
Asphalt (Wet)	Straight	254.55	238.54	75
	CCW	147.20	233.43	58
	CW	225.48	119.30	53

From this data, it is clear that the dampers did not have any effect on the HFN values measured in a curve being less than those measured in a straight.

Effect of the Test Tire

All testing had been performed with the ASTM E524 smooth test tire (as preferred by the original testing request from ODOT). To assure this tire was not the cause of the issue of measuring a lower HFN in a curve than in a straight, a 17” radial tire was installed and testing was repeated. Following is the data comparing the two tires:

The E-524 tire at 15psi was swapped with a 17” radial tire also at 15psi. Results are tabulated below for comparison. It is noted that both in both datasets the machine was at 2deg skew angle, with yaw dampers on.

Table 35 - Performance of the RT3 Curve device with E-524 test tire

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	128.71	130.71	40
	CCW	56.36	141.83	30
	CW	143.56	29.36	26
Asphalt (Wet)	Straight	268.99	247.99	79
	CCW	185.67	253.62	67
	CW	241.35	132.05	57

Table 36 - Performance of the RT3 Curve device with a 17" Radial Tire

Surface	Maneuver	Average Force Left (lbs)	Average Force Right (lbs)	Average HFN
Jennite (Wet)	Straight	177.75	180.58	55
	CCW	91.64	189.23	43
	CW	191.02	88.35	43
Asphalt (Wet)	Straight	246.91	235.57	74
	CCW	158.57	245.71	62
	CW	250.47	132.00	58

From this data, it is clear that the ASTM E524 tire did not have any effect on the HFN values measured in a curve being less than those measured in a straight.

Transition Testing

Testing was performed to better understand the dynamics of this condition. In this testing, the vehicle was accelerated in a straight line and recording was initiated. After allowing the vehicle to stabilize at speed, a steering input was initiated to transition to a 500' radius curve. After approximately 2 seconds, a steering input was initiated to transition to a 150' radius curve.

From this testing, it was found that a 500' radius curve had minimal effect on the HFN; however, once the steering wheel was turned to reduce the radius, the HFN began to be affected and was reduced. On the vehicle tested, the steering angle should not exceed 30 degrees or the average HFN will be affected. The graphs below show that as the steering angle increases, as would happen when traversing through a curve, the HFN decreases. Additionally, corresponding graphs with each load cell data are included to show that the inside wheel drops in value while the outside wheel stays nearly the same or increases slightly.

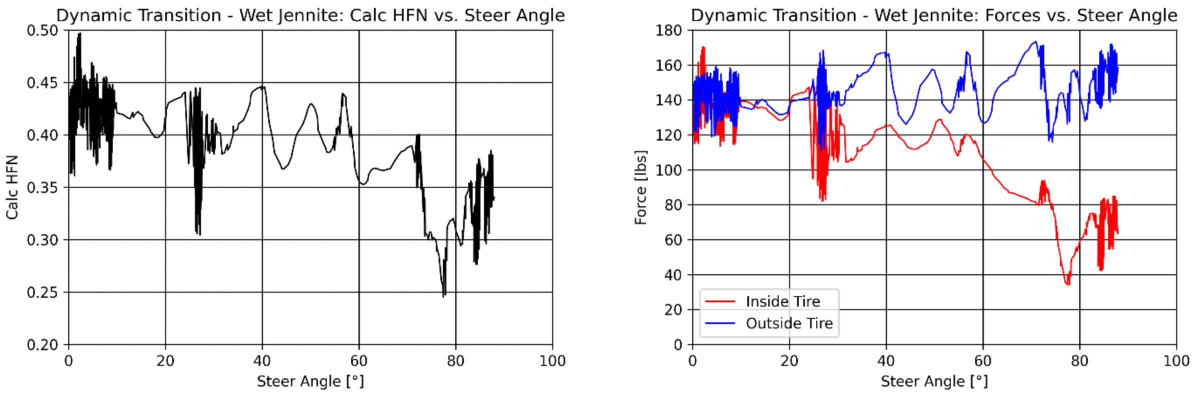

Figure 20 - Summary of Results of Dynamic Testing on Wet Jennite.

