Pavement Roughness Measurement Using Android Smartphones: Case Study of Missouri Roads and Airports

Prepared by
William G. Buttlar, Ph. D, P.E.
Amir Alavi, Ph. D
Henry Brown, P. E.
Graduate Students: Henry Sills, Amanda Mesa, Elizabeth Okenfuss
University of Missouri-Columbia and Applied Research Associates, Inc.

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16. Abstract

Keeping airport pavement in good condition requires accurate and timely data on existing pavement conditions. Since many existing pavement survey methods can be costly and labor intensive, there is a need for simple and low cost tools to facilitate the evaluation of airport pavement condition for smaller airports with limited resources. To address this need, a study was undertaken to evaluate an android smartphone application for use in assessing airport pavement condition. To perform this evaluation, an initial validation study was performed on two sections of I-70 in central Missouri. The smartphone application was utilized to collect IRI data for all 27 of the state funded general aviation airports in Missouri. The data were then analyzed and compared with the construction and maintenance records for the airports. The study found that the smartphone application (app) has the potential to be an effective low cost tool for assessing airport pavement condition. The smartphone estimated IRI values were close to those measured by ARAN. The measured IRI data classified most of the test sections in agreement with MAP-21 requirements. The obtained trends agreed well with the construction and maintenance records of the airports. An equation was developed to predict PCI based on the IRI values measured from the smartphone application. Future enhancements to the research could include the use of more vehicles and smartphones and the use of aircraft cab acceleration data. An improved graphical-user interface (GUI) should be developed for transfer of the app to airport managers.

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A Final Report

presented to

Missouri Department of Transportation

by the University of Missouri-Columbia

by

William G. Buttlar, Ph. D, P.E.

Amir Alavi, Ph. D

Henry Brown, P. E.

Henry Sills

Amanda Mesa

Elizabeth Okenfuss

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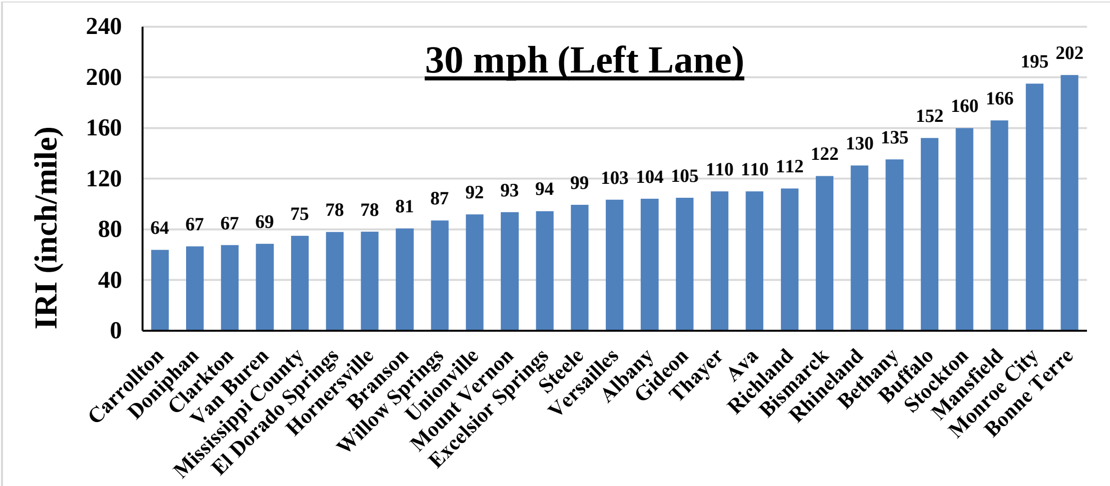
EXECUTIVE SUMMARY

Although obtaining data regarding existing airport pavement condition is an essential task for pavement maintenance, pavement condition surveys can be costly and labor intensive. The objective of this study was to investigate the use of an android smartphone application as a potential low cost and efficient tool to assess airport pavement condition. The smartphone application (app) records vehicle cab acceleration data, a timestamp, and GPS coordinates. The approximate pavement profile is then back-estimated from the acceleration data using an inverse state space model. The model considers the physics of the mass-spring-damper system of the vehicle sprung mass. The analyses were performed using a MATLAB script to calculate the IRI values.

The initial phase of this study focused on the validation of this monitoring technology for pavements in Missouri. To this end, the smartphone-measured IRI values were obtained for test sections of I-70 near Columbia, MO and compared with known IRI values measured by MoDOT's Automatic Road Analyzer (ARAN) van. The validation showed that the smartphone application performed well in estimating the IRI of the test sections. The measured IRI data accurately classified the pavement condition based on MAP-21 requirements.

In the second phase, the proposed technology was implemented to determine the IRI values at Missouri Airports. First, a calibration study was performed on a designated test section of MO-10E near Excelsior Springs, Missouri to find the optimal model parameters. Then, the smartphone application was used to collect acceleration data for airport pavements at the 27 state funded general aviation airports in Missouri. Each test run was conducted multiple times over right, centerline and left lanes of the airfield pavements. Finally, an extensive analysis was performed to calculate the IRI values for the airports. In order to reduce the uncertainties, only one smartphone model (Samsung Galaxy S8), one type of smartphone car mount, and one vehicle type (SUV) was used for data collection through the entire project.

Figures ES.1 and ES.2 show the ranking of the airports based on their pavement roughness for 30 and 40 mph speeds, respectively. It was observed that the IRI values ranged from 47 to 280 for the airfield pavements. Among the investigated airports, Bollinger-Crass Memorial Airport in Van Buren with an average IRI equal to 59 inch/mile was found to be in very good condition. Bonne Terre Municipal Airport pavement was found to have the highest roughness, with an average IRI of 227 inch/mile on the centerline lane. The remaining airports were classified as follows with respect to pavement condition assessed via the smartphone app: 10 airports in good condition, 13 airports in fair condition, and 2 airports in poor condition.



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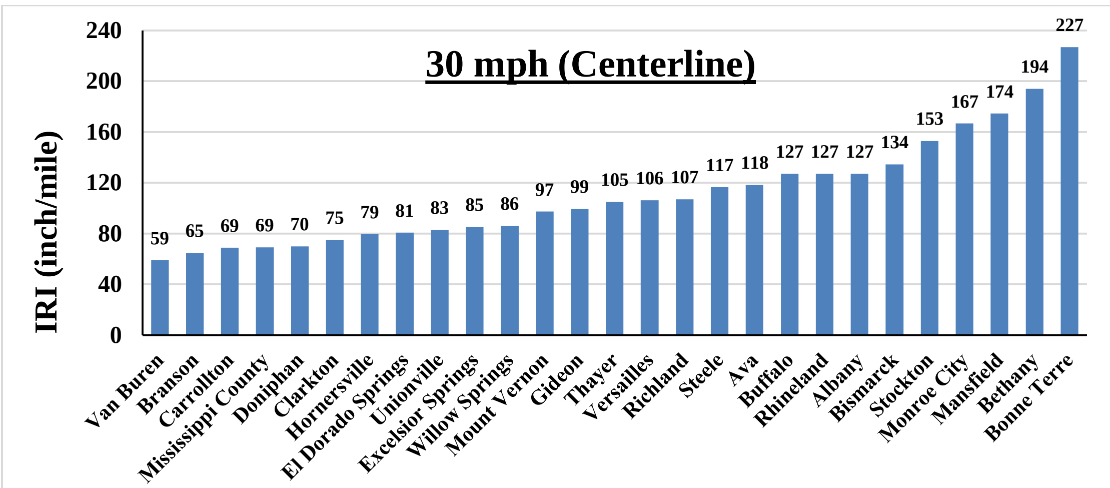

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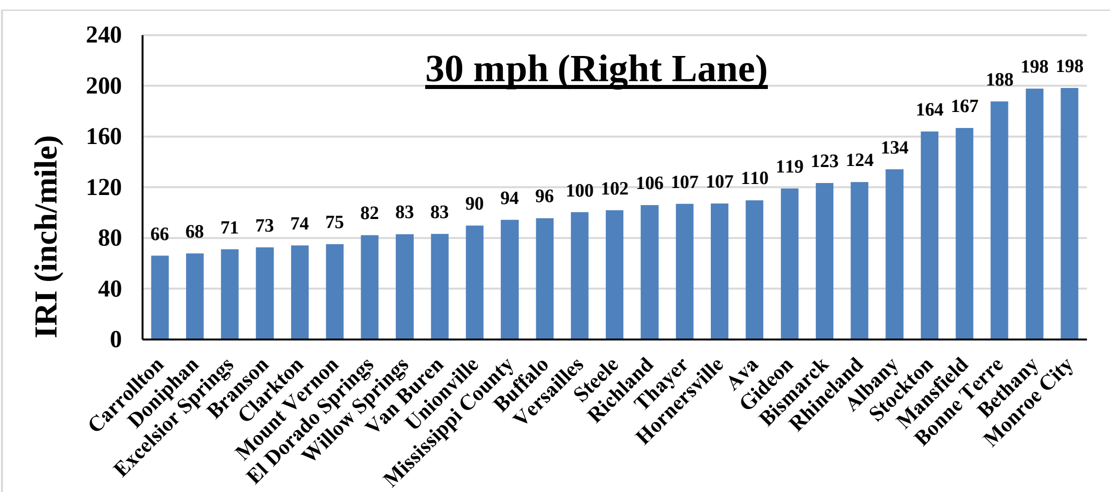

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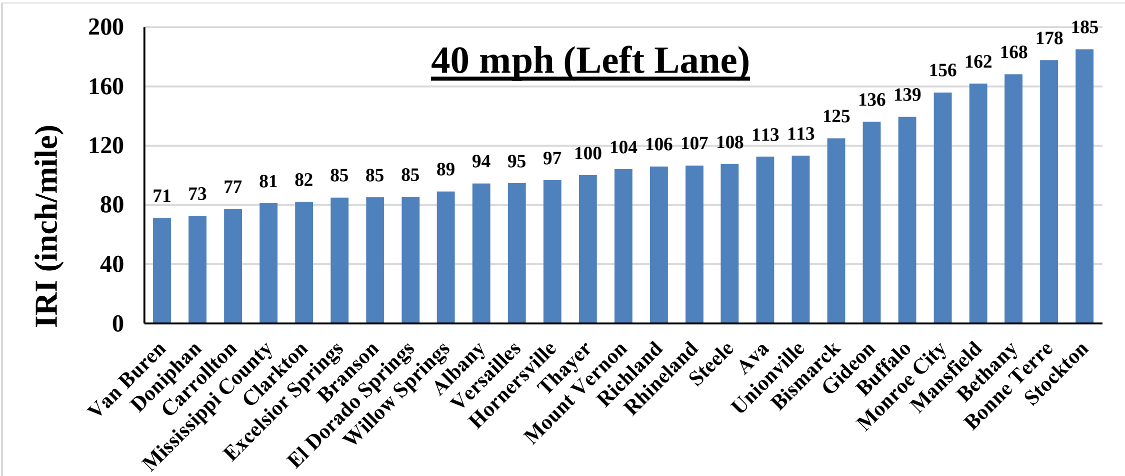
Figure ES.1. Ranking of airports based on their pavement roughness for 30 mph speed



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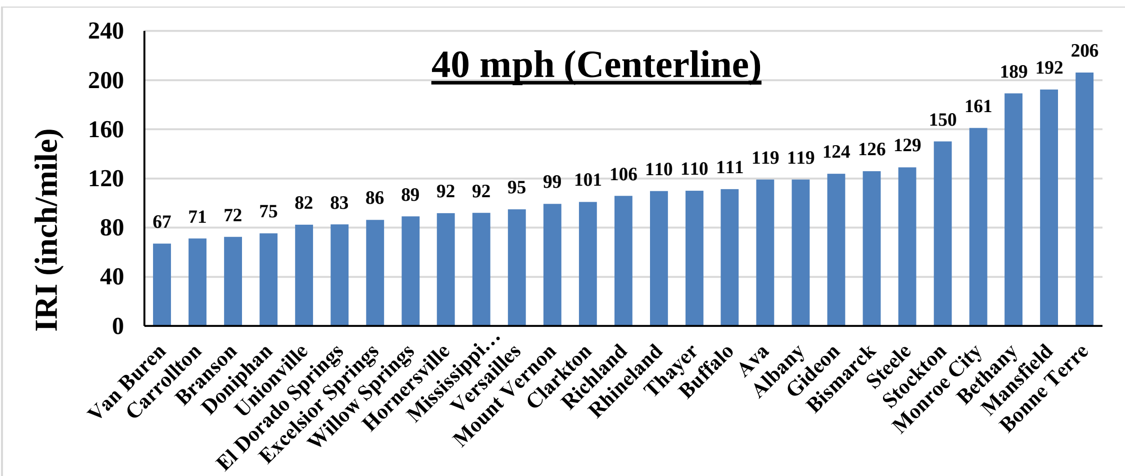

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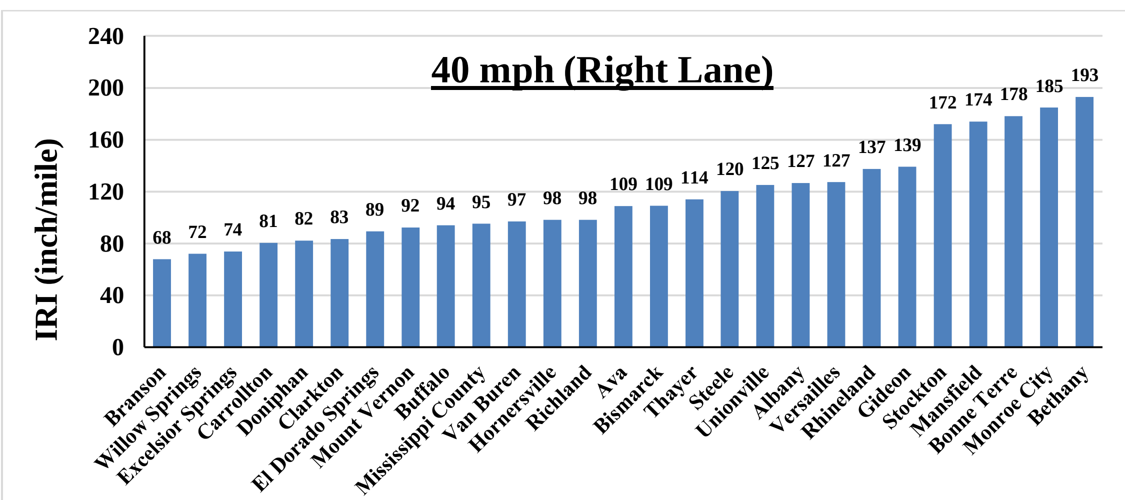

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Figure ES.2. Ranking of airports based on their pavement roughness for 40 mph speed

The study found that the smartphone application has the potential to be an effective low cost tool for assessing airport pavement condition. The validation results indicated that the IRI values measured by the smartphone were in good agreement with the ARAN-measured IRI. The obtained trends agreed well with the construction and maintenance records of the airports. An equation was developed to predict PCI based on the IRI values measured from the smartphone application. With a modest amount of app user interface development, the developed app and analytics could be used by airport managers to assess and track runway condition, and by MoDOT to prioritize scheduling of PCI surveys and to prioritize maintenance activities and investment.

The research presented in this study can be enhanced in several ways. For example, a more robust approach could be developed by including a large number of smartphones and a fleet of vehicles to collect pavement roughness data through crowd sourcing. In addition, estimating IRI based on aircraft cab acceleration data may lead to more realistic results and deserves study. Finally, finding a sound correlation between the smartphone-based IRI, PCI and Boeing Bump Index (BBI) could be an interesting topic for future research.

The pilot study at four airports using the low-cost, PaVision system, did not perform as hoped based on the existing algorithms developed for roads. However, preliminary efforts indicated that applying new machine learning algorithms could improve the performance of the PaVision system. Further research with larger data sets would be needed to determine if new approaches to developing algorithms could improve PaVision performance to a level that it becomes a useful tool for evaluating pavement conditions in the airport environment.

1. INTRODUCTION

Airport managers face many challenges in keeping airport pavements in good condition. One such challenge involves obtaining data regarding existing pavement conditions. Traditional Pavement Condition Index (PCI) surveys can be costly and labor intensive. Smaller airports such as state funded general aviation airports may not have sufficient resources to perform such surveys at the desired frequency. There is a need for simple, efficient, and low cost tools to facilitate the evaluation of airport pavement condition.