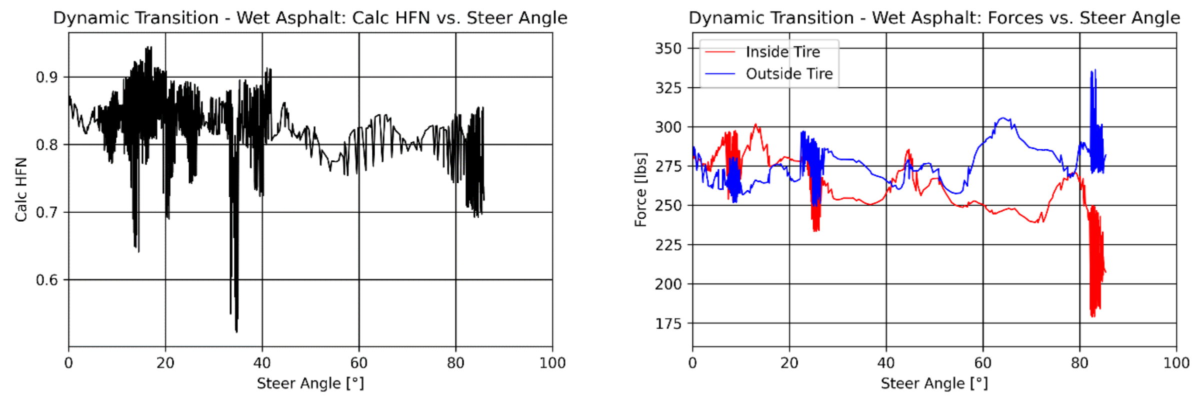

Figure 21 - Summary of Results of Dynamic Testing on Wet Asphalt.

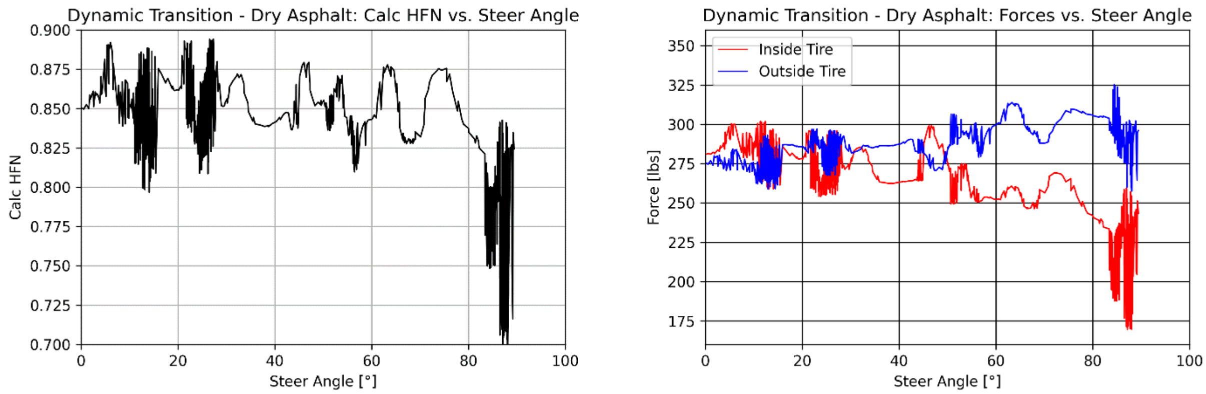

Figure 22 - Summary of Results of Dynamic Testing on Dry Asphalt.

It was found that as the device transitions from straight to a curve, the inside wheel friction value decreases at a faster rate than the outside wheel increases, thus the average value decreases. It seems this indicates that the inside wheel is seeing less friction due to the tire becoming more in line with the direction of travel and thus the effective skew angle decreases. The arc the outside tire travels is apparently not causing the effective skew angle to increase much over straight-line condition.

<u>LWFT Results</u>

The Locked Wheel Friction Tester has been used by ODOT for decades to measure the pavement’s available friction and as a result, ODOT has confidence in the values measured by the LWFT to represent the available friction as it relates to both microtexture and macrotexture by using both the ASTM E501 rib tire and the E524 smooth tire. Therefore, it was intended to measure the surfaces used for the evaluation of the RT3 Curve with the LWFT to document the conditions of the surfaces and know how they relate to roads traveled by the public. This testing was planned at 40 mph and straight only. However, it was decided to evaluate the capabilities of the LWFT in a curve at both 40 mph and 20 mph. It is commonly known that surfaces have a speed gradient resulting in higher friction values on the same surface as the speed is decreased. Therefore, an evaluation of speed gradient was also considered. Following is a description of how the LWFT was used to test and document its capabilities and the surface characteristics:

- Smooth Tire and Rib Tire – Both tires are typically used by ODOT on the LWFT and provides different information about texture.
- 40 mph and 20 mph Straight-line Testing – To better understand the speed gradient on all surfaces with both tires.
- 150’ radius at 20 mph, and 300’ radius at 40 mph – Although the 150’ radius at 20 mph has been the test parameter being used for evaluation of the proposed CFME, the 300 ft radius is a fair representation of testing that has been performed by ODOT on ramps at 40 mph. This will help validate any previous testing conducted with the LWFT device.
- Wet Jennite, Wet Asphalt VDA, Wet Asphalt VDA2 - These three surfaces have been used for the Dynamic Testing performed at TRC.

Following is the data collected on each surface with the smooth tire:

Table 37 - Tabulated LWFT performance on Jennite surface with Smooth Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	22.3	20.5	20.1	27.4	33.9	28.4
2	22.8	22.6	18.6	27.2	32.2	25.6
3	19.5	21.4	19.9	25.1	31.8	25.6
4	25.2	20.1	19.5	28.1	30.0	27.5
5	22.1	23.2	18.7	28.9	27.8	27.1
6	17.8	20.4	23.8	30.0	31.8	26.6
7	18.4	19.8	19.3	29.0	30.3	26.9
8	25.4	21.2	20.5	27.4	30.2	27.7
9	20.9	20.5	20	24.6	31.2	26.2
10	20.3	21.2	19.8	28.1	30.2	27.0
Avg.	**21.5**	**21.1**	**20.0**	**27.6**	**30.9**	**26.9**
St. Dev.	2.60	1.09	1.46	1.68	1.64	0.90

Table 38 - Tabulated LWFT performance on Wet Asphalt surface with Smooth Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	66.0	70.3	60	83.9	83.7	84.6
2	63.6	69	60.5	85.4	86.2	86.4
3	61.8	75.2	66.3	87.7	86.0	86.2
4	63.8	71.7	61.7	87.6	84.2	84.4
5	61.8	70.3	63.2	84.5	87.2	84.7
6	60.4	68.1	60.3	84.3	88.8	86.4
7	61.2	71.7	67.0	82.7	88.0	85.2
8	67.8	73.7	66.3	83.5	85.7	84.8
9	66.7	68.7	63.2	86.3	85.0	85.3
10	60.6	67.1	61.2	84.5	87.7	83.1
Avg.	63.4	70.6	63.0	85.0	86.3	85.1
St. Dev.	2.67	2.54	2.69	1.69	1.67	1.03

Table 39 - Tabulated LWFT performance on Wet Asphalt VDA2 surface with Smooth Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	76.6	75.5	70.9	86.8	89.4	86.3
2	77.0	76.3	70.1	87.2	89.4	87.7
3	78.6	76.4	69.9	88.0	85.4	86.3
4	78.6	77.4	70.5	89.3	85.1	84.6
5	79.6	73.0	73.7	85.3	90.9	83.7
6	73.6	74.5	70.6	83.6	90.8	85.7
7	71.3	78.0	73.3	90.3	91.1	87.6
8	72.0	78.0	72.0	87.2	87.6	84.5
9	73.5	79.1	70.7	86.0	92.7	89.0
10	75.3	78.5	70.5	91.0	90.0	86.2
Avg.	75.6	76.7	71.2	87.5	89.2	86.2
St. Dev.	2.92	1.92	1.33	2.27	2.49	1.63