To address this need, a research study was undertaken to evaluate an android smartphone application (app). The goal of the study was to provide additional low cost tools for assessing airport pavement condition. The objective of the study was to investigate the use of an android smartphone application to assess pavement condition at all of the 27 state funded general aviation airports in Missouri. The android application is called "Roughness Capture" and was developed by Applied Research Associates (ARA). The application is described in greater detail in Chapter 2 of this report.

To perform this evaluation, an initial validation study was performed on two sections of I-70 in central Missouri. The validation study was used to determine optimal model parameters. A calibration study was then undertaken on a section of MO-10E near Excelsior Springs, Missouri. After the calibration study, the smartphone application was utilized to collect IRI data for all 27 state funded general aviation airports in Missouri. These data were analyzed and compared with the construction and maintenance records for the airports. In addition, a model was developed to predict PCI based on the IRI values measured from the smartphone.

In addition to the research using a smartphone to determine IRI values, a separate pilot study was conducted at four airports using a low cost camera system coupled with algorithms that automatically determined the quantity of cracking. This analysis was conducted by ARA using algorithms developed by D-Vision, a company that specializes in computer vision solutions for civil and defense applications. The pilot study determined that the existing algorithms were unable to accurately differentiate between low-, medium-, and high-severity cracking, and that total cracking quantities showed poor correlation with the foot-on-ground survey. Preliminary research by the authors indicates that the algorithms can be improved using new machine learning techniques. However, additional research is needed to determine if new machine learning algorithms could improve the PaVision results to the point that it becomes a potential replacement for traditional foot-on-ground surveys.

This report is organized as follows. Chapter 2 describes the initial I-70 validation study while Chapter 3 describes the calibration and the methodology and results for the data collection at the individual airports. Chapter 4 describes the prediction of PCI based on measured IRI values, and Chapter 5 presents the conclusions of the research.

2. PHASE I: VALIDATION

The first phase of the study consisted of an initial validation of the smartphone application. This chapter describes this initial validation and includes discussions of the smartphone characteristics, test sections, optimal parameter selection, and application of optimal parameters.

2.1. Description of Smartphone Application

The Roughness Capture application collects acceleration in three orthogonal directions, a timestamp, and GPS coordinates and stores them in an ASCII text file. The data collection rate is specified by the user, generally in the range of 10–140 samples per second. Higher sampling rates are possible depending upon smartphone hardware. In general, the higher the data collection rate, the better the accuracy of the estimated pavement profile (Islam 2015). In this study, the data collection from the application was set to 7 milliseconds per data point or approximately 142 data points per second.

2.2. Smartphone Characteristics

Measurements showed that a maximum of about 135 points/second can be reliably obtained from the cellphone (Samsung Galaxy S8) used in this study. For the standard speed of 50 mph, the vehicle travels 880 inches/second. Thus, the spacing of acceleration data points is 6.52 inches. The application can collect localization information either from the internal GPS or from a cellular network. While the GPS sampling rate is usually limited to 1 Hz, the acceleration data sampling rate is limited to roughly 140 points per second. The measurement type may also be specified as acceleration only, gravity only, or gravity and acceleration. Roughness is mostly influenced by the wavelength ranging from 4 to 100 feet (1.23 to 30.48 m), whereas maximum sensitivity resides in the range of 8 to 51 feet (2.46 to 15.54 m) because of the high gain for profile slope (Islam et al. 2015). Therefore, both low-pass and high-pass filters have been utilized to remove wavelengths greater than 100 feet (30.48 m) and less than 4 feet (1.22 m), respectively from the acceleration data. Roughness is estimated in terms of IRI of each 0.1-mile section.

2.3. Validation Methodology

An initial validation was performed on two segments of I-70 in May 2017. Prior to this initial validation, some preliminary testing was undertaken at Linn State Technical College Airport on April 14, 2017. In the preliminary testing at Linn, a trial and error approach was followed to see how the smartphone system works. The smartphone used for this preliminary testing was a Samsung Galaxy Edge 7, which was a different model than the smartphone that was used in subsequent testing.

For the initial validation on I-70, two test sites were selected to collect acceleration data using the smartphone application. The selected test roads and data collection dates are as follows:

- I-70 W (Log 126 -131), Travelway Id 3506 (May 7, 2017)
- I-70 W (Log 113 -118), Travelway Id 3506 (May 6, 2017)

The test locations are shown in Figures 2.1 and 2.2. The corresponding IRI values measured by the Automatic Road Analyzer (ARAN) van were obtained from MoDOT's Transportation Management System (TMS) database. The ARAN-based IRI measurements were taken on December 7, 2016.

The vehicle used was a 2015 Chevy Traverse. The vehicle suspension and smartphone parameter settings for this phase of the study are shown in Table 2.1. The test runs were conducted at 4 different speeds (+/-2 mph): 30 mph (48 km/hr), 40 mph (64 km/hr), 50 mph (80 km/hr), and 60 mph (97 km/hr). Each test run for each speed across each test section was conducted six times to test the repeatability and to achieve a reasonable average. The android-based smartphone was positioned horizontally on the vehicle dashboard.

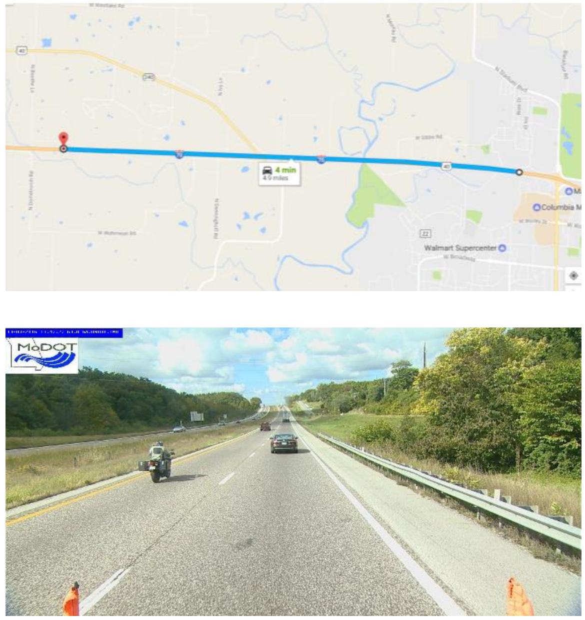


Figure 2.1. Test Location in Columbia, MO (I-70 W (Log 126 -131)) (Google, MoDOT)

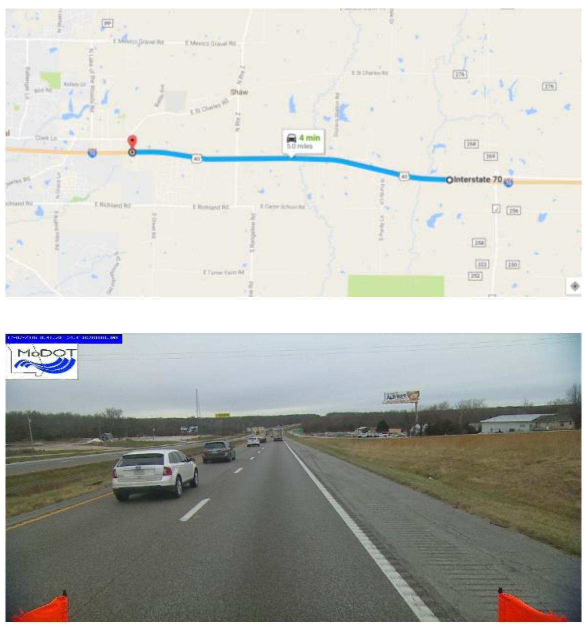


Figure 2.2. Test Location in Columbia, MO (I-70 W (Log 113 -118)) (Google, MoDOT)

Table 2.1. Vehicle suspension and smartphone parameter setting for Phase I

	Parameter	Value
Vehicle	Make/Model/Year	Chevy Traverse LT 2015
	Curb Weight	4647 lbs (2108 kg)
	Sprung Mass, m1	1464 lbs (664 kg)
	Unsprung Mass, m2	176 lbs (80 kg)
	Suspension Spring, k1	372 lb/in (65135 N/m)
	Dampening Coefficient, ζ	0.2, 0.3, 0.4
	Dashpot, c1	15 lbs/in (2631 Ns/m) 22.5 lbs/in (3946 Ns/m) 30 lbs/in (5261 Ns/m)
	Tire Spring, k2	457 lb/in (80000 N/m)
Smartphone	Model	Samsung Galaxy S8
	Localization (GPS, Cellular network)	GPS
	Measurement type (acceleration, gravity, gravity and acceleration)	Acceleration
	Collection Rate	7 milliseconds per data point (≈ 142 data points per second)

2.4. Selection of Optimal Parameters

First, the model was calibrated using the data collected for a part of these sections (Log 126 -129 and Log 113 -115) for different damping ratios. The calibration results for Logs 126 to 129 and Logs 113 to 115 are shown in Figures 2.3 and 2.4, respectively. As seen in these figures, the averaged IRI values measured by smartphone are in good agreement with the ARAN measured IRI for different speeds. Also, the smartphone results for 50 mph speed seemed to have a better match with ARAN data for the starting logs compared to those for other speeds. Moreover, the best results were obtained for $\zeta = 0.4$ (c1 = 30 lbs/in (5261 Ns/m)) (Figures 2.3 and 2.4(a)).

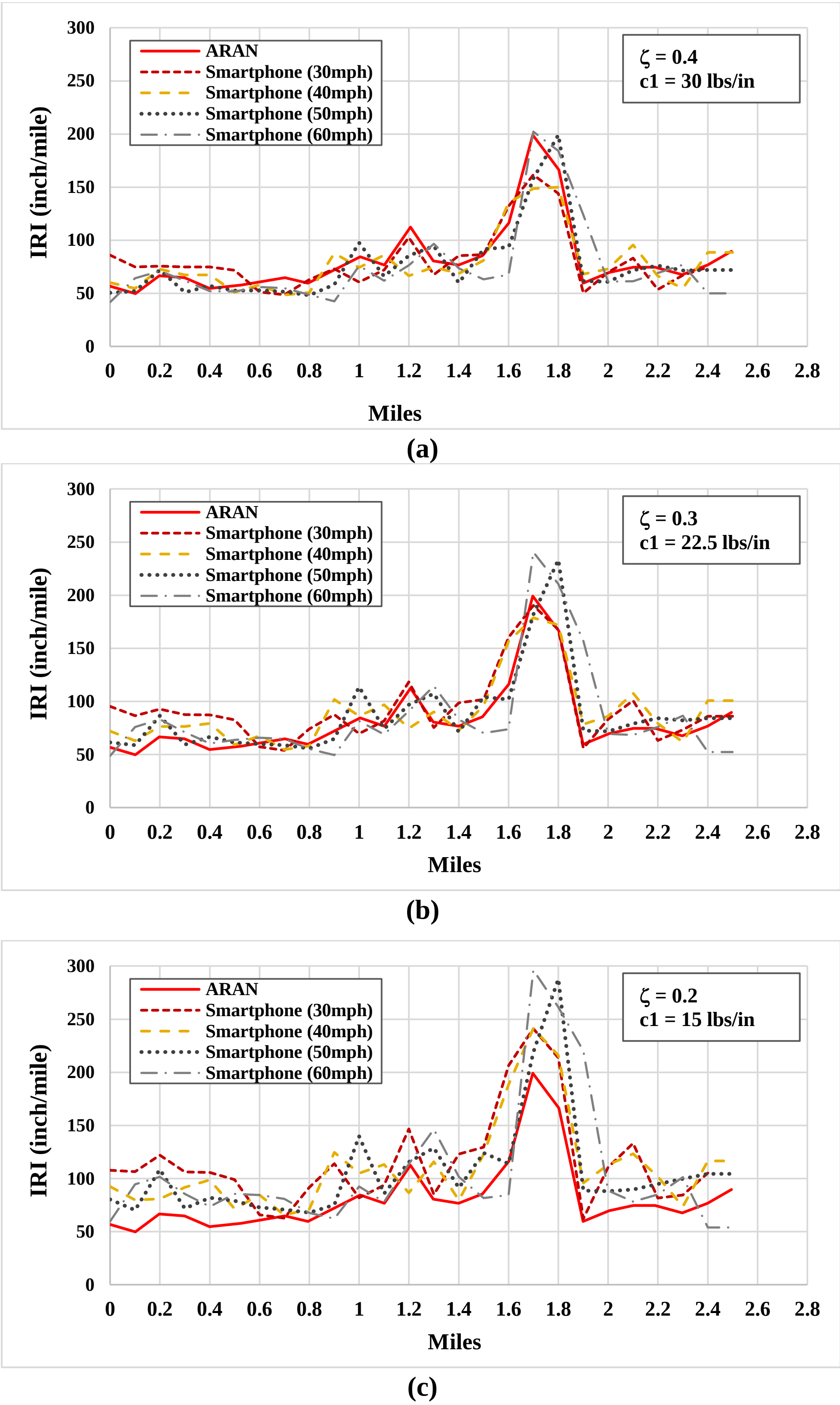
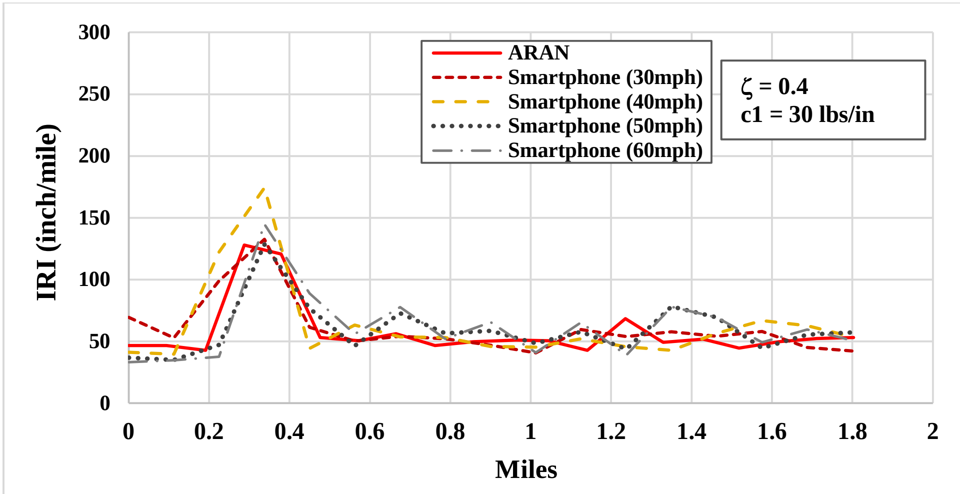


Figure 2.3. Estimated average IRI values for different damping ratios on I-70 W (Log 126 - 129)



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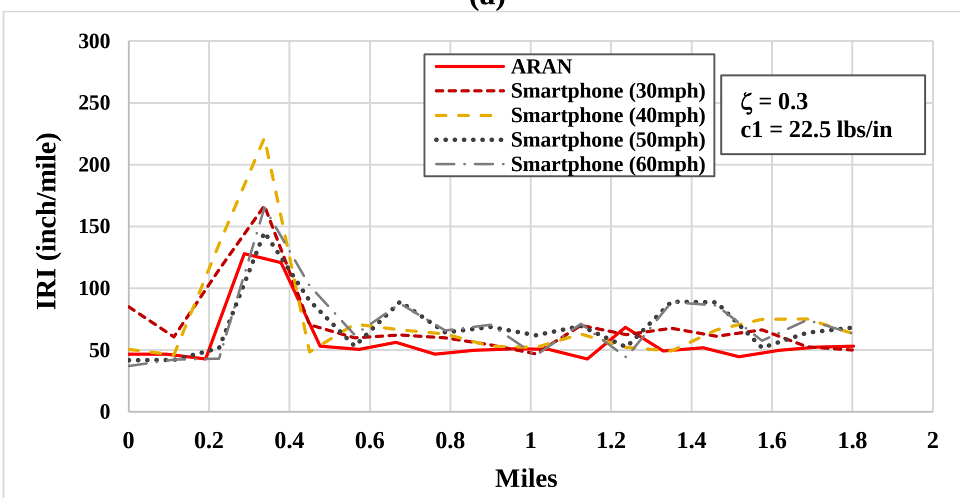

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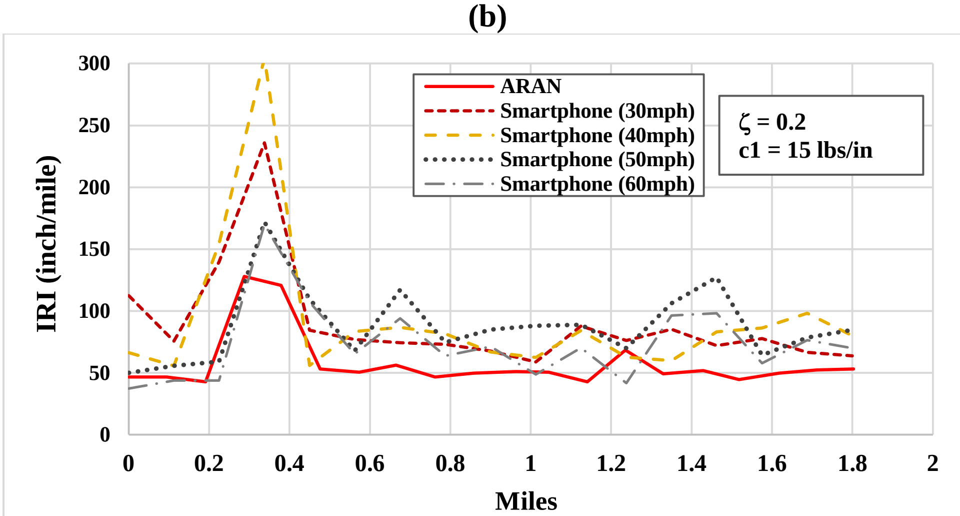

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Figure 2.4. Estimated average IRI values for different damping ratios on I-70 W (Log 113 - 115)

2.5. Evaluation of Calibrated Model with Optimal Parameters

After the initial calibration, the calibrated model with optimal damping ratio was then evaluated with new test runs over the entire length of sections, i.e. Log 126 -131 and Log 113 -118. The validation phase was performed using c1 = 30 lbs/in and 50 mph speed. The increased suspension dampening seemed to help provide more consistency across the test runs. According to Sayers et al. (1986), the suspension characteristics of a vehicle is the single most important factor in measuring IRI. A vehicle possessing a softer suspension will oscillate with a longer wavelength than one with a stiffer suspension. This difference in oscillation can alter the perceived roughness in a road when measuring accelerations in the vehicle cab, sometimes referred to as the sprung mass (Stribling et al. 2016).

Figures 2.5 and 2.6 present the final validation results for Logs 126 to 131 and Logs 113 to118, respectively. It can be observed from these figures that the accuracy of the smartphone-based IRI predictions are quite acceptable, specifically for I-70 W (Log 126 -131). The smartphone-based roughness system was also assessed in terms of its ability to classify pavement according to MAP-21 criteria. MAP-21 requires the States to provide pavement IRI data for every 0.1-mile pavement section for the Interstate and Non-Interstate highway systems annually and biannually, respectively (AASHTO 2013). Pavement ride quality can be categorized into five groups (U.S. Department of Transportation 2000), as shown in Table 2.2. Figures 2.5 and 2.6 show these pavement ride quality levels relative to the IRI values measured from ARAN and the smartphone application. The vertical axis has been labeled according to MAP-21 smoothness criteria threshold values. As can be seen in Figures 2.5 and 2.6, the smartphone based-IRI assessment system developed herein was able to categorize pavement condition based on roughness accurately for most of the pavement sections between Logs 126 to 131 and Logs 113 to118.

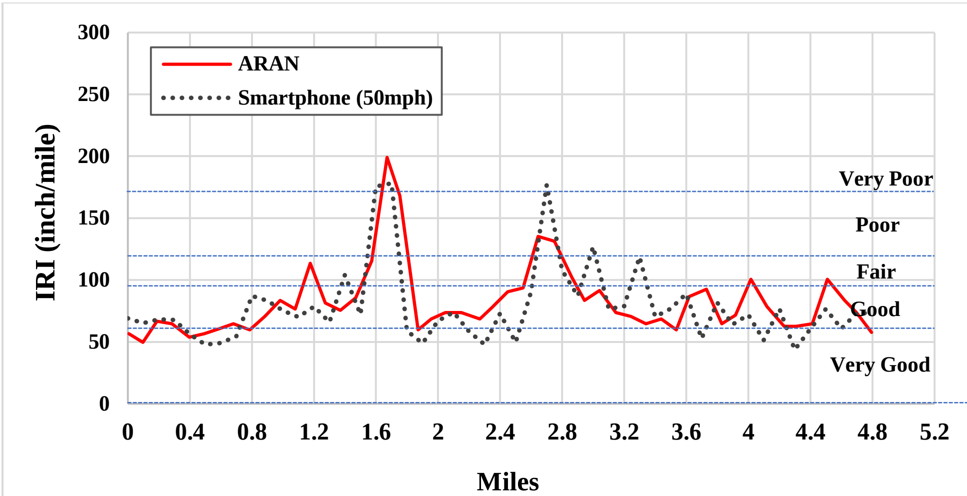


Figure 2.5. Validation study for I-70 W (Log 126 -131) for optimal damping ratio

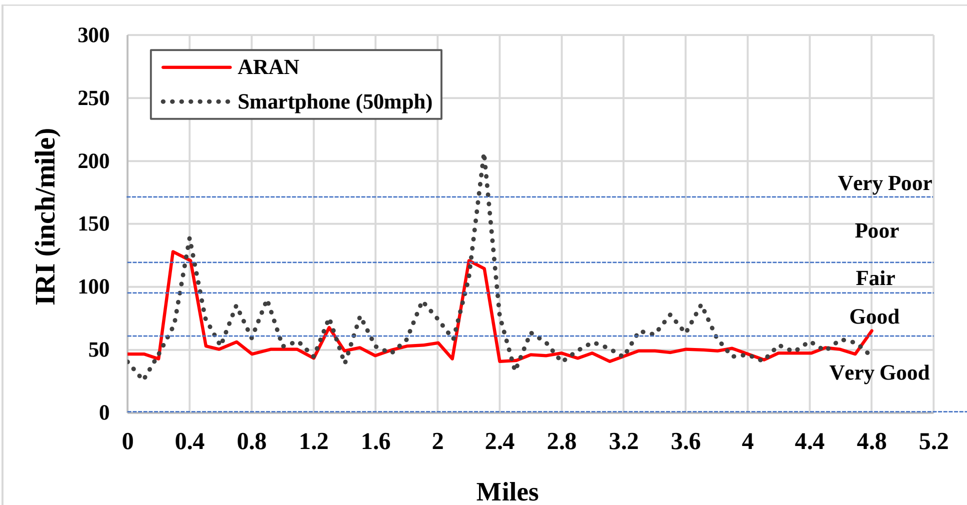


Figure 2.6. Validation study for I-70 W (Log 113 -118) for optimal damping ratio

Table 2.2. Pavement ride quality for Interstate and non-Interstate facilities based on roughness (U.S. Department of Transportation 2000)

Category	IRI Rating (inch/mile)		Interstate and NHS Ride Quality
	Interstate	Non-Interstate	
Very Good	< 60	< 60	Acceptable 0 - 170
Good	60 - 94	60 - 94	
Fair	95 - 119	95 - 170	
Poor	120 - 170	171 - 220	Less than acceptable > 170
Very Poor	> 170	> 220	

3. PHASE II: CASE STUDY OF MISSOURI AIRPORTS

To investigate the potential for the smartphone application to be used as a tool for assessing airport pavement condition, a case study was undertaken for Missouri state funded general aviation airports. This chapter describes the case study, including the calibration process, data collection methodology, and the results.

3.1. Calibration Study

In order to find the optimal model parameters, a calibration study was first performed on a nominated test road on MO-10E (Figure 3.1). The vehicle used for both the MO-10E calibration and the airport data collection was a 2009 Chevy Traverse, which was not the same vehicle that was used for the I-70 calibration. The test section was selected based on its proximity to Excelsior Springs airport and the availability of ARAN data in TMS. The characteristics of the MO-10E test section are as follows:

- Road: Excelsior Springs, MO-10 E, Travelway Id: 5015
- Start: Log 40.449 (Coordinates: 39.3350614, -94.1341107)
- End Log: 43.74 (Coordinates: 39.3406533, -94.192451)

Figure 3.1. Street view of MO-10E test section (Google)

The corresponding ARAN measured IRI values were obtained from the MoDOT TMS database. The ARAN-based IRI measurements were taken in April 2016. The ARAN-based IRI values are calculated at speed of 50 mph (80 km/hr). Therefore, the test runs were conducted at the same speed. Figure 3.2 shows the ARAN and smartphone data that were used for the calibration. The vehicle suspension and smartphone parameter settings from the calibration are shown in Table 3.1. The smartphone parameters shown in Table 3.1 were used during the data collection process for each of the 27 Missouri airports in this study.

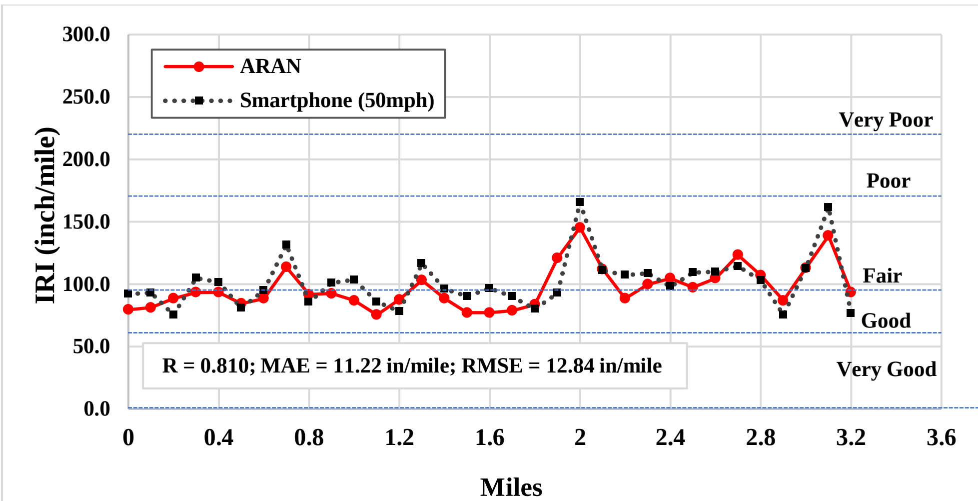


Figure 3.2. Smartphone calibration on MO-10 E (Log 40.449-43.74)

Table 3.1. Vehicle suspension and smartphone parameter setting for the airport project

	Parameter	Value
Vehicle	Make/Model/Year	Chevrolet Traverse LE 2009
	Curb Weight	5066 lbs (2298 kg)
	Sprung Mass, m1	1596 lbs (2108 kg)724 kg
	Unsprung Mass, m2	176 lbs (80 kg)
	Suspension Spring, k1	405.5 lb/in (71008 N/m)
	Dampening Coeff., ζ	0.2, 0.3, 0.4
	Dashpot, c1	16.5 lbs/in (2868 Ns/m) 24.5 lbs/in (4302 Ns/m) 33 lbs/in (5735 Ns/m)
	Tire Spring, k2	457 lb/in (80000 N/m)
Smartphone	Model	Samsung Galaxy S8
	Localization (GPS, Cellular network)	GPS
	Measurement type (acceleration, gravity, gravity and acceleration)	Acceleration
	Collection Rate	7 milliseconds per data point (≈ 142 data points per second)

3.2. Missouri Airport Smartphone Data Collection Methodology

The roughness data for the Missouri state funded airports were collected using a 2009 Chevy Traverse and Samsung Galaxy S8. The IRI values are reported for the right, centerline and left lanes of the 27 airfield pavements. The test runs were conducted at 2 different speeds (+/-2 mph): 30 mph (48 km/hr) and 40 mph (64 km/hr). Each test run for each speed across each lane was conducted three times to achieve a reasonable average. The IRI values were calculated for each 0.1-mile using the smartphone acceleration data and MATLAB script. Vehicle suspension and smartphone parameter settings are presented in Table 3.1.

3.3. Missouri Airport Smartphone Data Collection Results for Each Airport

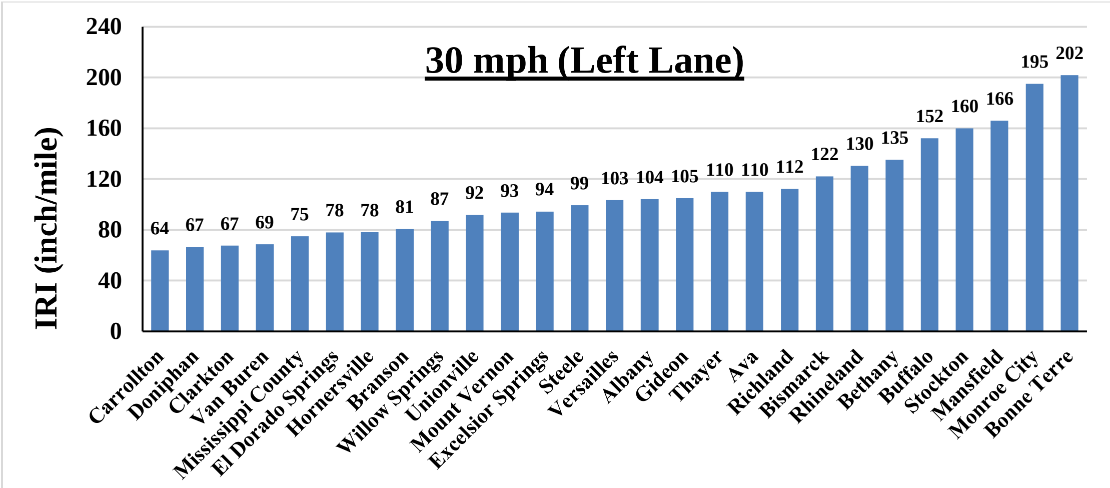
The results from the smartphone data collection for each of the 27 individual airports are shown in Appendix A. For each airport, the following figures are shown: aerial photograph, ground level photograph, plot of IRI values by location, and estimated average IRI values.

3.4. Ranking of Airports Based on IRI Results

Figures 3.3 and 3.4 show the ranking of the airports based on their pavement roughness for 30 and 40 mph speeds, respectively. Based on the results for 30 mph, the classification of ride quality of airfield pavements is as follows:

- Very Good: Bollinger-Crass Memorial Airport (Van Buren)
- Good: Branson, Carrollton, Mississippi County, Doniphan, Clarkton, Hornersville, El Dorado Springs, Unionville, Excelsior Springs, Willow Springs
- Fair: Mount Vernon, Gideon, Thayer, Versailles, Richland, Steele, Ava, Buffalo, Rhineland, Albany, Bismarck, Stockton, Monroe City
- Poor: Mansfield, Bethany
- Very Poor: Bonne Terre

The average IRI values for Bonne Terre Municipal Airport and Bollinger-Crass Memorial Airport (Van Buren) are shown in Figures 3.5 and 3.6, respectively.