Following is the data collected on each surface with the rib tire:

Table 40 - Tabulated LWFT performance on Jennite surface with a Ribbed Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	27.7	30.9	26.6	34.3	37.2	36.2
2	28.2	31.9	26.6	34.4	36.0	34.5
3	28.6	28.6	25.7	36.5	40.5	35.4
4	28.8	30.8	28	35.2	36.1	36.2
5	28.4	29.9	26.9	36.7	34.5	35.7
6	28.4	31.7	25.9	31.4	40.1	33.5
7	25.2	31.6	27.1	34.1	33.7	34.8
8	26.0	32.1	25.7	35.4	36.2	35.5
9	31.2	28.8	25	35.0	36.2	39.8
10	28.1	32.8	24.6	32.7	36.0	35.3
Avg.	28.1	30.9	26.2	34.6	36.7	35.7
St. Dev.	1.62	1.41	1.02	1.61	2.16	1.66

Table 41 - Tabulated LWFT performance on Wet Asphalt surface with Ribbed Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	73.0	76.2	72.2	82.3	86.7	84.1
2	79.7	76.2	73.5	87.6	85.2	82.9
3	77.0	75.5	74.4	87.3	88.4	83.3
4	79.1	81.0	77.5	80.0	90.4	85.0
5	70.4	77.1	73.2	85.3	93.6	86.2
6	74.9	75.1	73.6	84.9	88.5	78.3
7	79.3	72.8	76.3	83.5	93.8	82.8
8	70.9	76.1	77.6	87.0	85.0	85.2
9	70.6	80.6	75.5	84.0	87.7	84.1
10	72.4	76.4	74.0	87.5	91.8	80.2
Avg.	74.7	76.7	74.8	84.9	89.1	83.2
St. Dev.	3.78	2.45	1.86	2.54	3.20	2.38

Table 42 - Tabulated LWFT performance on Wet Asphalt VDA2 surface with Smooth Tire.

Speed	40 mph			20 mph		
Mode	**Straight**	**300 L**	**300 R**	**Straight**	**150 L**	**150 R**
1	77.0	82.7	75.6	82.5	85.2	78.6
2	81.9	82.0	76.5	81.3	86.7	81.3
3	80.0	84.3	74.6	83.6	83.3	81.4
4	80.3	78.6	75.3	83.3	82.4	82.1
5	79.8	76.5	78.1	79.7	85.2	80.0
6	78.0	82.3	72.3	83.3	89.3	82.8
7	76.5	81.4	76.1	82.7	80.7	82.5
8	74.8	79.0	73.1	82.3	87.7	77.6
9	83.5	80.9	78.9	83.7	79.8	84.2
10	79.9	81.7	75.5	80.8	82.5	84.5
Avg.	79.2	80.9	75.6	82.3	84.3	81.5
St. Dev.	2.61	2.29	2.01	1.33	3.07	2.24

A summary of the data collected on the three surfaces with both tires follows:

Table 43 - Speed and Curve Gradient data for LWFT using Smooth Tires.

Surface	Speed (Straight) 40 to 20	Curve Gradient vs. Straight Smooth (Values)				Speed (Straight) 40 to 20 [%]	Curve Gradient vs. Straight Smooth (%)			
		300’ @ 40mph		150’ @ 20mph			300’ @ 40mph		150’ @ 20mph	
		Left	Right	Left	Right		Left	Right	Left	Right
Jennite	6.1	-0.4	-1.5	3.4	-0.7	28	-2	-7	12	-3
Asphalt	21.7	7.2	-0.4	1.2	0.1	34	11	-1	1	0
VDA2	11.9	1.1	-4.4	1.8	-1.3	16	1	-6	2	-1

Table 44 - Speed Gradient data for LWFT using Ribbed Tires.