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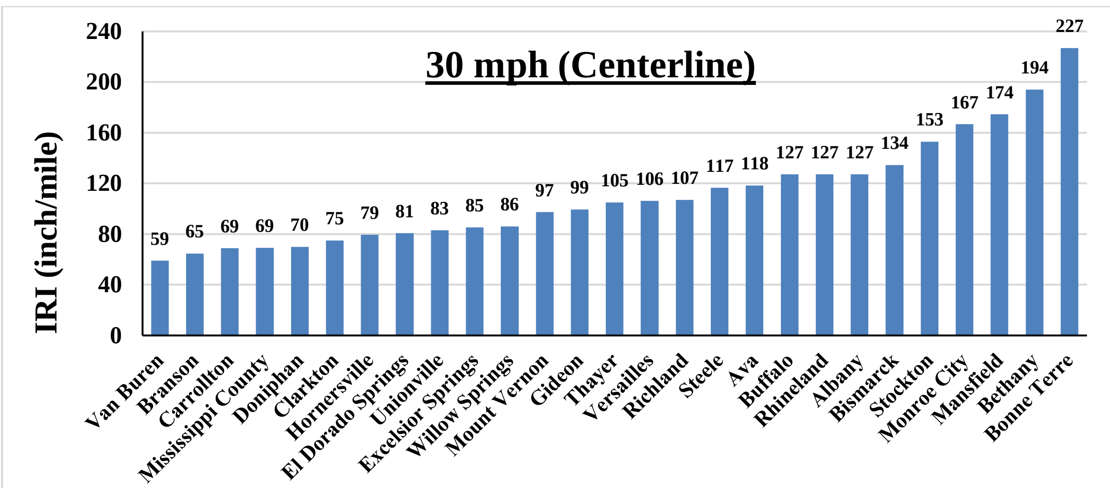

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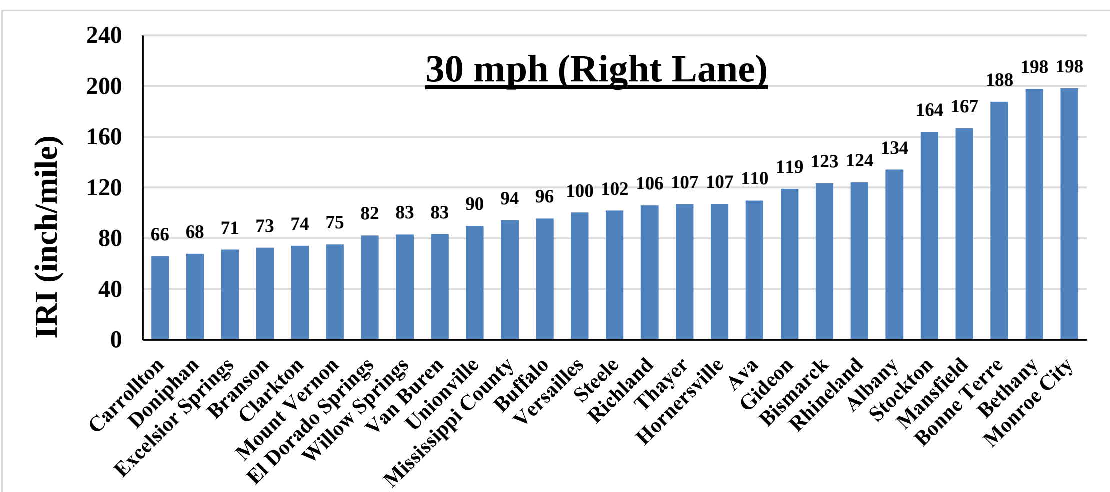

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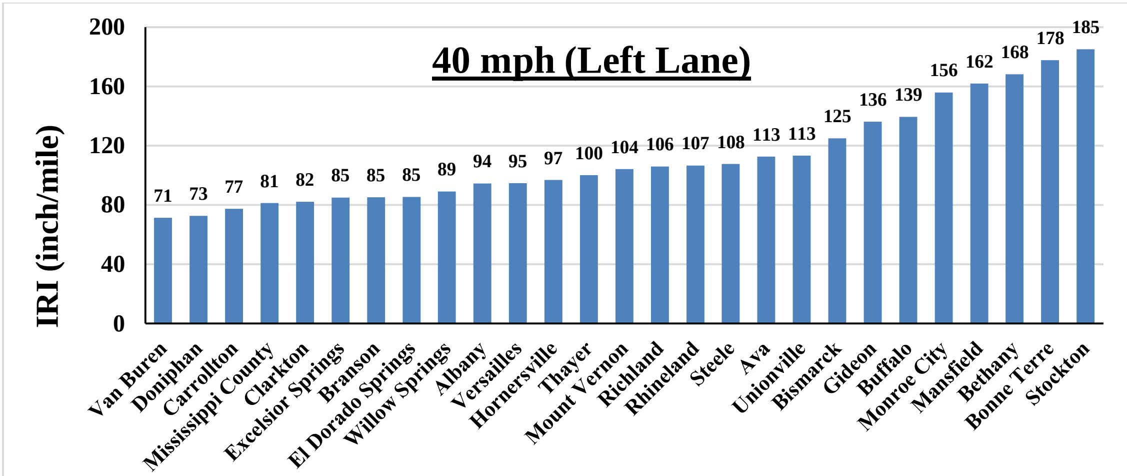
Figure 3.3. Ranking of airports based on their pavement roughness for 30 mph speed



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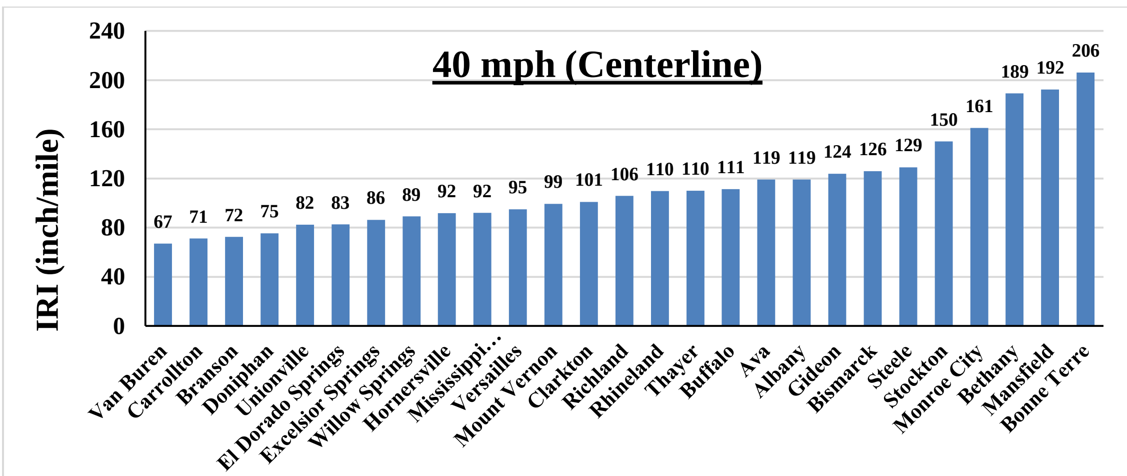

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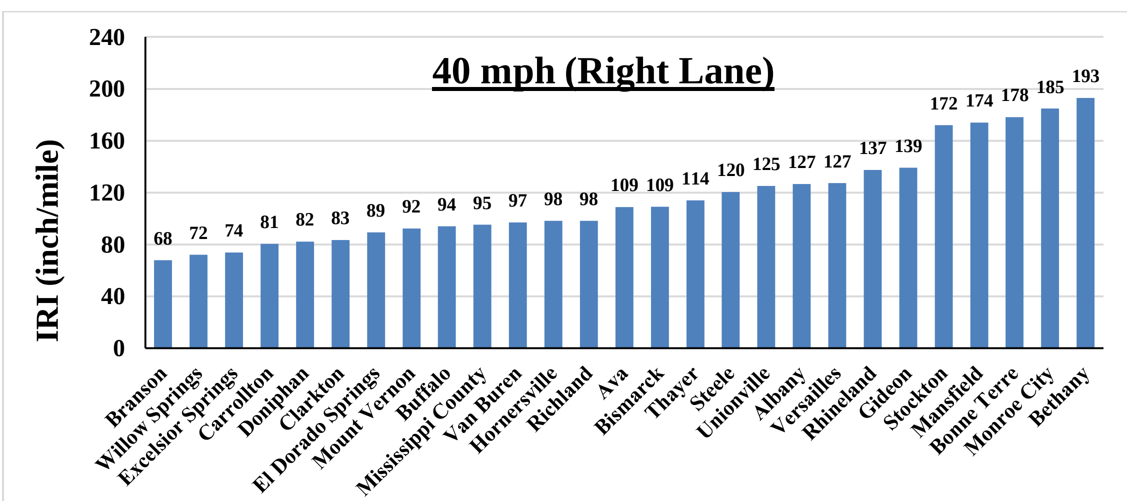


(c)

Figure 3.4. Ranking of airports based on their pavement roughness for 40 mph speed

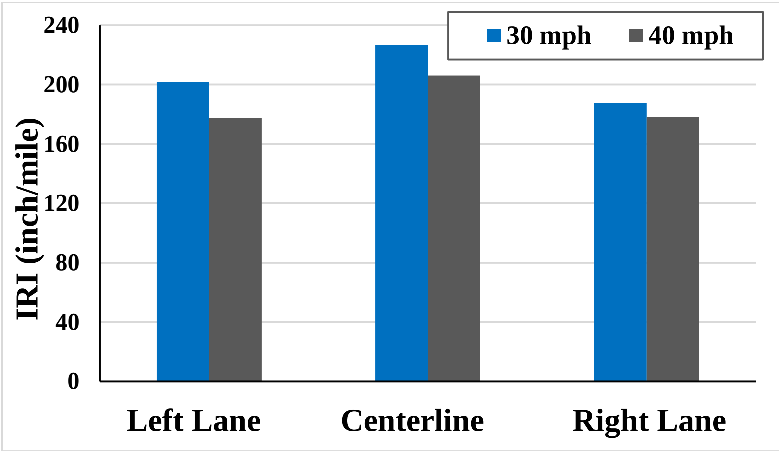


Figure 3.5. Estimated average IRI values for Bonne Terre Airport

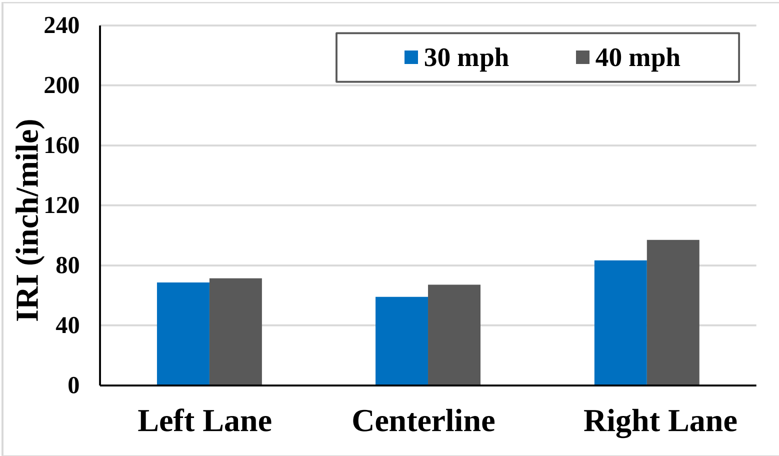


Figure 3.6. Estimated average IRI values for Bollinger-Crass Memorial Airport (Van Buren)

3.5. Discussion of Results

The results are in good agreement with the construction and maintenance records for each airport shown in Table 3.2. This table ranks the airports based on their smoothness on the centerline for 30 mph speed. As seen in Figure 3.3(b), the Bonne Terre Municipal Airport pavement has the worst condition. Although this airport was constructed in 1966, there are no records of pavement maintenance for it. The lowest IRI belongs to the Bollinger-Crass Memorial Airport (Van Buren) which was constructed in 1971, sealed in 1985 and 1987, and rehabilitated between 2012 and 2013.

Table 3.2. Construction and maintenance records for the Missouri airports

No.	Airport	Smartphone-based IRI on the centerline at 30 mph (inch/mile)	Construction and maintenance records
1	Bollinger-Crass (Van Buren)	59	1971: Original construction (runway, taxiway, apron) 1985: Surface seal (runway, taxiway) 1997: Surface seal (runway, taxiway, apron) 2012/2013: Pavement Rehab (runway, connecting taxiway)
2	Branson	65	1971: Original construction (runway, connecting taxiway, parallel taxiway, apron) 2009: Maintenance (runway, taxiway), Seal coat, crack repair, and isolated pavement removal and replacement (apron, taxiway) 2013: Pavement removal (runway, connecting taxiway, apron)
3	Carrollton	69	1963: Originally paved 1968: Overlay (runway, taxiway), Expansion (apron) 1980: Pavement rehab (runway, taxiway) 1984: Crack seal (runway, taxiway) 1986: Asphalt reconstruction (apron) 2004: Crack seal (runway, taxiway) 2009: Pavement Maintenance: Crack seal, clean joints, patching (runway)
4	Mississippi County	69	1973: Original construction (runway, taxiway, apron) 1998: Repair and seal (runway, taxiway, apron) 2012: Bituminous overlay and crack seal (runway, taxiway, turnaround, apron), Additional reconstruction (apron)
5	Doniphan	70	1989: Original construction 1991: Seal (runway, taxiway) 1992: Unknown construction/maintenance (no detailed records) 1994: Resurfacing (runway) 1996: Overlay (runway) 2009: Seal coat and crack seal (runway, connecting taxiways 1 and 2, taxiway 3c)
6	Clarkton	75	1967: Runway constructed 2007: Pavement Removal, Replacement, 6" crushed aggregate base, 3" pavement layer, 1.75" overlay, crack seal (runway, taxiway), Pavement removal, replacement, 6" crushed aggregate base, 3" pavement layer, 1.75" overlay, 1.75" cold mill, crack seal (apron, hanger)

No.	Airport	Smartphone-based IRI on the centerline at 30 mph (inch/mile)	Construction and maintenance records
7	Hornersville	79	*Initial construction date unknown 2009: Slurry seal and apron expansion, removal of existing angled taxi lane, and rigid pavement for taxiway and apron, along with crack sealing 2010: Seal coat, pavement removal, 6" asphalt overlay, crack seal (apron and runway)
8	El Dorado Springs	81	* Initial construction date unknown 1982: Construct apron, reconstruct taxiway 1983: Seal runway 1999: Reconstruct apron, runway and taxiway 2005: Seal runway, taxiway and apron 2013: Runway and taxiway seal coat and apron reconstruction
9	Unionville	83	*Initial construction date unknown 2012: Crack repair, full-depth bituminous patching, bituminous overlay (runway, connecting taxiway, apron)
10	Excelsior Springs	85	1952: Original construction date 1986: Seal runway and taxiway 1987: Pave runway and taxiway 2015: Reconstruct runway, seal coat and crack seal (apron, connecting taxiway)
11	Willow Springs	86	*Initial construction date unknown 2006: Runway rehabilitation (widening and 2" overlay, new pavement construction) 2010: Seal coat (runway, taxiways, aprons)
12	Mount Vernon	97	*Initial construction date unknown 2002: 2" bituminous overlay (runway, taxiway, aprons) 2009: Runway, taxiway, apron, and south turnaround were routed/sealed and seal coated (About 4000 linear feet).
13	Gideon	99	1942: Original construction date 1960s: Some maintenance and overlay (details unknown) 1970s: Some maintenance and overlay (details unknown) 1990s: Some patchwork (details unknown) 2000s: Some patchwork (details unknown) 2013: Mill and overlay of runway. Alternative 1: overlay of parallel taxiway and connecting taxiway (existing footprint). Alternative 2: overlay of parallel taxiway and connecting taxiway (25' width).
14	Thayer	105	*Initial construction date unknown 2012: Seal coat (runway, taxiway)

No.	Airport	Smartphone-based IRI on the centerline at 30 mph (inch/mile)	Construction and maintenance records
15	Versailles	106	1970: Original construction 1981: Overlay (runway, taxiway, apron) 1986: Seal runway and taxiway 1995: Seal runway, taxiway, and apron resurfacing (001-003 assumed, no documentation) 2006: Overlay (runway, connecting taxiway), Seal apron, rehab hanger 2007: Joint and crack repair, some full depth , some pavement removal and overlay (Connecting taxiway and aprons). Joint and crack repair, Petromat 2" overlay (Runway). Seal coat (TLA-001). Reconstruct with PCC (TLA-002/03). 2009: Seal runway, connecting taxiway 2014: Crack and joint seal (runway, connecting taxiway and TLA), Seal coat (runway), reconstruct pavement on apron. 2015: Pavement removal, crack seal, seal coat (location unknown)
16	Richland	107	1970: Airport constructed 1985: Pavement repair on runway, taxiway, and apron 2002: 2" bituminous overlay on runway, taxiway, and apron 2010: Seal coat, crack repair (runway, taxiway, apron)
17	Steele	117	1944: Original construction date 1973: Overlay runway (date approximate) 1985: Possible overlay (date approximate, unable to confirm) 1995: Possible seal coat (date approximate, unable to confirm). Per airport personnel, generally try to seal coat every 10 years but unsure of dates prior to 2005. 2005: Seal coat, crack repair (runway, taxiway, apron) 2007: Widened runway, removal of existing deteriorated pavements 2013: Crack seal, seal coat (runway, taxiway, apron)
18	Ava	118	1967: Apron fencing constructed, no documents 1974: Runway extended, no documents 1979: Mill and Overlay (runway, connecting taxiway, TLA, RTA), apron expansion, no documents 1984: Seal coat (runway, taxiway, apron), no documents 1989: Leveling overlay course on runway, no documents 1994: Seal coat (runway, taxiway, apron), no documents 2006: Crack and joint sealing, seal coat (runway) 2015: Hanger taxiway reconstruction, no documents
19	Buffalo	127	1952: Airport constructed 1988: Runway resurfacing, no documents 1997: Pavement rehab (runway, connecting taxiway, apron) 2004: Seal coat (runway, connecting taxiway, apron) 2013: Seal coat, crack seal and repair (runway, connecting taxiway, heliport)

No.	Airport	Smartphone-based IRI on the centerline at 30 mph (inch/mile)	Construction and maintenance records
20	Rhineland	127	1974: Constructed (Phase 1) 1981: Constructed (Phase 2) 1986: Seal runway and taxiway 1988: Seal runway and taxiway 1993: Seal runway 1995: Extensive flood damage, required overlay and replacement of damage with new surface 2001: Reconstruct, expand apron and taxiway 2002: Seal runway and connecting taxiway 2014: General maintenance: crack and joint seal, seal coat (runway, turnarounds, connecting taxiway) 2015: Clean and seal joints, seal coat (runway, taxiway, turnarounds)
21	Albany	127	1982: Runway paved (original construction), no documents 1987: Pavement rehab: 5" PCC Runway Overlay and PCC Panel repairs, apron expansion 1990: Runway Expansion 2008: 5" PCC Runway: crack and joint sealing, 12 panel repairs 2010: Crack repair, panel replacement, partial depth patching on runway
22	Bismarck	134	1965: Runway originally constructed 1982: Runway sealcoat 1999: Runway, taxiway, apron repair/resurface, no documents 2008: Runway, taxiway, apron seal coat, no documents 2010: Crack and joint seal, and friction surface seal (runway, connecting taxiway, apron)
23	Stockton	153	1964: Airport is constructed 2007: Slurry sealing, crack and joint sealing, sealcoat surface (apron) 2009: Full depth pavement repair, crack and joint sealing, seal coat treatment (runway and taxiway)
24	Monroe City	167	*Initial construction date unknown 1979: Extend/expand runway 2006: Crack and joint seal, seal coat (runway, taxiways, aprons) 2010: Full depth, crack repair, and seal coat (runways, taxiways, aprons)
25	Mansfield	174	*Initial construction date unknown 2010: Seal coat and crack seal (runway, taxiway, apron) 2013: Crack seal, seal coat (runway, taxiway, apron)
26	Bethany	194	1969: Runway constructed (oil and gravel) 1982: Runway seal, no documents 1996: Runway paved, no documents 2006: Runway sealed 2016: Runway sealed 1996 - Present: Pothole patching
27	Bonne Terre	227	1966: Runway paved (Lead Belt Materials, 2") 1966 - Present: No pavement maintenance, occasional crack sealing and weed killer in cracks

3.6. Recommendations for Future Research

While the smartphone-based IRI roughness results appear to be quite reasonable, there are several issues that should be addressed in future research:

- During the measurement at airports with rough pavements (e.g. Bonne Terre Airport), it was observed that the data had outliers. These outliers were excluded from the analyses. The outliers show the significant effect of vehicle wander on collecting pavement roughness given that all other conditions remain constant (with weather/temperature being relatively the same). However, the effect of vehicle wander can be overcome by collecting and averaging larger volumes of data. It is recommended that at least six replications be performed for each section. In general, further validation should be done for very rough pavement sections. In addition, the current android application does not automatically eliminate outliers in the data nor does it conduct any analysis. These features can be added to the application along with real-time estimation of IRI.
- The smartphone application used in this study collected about 135 acceleration points per second. The vehicle running at 50 mph travels 880 inches per second, resulting in spatial distance between acceleration data points of 6.52 inches. Therefore, the smartphone application may very likely be missing peak accelerations due to the relatively slow data collection rate. Unlike the smartphones, the inertial profilers have a very high sampling rates (1 kHz). However, with the expected advancement of smartphone technology, higher data collection rates will be possible, potentially rendering IRI estimates on rough pavements even more accurate. Another idea is to attach commercially available accelerometers with higher data collection frequency to a smartphone, which will also make the measurements more consistent for the entire pavement.
- The calibration phase in the present study is based on checking a few values for the vehicle suspension parameters. In this context, a robust optimization algorithm should be developed to extensively search for the optimal vehicle suspension parameters and minimize the differences between IRI values estimated with the smartphone-based system with those obtained using the inertial profilers such as ARAN.
- This study concerns the use of a simple and cost-effective technology to measure pavement roughness for airports. The results are based on back-estimating the pavement profile from vehicle cab acceleration data. In order to obtain more realistic results, it is recommended that new measurements be done by mounting a smartphone on aircraft and using aircraft cab acceleration data.
- Based on the obtained trends, there should be a reasonable correlation between the smartphone-based IRI roughness results and PCI. It is possible to extract some additional parameters directly from the discrete acceleration data and develop algorithms for PCI estimation that are even more precise than the IRI only prediction of PCI. For instance, we already know that the smart phone acceleration trace can identify joints in PCC and larger cracks in asphalt. It seems feasible to characterize asphalt cracks of high severity that are related to thermal cracks, reflective cracks, block cracks and other linear cracking. Since many of these (if severe) would lead to high PCI deductions (but not necessarily lending directly to high IRI), adding the number and magnitude of these discrete events to a prediction algorithm would make it more accurate, or help us to develop new rating parameters only for airports.

4. PREDICTION OF PCI BASED ON SMARTPHONE-MEASURED IRI

The main goal of this phase was to formulate PCI in terms of smartphone-measured IRI using a powerful machine learning technique called Genetic Programming (GP). GP is a symbolic optimization technique that creates computer programs by simulating the biological evolution of living organisms (Darwinian natural selection) (Koza 1992). GP is known as an extension of classical genetic algorithms (GAs). However, there are major differences between GP and GA. The traditional optimization techniques, like GA, are generally used in parameter optimization to evolve the best values for a given set of model parameters. GP, on the other hand, gives the basic structure of the approximation model together with the values of its parameters. In fact, the GP solutions are computer programs that are represented as tree structures and expressed in a functional programming language (like LISP) (Figure 4.1). Unlike GP, artificial neural network (ANN), support vector machines (SVM) or other soft computing techniques are black-box models as they do not provide the functional relationship between the input and output parameters.

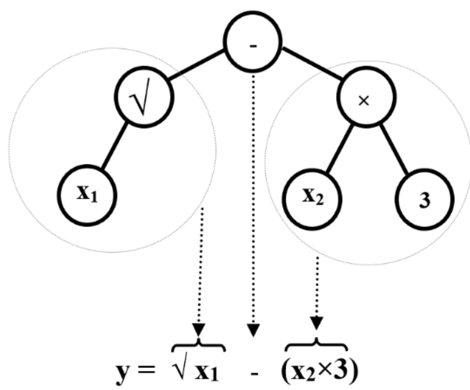


Figure 4.1. Tree representation of a GP model

The available database for Missouri airports was used to develop the prediction models. Figure 4.2 shows the variation of PCI with respect to smartphone-measured IRI on the centerline lanes of the airfield pavements at the speed of 30 mph. For the GP analysis, the database was randomly divided into the training and testing data. Several runs were conducted considering different values for the GP parameters. A large number of generations were tested to find a model with minimum error. In order to obtain optimum GP models, several arithmetic operators and mathematical functions (e.g., +, sqrt, exp, log, ln, sin, cos) were used. The best GP model for predicting PCI in term of the smartphone IRI is as follows:

$$PCI = 85.485 + cos(-6.02 + 8.1679IRI^2) + 8.756sin(IRI)^3 + 5.618cos(IRI^3) - 4.922cos((IRI + 6.036407)^3) - \frac{SIN(IRI)*11.178+IRI-5.056}{-5.938} \quad \textbf{(4.1)}$$

As seen, the developed model is a highly nonlinear equation. It was generated by the GP algorithm after controlling millions of linear and nonlinear models. Thus, it can efficiently consider the interactions between the IRI and PCI. Note that excluding trigonometric functions during the GP analysis resulted in remarkably lower performance. Figure 4.3 shows the acceptable predictions made by the proposed model on the training and testing data.

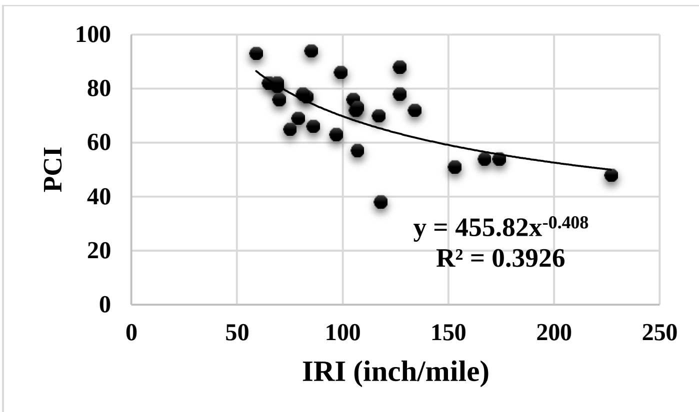
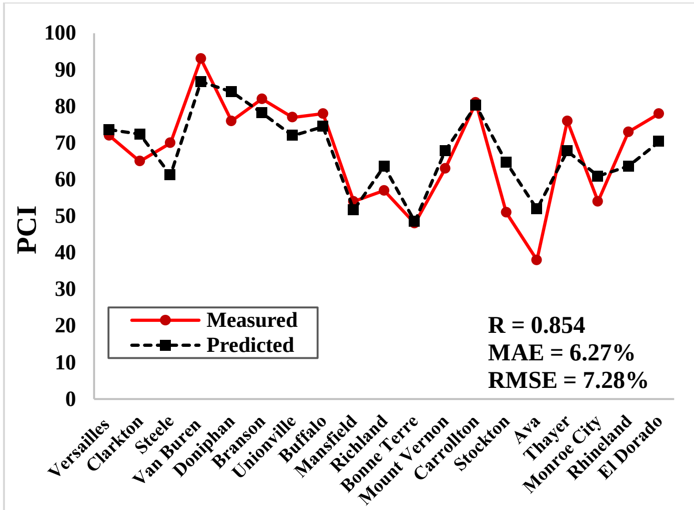
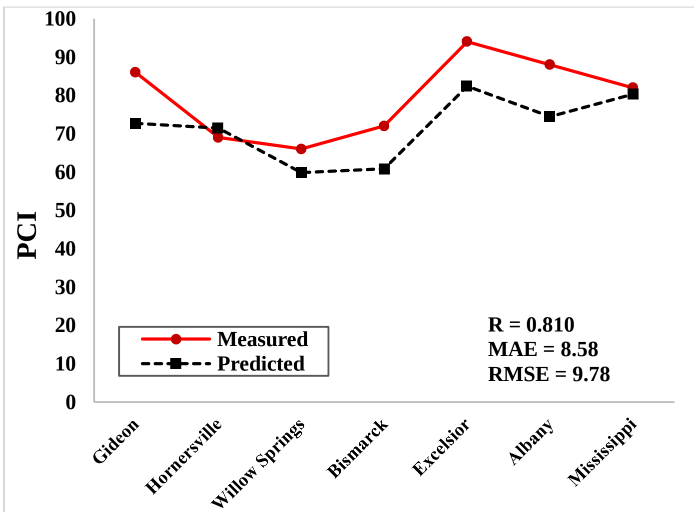


Figure 4.2. Variation of PCI with respect to smartphone-measured IRI



(a)



(b)

Figure 4.3. Predicted PCI using the GP model (a) Training data (b) Testing data

5. CONCLUSIONS

This project presents a new approach for the estimation of pavement roughness using acceleration data recorded by an android-based smartphone application. A validation study was first performed on two test roads near Columbia, MO to evaluate this monitoring technology for pavements in Missouri. The validation showed that the smartphone application performed well in estimating IRI, and the IRI results classified most of the test sections in agreement with MAP-21 requirements. After the validation study was completed, the proposed technology was implemented to determine the IRI values at 27 Missouri state funded general aviation airports. The IRI values were reported for the right, centerline and left lanes of the airfield pavements.

A wide range of IRI values was observed in the airfield pavements. Among the 27 airports, 1, 10, 13 and 2 airports are in very good, good, fair and poor conditions, respectively. Bonne Terre Municipal Airport pavement has the worst condition with an average IRI of 227 inch/mile while Bollinger-Crass Memorial Airport (Van Buren) pavement has the best condition with an average IRI of 59 inch/mile.

The study found that the smartphone application has the potential to be an effective low cost tool for assessing airport pavement condition. The smartphone estimated IRI values were close to those measured by ARAN. The obtained trends agreed well with the construction and maintenance records of the airports. An equation was developed to predict PCI based on the IRI values measured from the smartphone application. For implementation, it is suggested that an improved graphical-user interface (GUI) be developed for the smartphone roughness capture app, geared towards ease-of-use for airport managers.

The study results suggest several ways in which this research can be enhanced in the future. In this study, only one smartphone model (Samsung Galaxy S8), one type of smartphone car mount, and one vehicle type (SUV) were used for data collection to reduce the uncertainties. A more robust approach could be developed by including a large number of smartphones and a fleet of vehicles to collect pavement roughness data through crowd sourcing. Moreover, estimating IRI based on the aircraft cab acceleration data may lead to more realistic results. Finding a sound correlation between the smartphone-based IRI, PCI and Boeing Bump Index (BBI) could be an interesting topic for future research.

REFERENCES

AASHTO (2013). AASHTO SCOPM MAP-21 Notice of Proposed Rule-Making Checklist. Standing Committee on Performance Management (SCOPM), AASHTO, Washington, D.C.

Google. Google Maps. https://www.google.com/maps.

Islam, MS. (2015). Development of a smartphone application to measure pavement roughness and to identify surface irregularities. Ph.D. Dissertation, University of Illinois at Urbana-Champaign.

Koza J.R., Genetic Programming, on the Programming of Computers by Means of Natural Selection, MIT Press, Cambridge (MA), 1992.

Missouri Department of Transportation (MoDOT). ARAN Viewer.

Sayers, M.W., Gillespie, T.D. and Paterson, W.D.O. (1986). Guidelines for Conducting and Calibrating Road Roughness Measurements. World Bank, Washington, D.C.: World Bank Technical Paper 46.

Stribling J., Buttlar W. Islam MS. (2016) Use of Smartphone to Measure Pavement Roughness Across Multiple Vehicle Types at Different Speeds. The 96th TRB Annual Meeting, Washington, D.C.

U.S. Department of Transportation (2000). 1999 Status of the Nation’s Highways, Bridges and Transit: Conditions and Performance. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

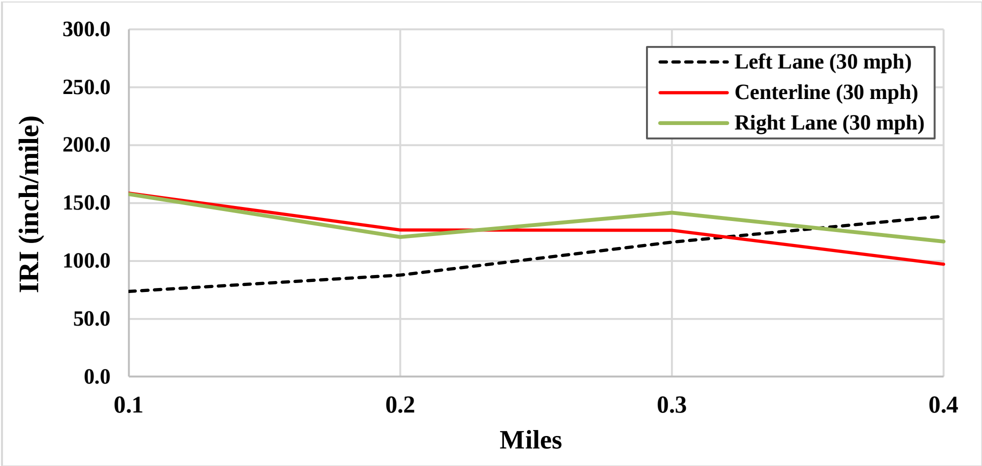
APPENDIX A: IRI RESULTS FOR INDIVIDUAL AIRPORTS

The following figures present the results of the smartphone data collection for each of the 27 state funded general aviation airports in Missouri. For each airport, the following figures are shown: aerial photograph, ground level photograph, plot of IRI values by location, and estimated average IRI values. The MATLAB script provides the IRI values at each 0.1 mile.