Surface	Speed (Straight) 40 to 20	Curve Gradient vs. Straight Ribbed (Values)				Speed (Straight) 40 to 20 [%]	Curve Gradient vs. Straight Ribbed (%)			
		300’ @ 40mph		150’ @ 20mph			300’ @ 40mph		150’ @ 20mph	
		Left	Right	Left	Right		Left	Right	Left	Right
Jennite	6.5	2.9	-1.8	2.1	1.1	23	10	-7	6	3
Asphalt	10.2	2.0	0.1	4.2	-1.7	14	3	0	5	-2
VDA2	3.2	1.8	-3.6	2.0	-0.8	4	2	-5	2	-1

When combining the data collected on all three surfaces by the LWFT we have the following combined values:

Table 45 - Summary of LWFT performance with smooth and ribbed tires in straight line and on two curves

Tires	Speed Gradient (Straight) 40 to 20	Curve Gradient vs. Straight 300' radius @ 40 mph		Curve Gradient vs. Straight 150' radius @ 20 mph	
		Left	Right	Left	Right
Smooth	13.2	2.6	-2.1	2.1	-0.7
Rib	6.6	2.2	-1.8	2.7	-0.5
Overall	9.9	2.4	-1.9	2.4	-0.6

The same data calculated as percentages are as follows:

Table 46 - Summary of LWFT performance with smooth and ribbed tires in straight line and on two curves, in percentage format.

	Speed Gradient (Straight) 40 to 20	Curve Gradient vs. Straight 300' radius @ 40 mph [%]		Curve Gradient vs. Straight 150' radius @ 20 mph [%]	
		Left	Right	Left	Right
Smooth	26%	4	-4	5	-1
Rib	14%	5	-4	4	0
Overall	20%	4	-4	5	-1

In an attempt to compare testing performed by both the RT3 Curve and the LWFT, the following table was created from data collected with the smooth tire at 20 mph on the 150' radius:

Table 47 –Comparison between LWFT and RT3 Curve performance under applicable operating conditions.

	Curve Gradient vs. Straight 150' radius @ 20 mph [%]			
	RT3 Curve		LWFT	
	Left	Right	Left	Right
Jennite	-33	-29	12	-3
Asphalt	-25	-19	1	0
VDA2	-11	NA	2	-1

8. Appendix - B

8.1. Instrumentation on RT3 Curve Device

Instrumentation was installed on the RT3 Curve to objectively evaluate the various parameters in regard to the stated goals.

- Ride Height Sensors were installed at the test wheels to measure change in axle height relative to the test surface.
- Specially designed tone rings were installed on the test wheels and pulse sensors were installed to measure speeds of each test wheel.
- String Potentiometers were installed to measure the relative distance between the truck and the trailer.
- Temperature sensors were installed to monitor the tire temperatures during testing.
- Cameras were installed on the trailer swingarm to monitor the tire to road interface, on the truck tailgate to monitor the action of the trailer behind the truck, and inside the cab to monitor the Halliday display console.
- Splicing harnesses were installed in the cab of the truck to tie into the signals from each of the RT3 Curve load cells to measure the side forces.
- Splicing harnesses were installed in the cab of the truck to tie into the speed signals from each of the load cells to measure the wheel speeds (to compare with the values from the tone rings and pulse speed sensors, although with much less resolution).
- A splicing harness was installed in the cab of the truck to measure the steering wheel position.

Figure 23 - Halliday RT3 Curve Control and User Interface Console

Figure 24 - TRC Inc. installed wheel speed and ride height sensors on RT3 Curve

Figure 25 - TRC Inc. installed string potentiometer on the RT3 Curve device.

Figure 26 - Temperature sensor

Figure 27 - Tailgate camera installed on the truck to provide rearward view

Figure 28 - Tire sidewall camera installed on the RT3 Curve device

Figure 29 - In-cab camera