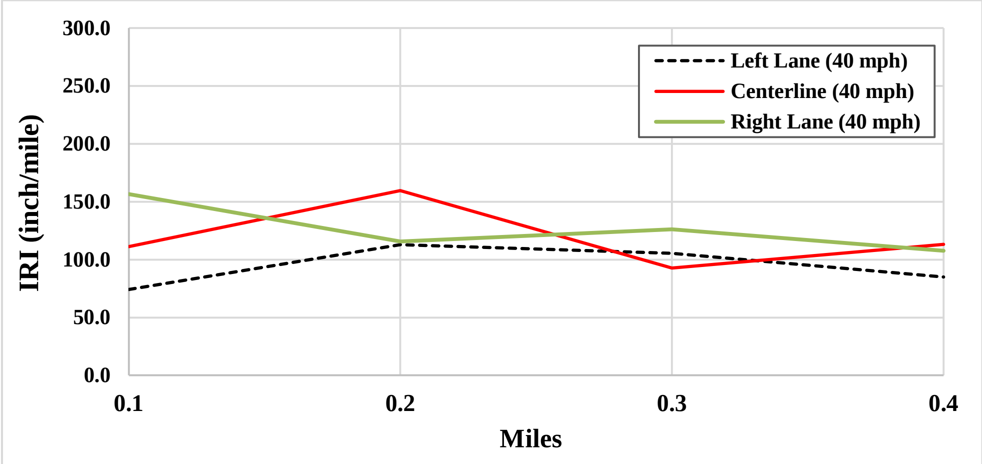
A.1. Albany Municipal Airport (Albany, MO)

Measurement length: 2,325 ft (0.44 mile)

Figure A.1. Test Location at the Albany Municipal Airport (Google)



(a)



(b)

Figure A.2. Plot showing the estimated IRI values for Albany Municipal Airport: (a) 30 mph (b) 40 mph

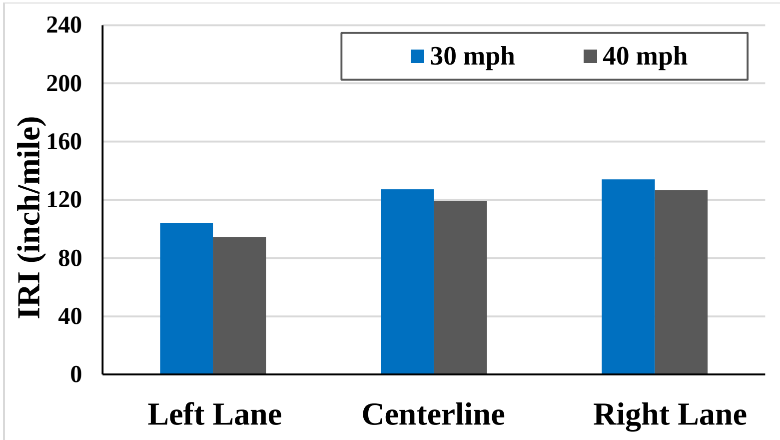
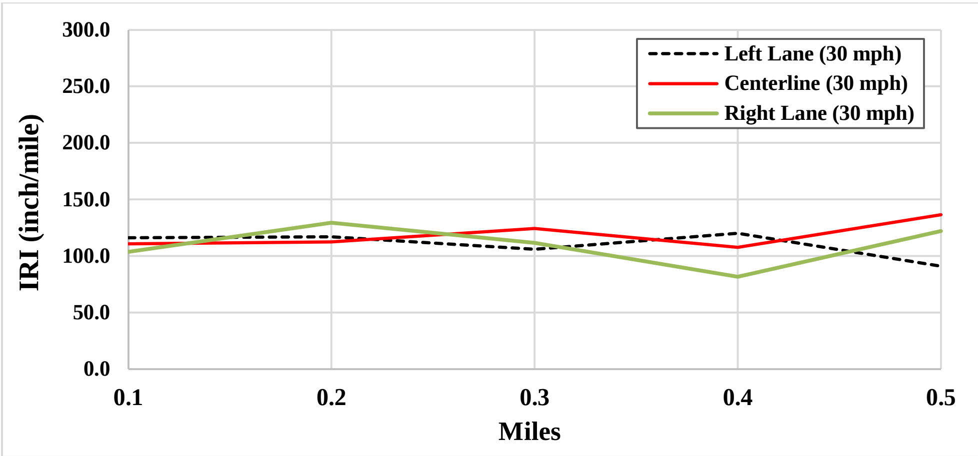


Figure A.3. Estimated average IRI values for Albany Municipal Airport

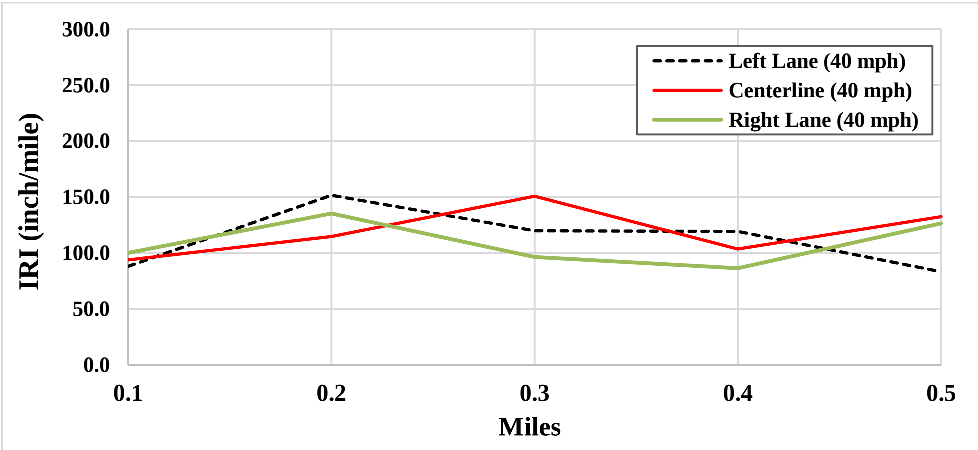
A.2. Ava Bill Martin Memorial Airport (Ava, MO)

Measurement length: 2,709 ft (0.51 mile)

Figure A.4. Test Location at the Ava Bill Martin Memorial Airport (Google)



(a)



(b)

Figure A.5. Plot showing the estimated IRI values for Ava Bill Martin Memorial Airport: (a) 30 mph (b) 40 mph

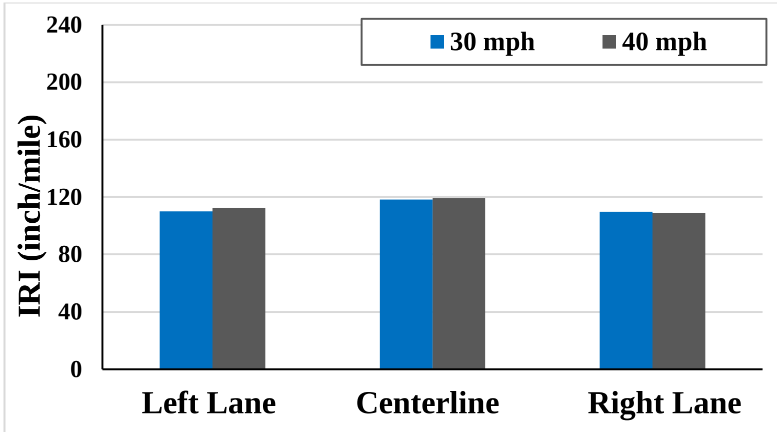
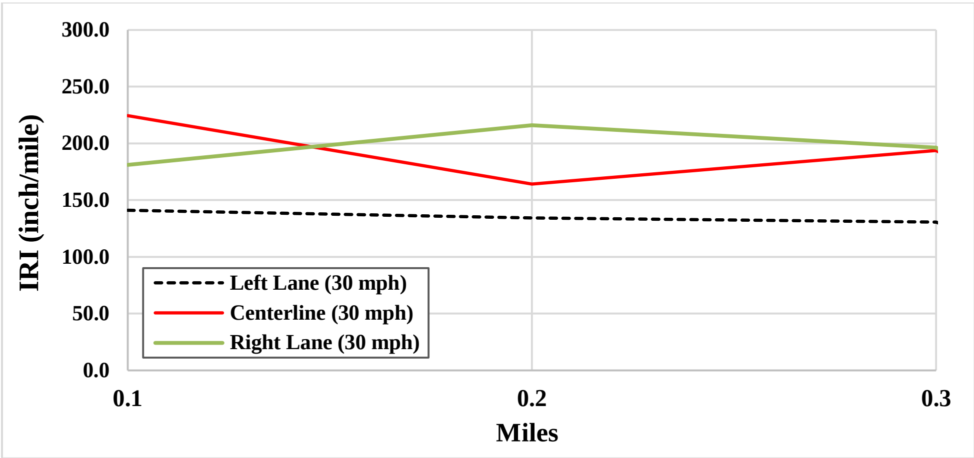


Figure A.6. Estimated average IRI values for Ava Bill Martin Memorial Airport

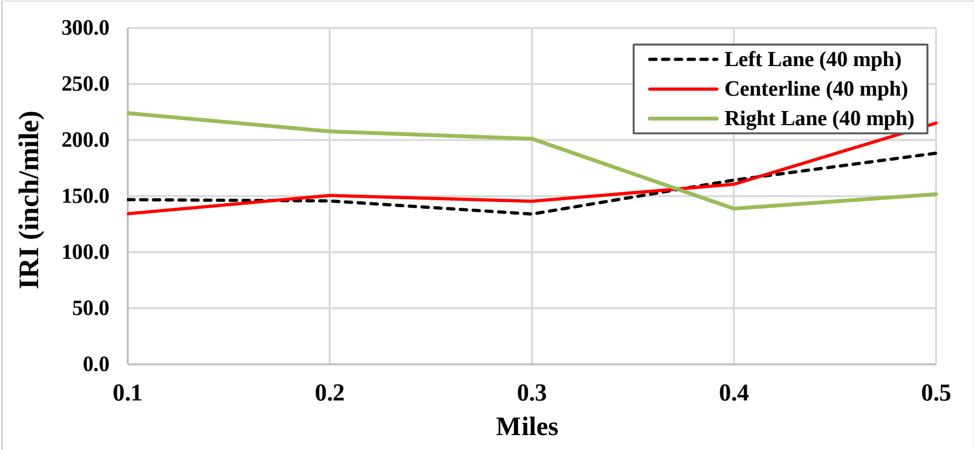
A.3. Bethany Memorial Airport (Bethany, MO)

Measurement length: 1,788 ft (0.33 mile)

Figure A.7. Test Location at the Bethany Memorial Airport (Google)



(a)



(b)

Figure A.8. Plot showing the estimated IRI values for Bethany Memorial Airport: (a) 30 mph (b) 40 mph

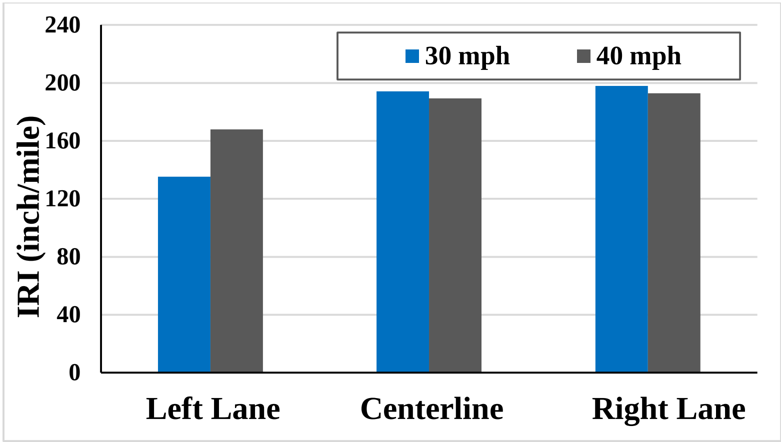
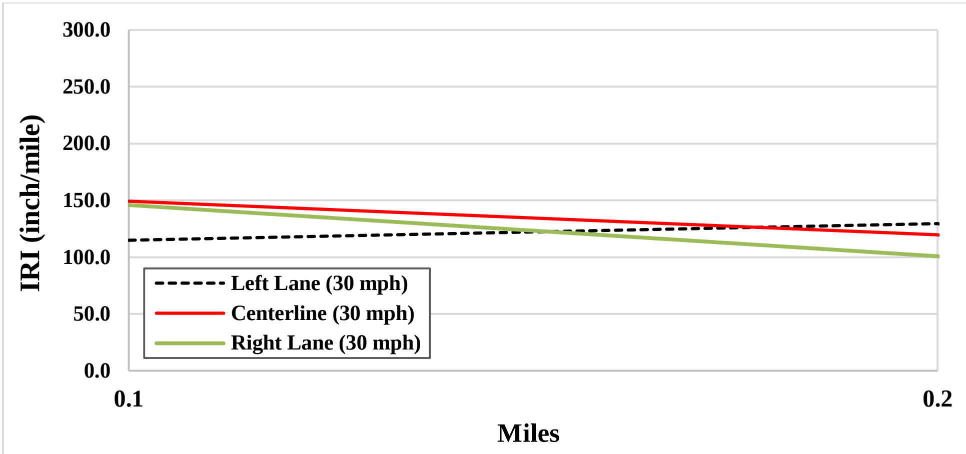


Figure A.9. Estimated average IRI values for Bethany Memorial Airport

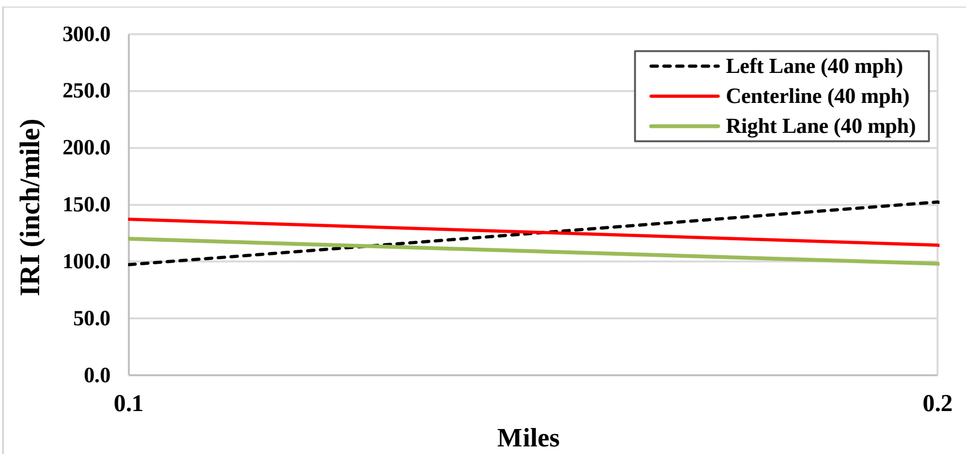
A.4. Bismarck Memorial Airport (Bismarck, MO)

Measurement length: 1,463 ft (0.27 mile)

Figure A.10. Test Location at the Bismarck Memorial Airport (Google)



(a)



(b)

Figure A.11. Plot showing the estimated IRI values for Bismarck Memorial Airport: (a) 30 mph (b) 40 mph

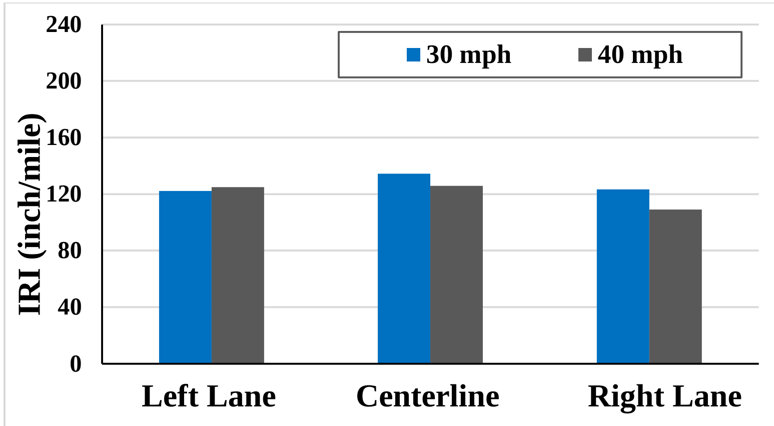
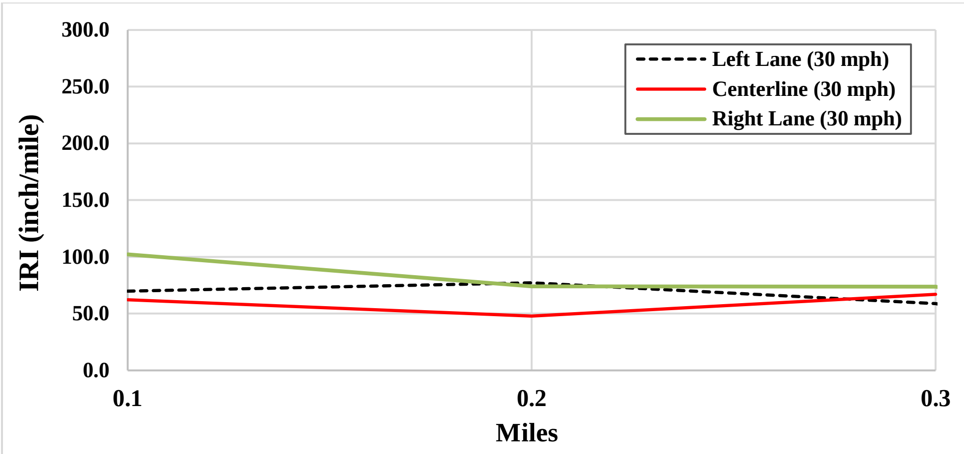


Figure A.12. Estimated average IRI values for Bismarck Memorial Airport

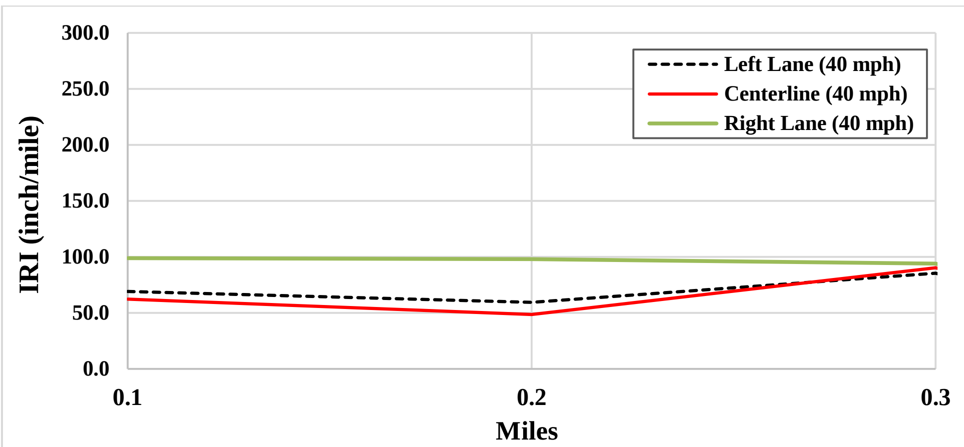
A.5. Bollinger-Crass Memorial Airport (Van Buren, MO)

Measurement length: 1,810 ft (0.34 mile)

Figure A.13. Test Location at the Bollinger-Crass Memorial Airport (Van Buren) (Google)



(a)



(b)

Figure A.14. Plot showing the estimated IRI values for Bollinger-Crass Memorial Airport (Van Buren): (a) 30 mph (b) 40 mph

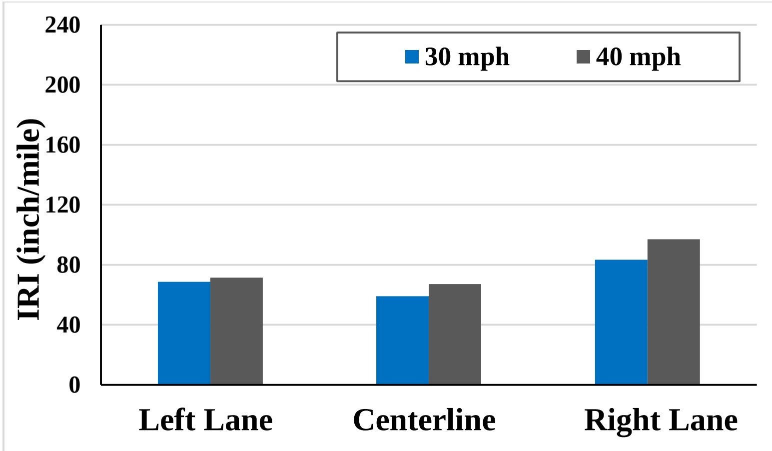
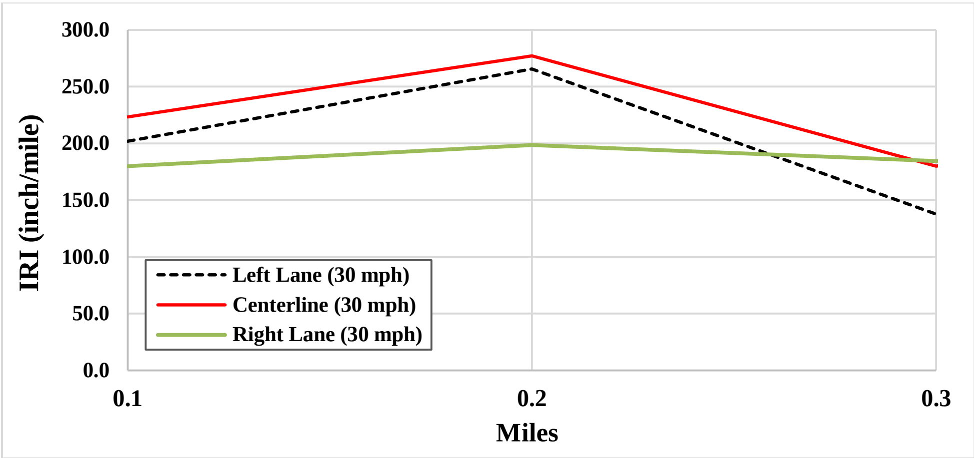


Figure A.15. Estimated average IRI values for Bollinger-Crass Memorial Airport (Van Buren)

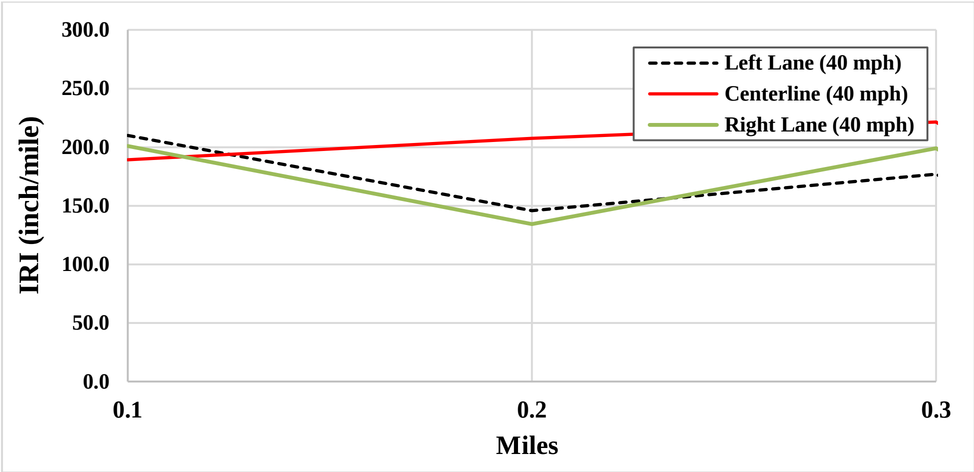
A.6. Bonne Terre Airport (Bonne Terre, MO)

Measurement length: 2,065 ft (0.39 mile)

Figure A.16. Test Location at the Bonne Terre Airport (Google)



(a)



(b)

Figure A.17. Plot showing the estimated IRI values for Bonne Terre Airport: (a) 30 mph (b) 40 mph

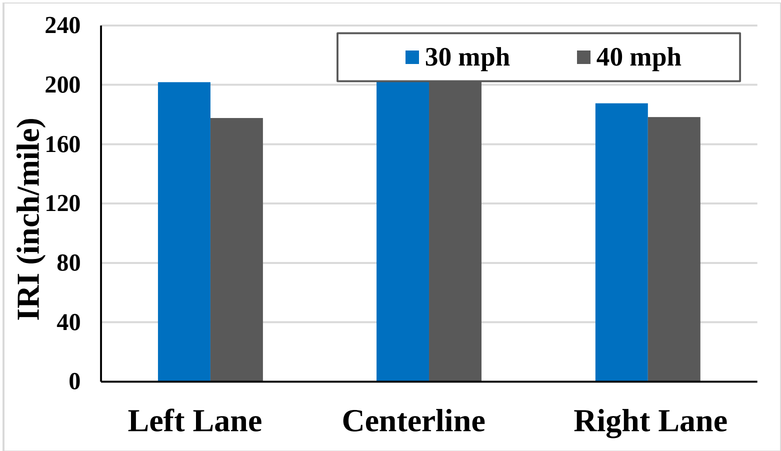
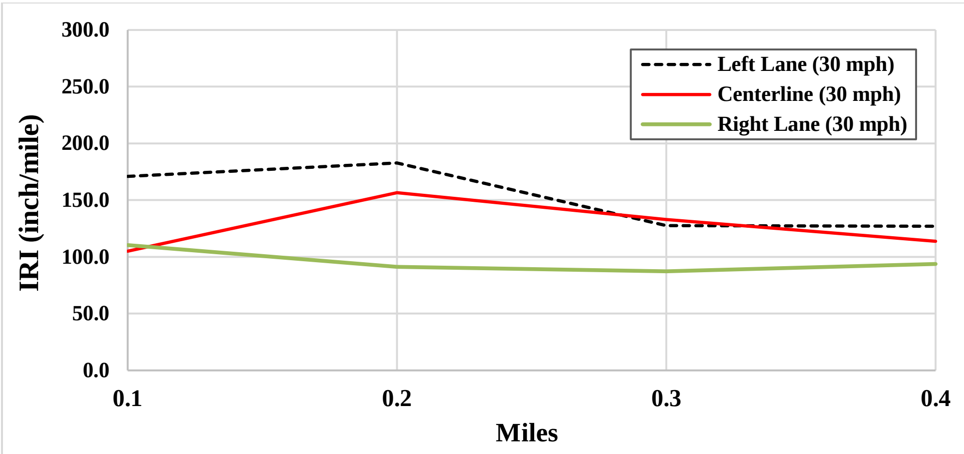


Figure A.18. Estimated average IRI values for Bonne Terre Airport

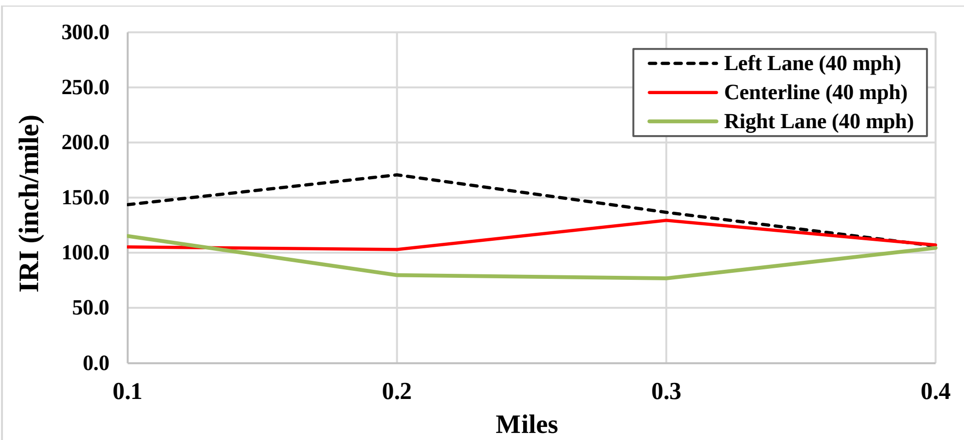
A.7. Buffalo Municipal Airport (Buffalo, MO)

Measurement length: 2,373 ft (0.44 mile)

Figure A.19. Test Location at the Buffalo Municipal Airport (Google)



(a)



(b)

Figure A.20. Plot showing the estimated IRI values for Buffalo Municipal Airport: (a) 30 mph (b) 40 mph

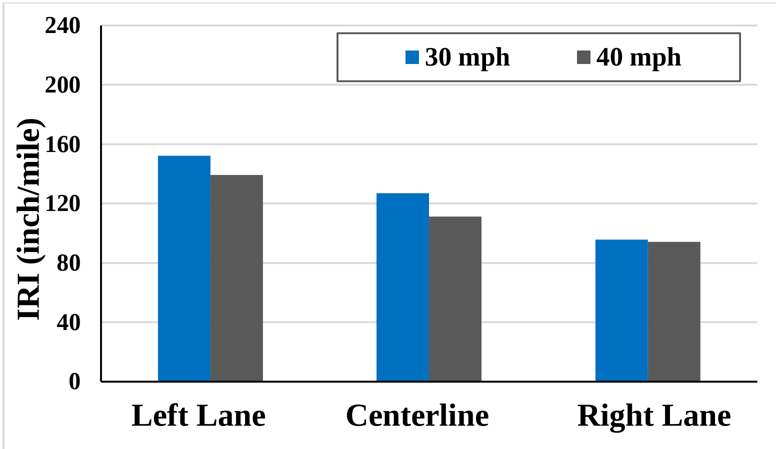
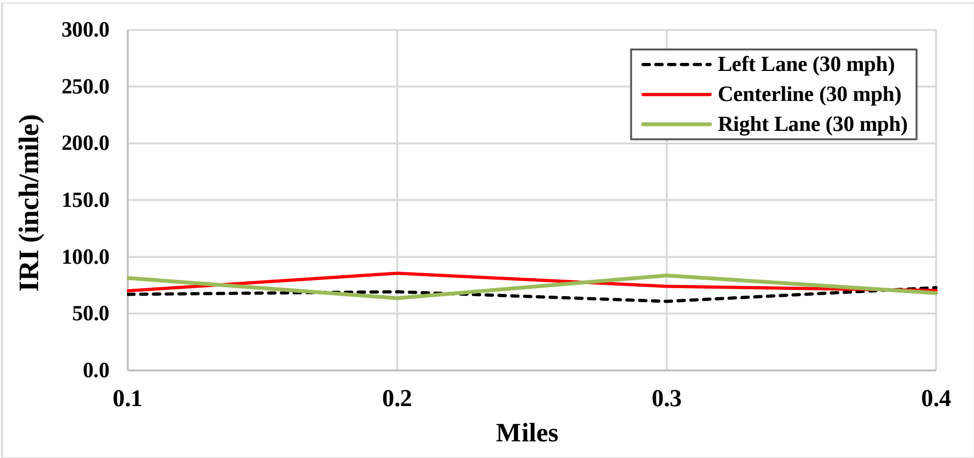


Figure A.21. Estimated average IRI values for Buffalo Municipal Airport

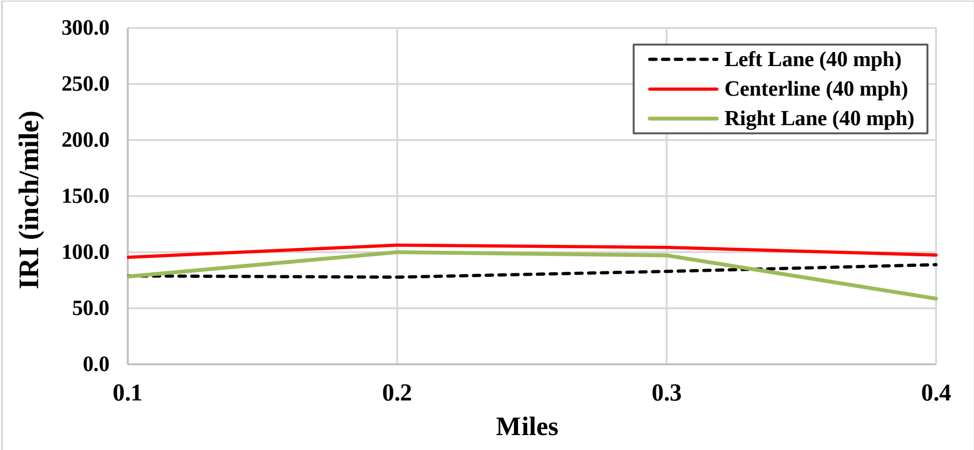
A.8. Campbell Municipal Airport (Clarkton, MO)

Measurement length: 2,374 ft (0.45 mile)

Figure A.22. Test Location at the Campbell Municipal Airport (Google)



(a)



(b)

Figure A.23. Plot showing the estimated IRI values for Campbell Municipal Airport: (a) 30 mph (b) 40 mph

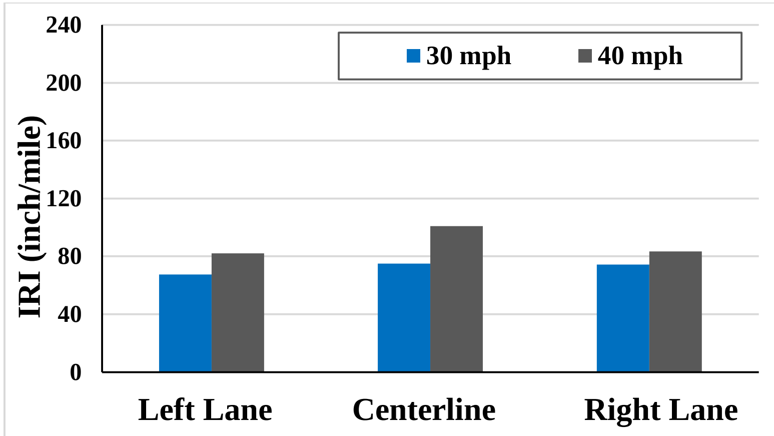
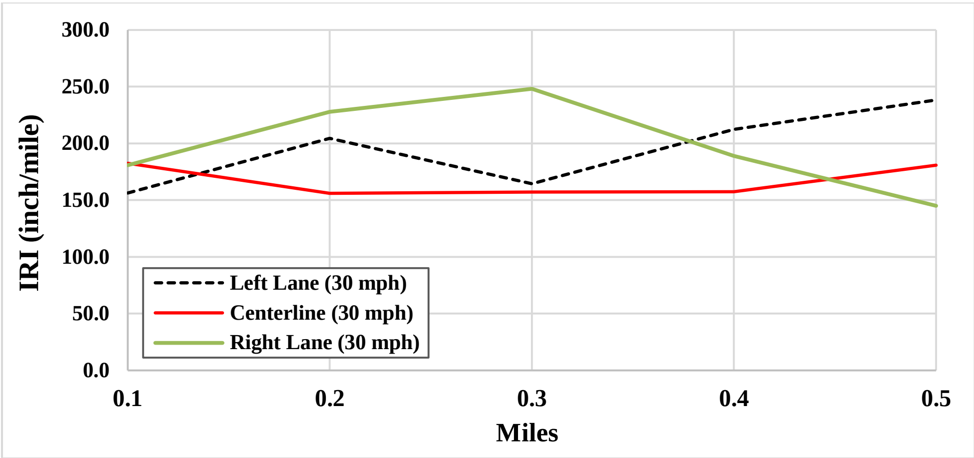


Figure A.24. Estimated average IRI values for Campbell Municipal Airport

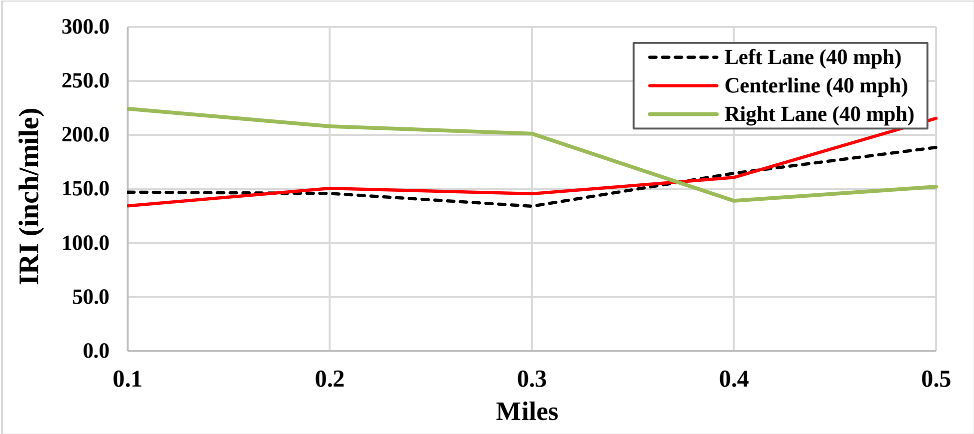
A.9. Capt. Ben Smith Airfield (Monroe City, MO)

Measurement length: 2,692 ft (0.51 mile)

Figure A.25. Test Location at the Capt. Ben Smith Airfield (Google)



(a)



(b)

Figure A.26. Plot showing the estimated IRI values for Capt. Ben Smith Airfield: (a) 30 mph (b) 40 mph

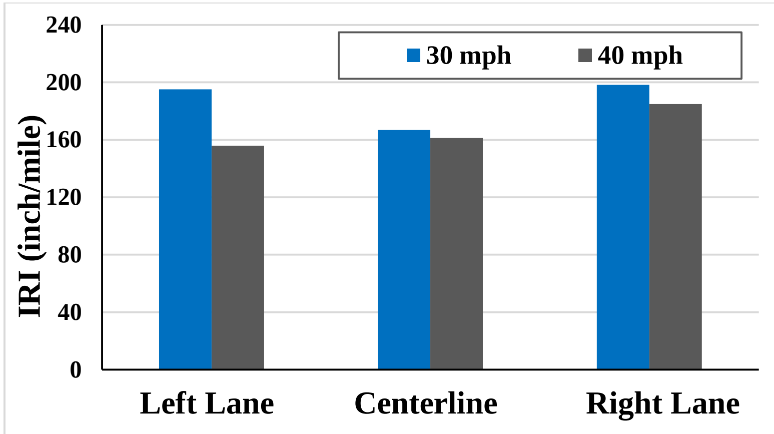
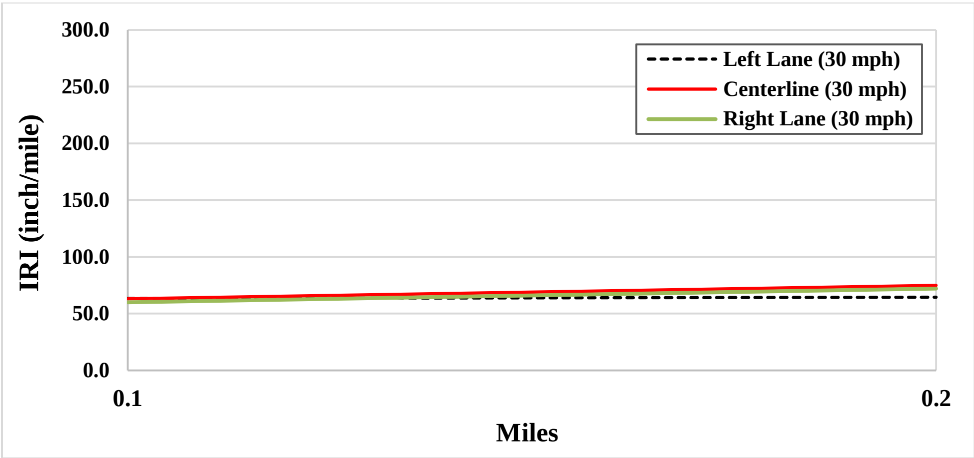


Figure A.27. Estimated average IRI values for Capt. Ben Smith Airfield

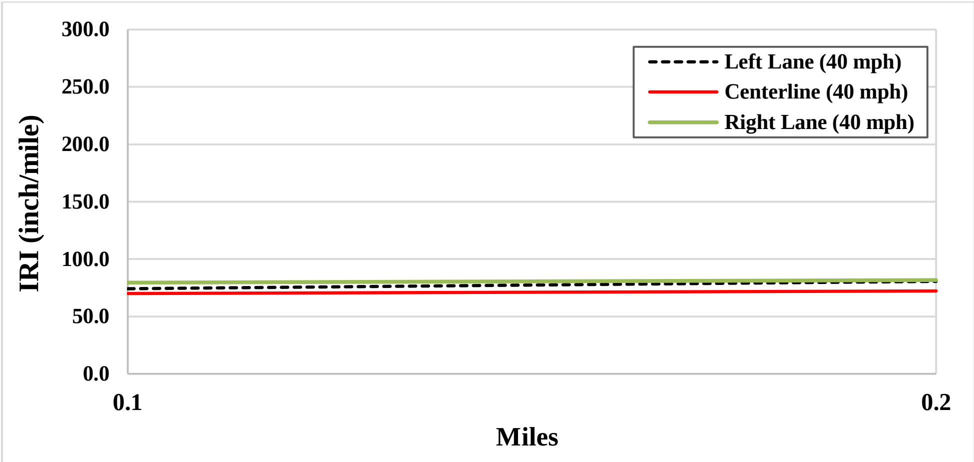
A.10. Carrollton Memorial Airport (Carrollton, MO)

Measurement length: 1,577 ft (0.29 mile)

Figure A.28. Test Location at the Carrollton Memorial Airport (Google)



(a)



(b)

Figure A.29. Plot showing the estimated IRI values for Carrollton Memorial Airport: (a) 30 mph (b) 40 mph

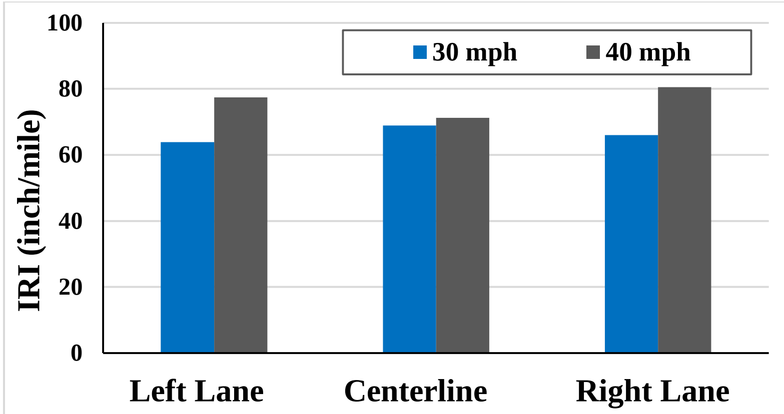
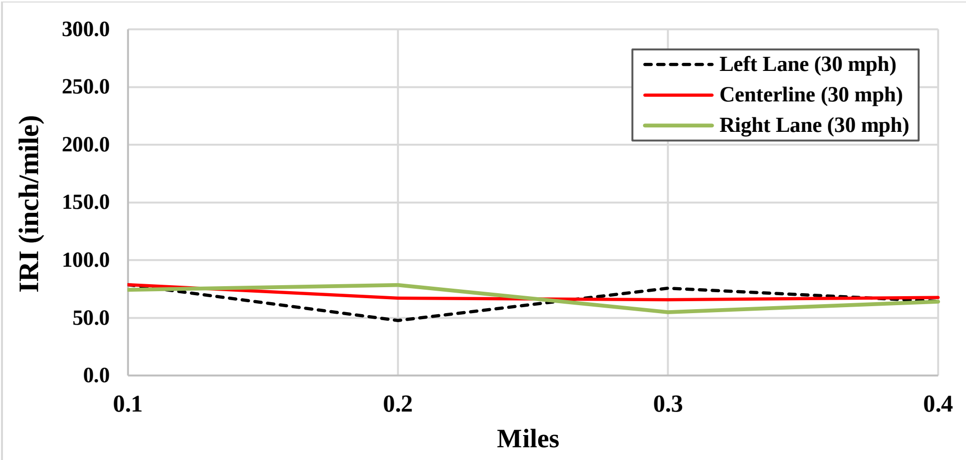


Figure A.30. Estimated average IRI values for Carrollton Memorial Airport

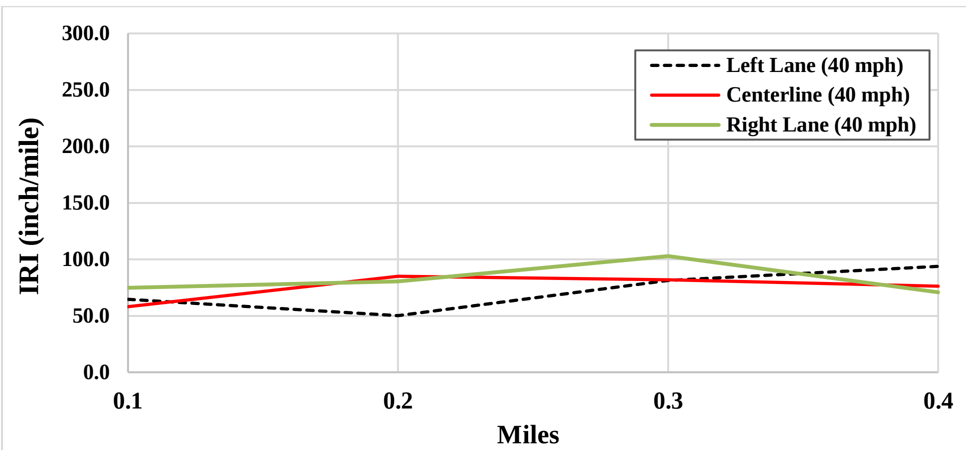
A.11. Doniphan Municipal Airport (Doniphan, MO)

Measurement length: 2,190 ft (0.41 mile)

Figure A.31. Test Location at the Doniphan Municipal Airport (Google)



(a)



(b)

Figure A.32. Plot showing the estimated IRI values for Doniphan Municipal Airport: (a) 30 mph (b) 40 mph

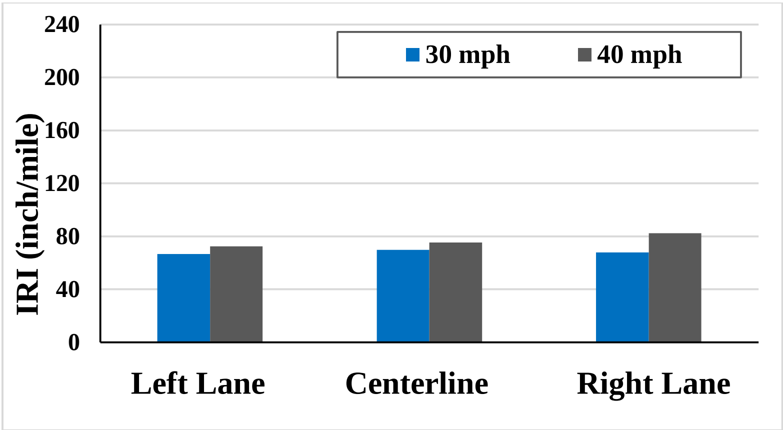
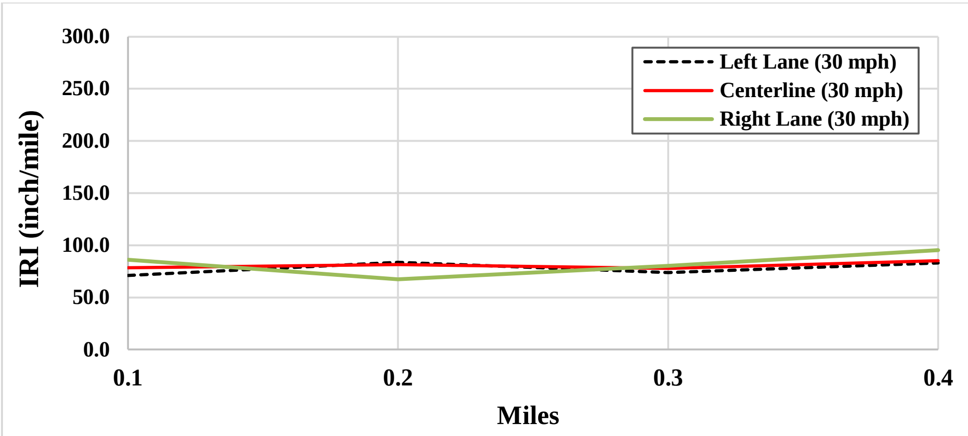


Figure A.33. Estimated average IRI values for Doniphan Municipal Airport

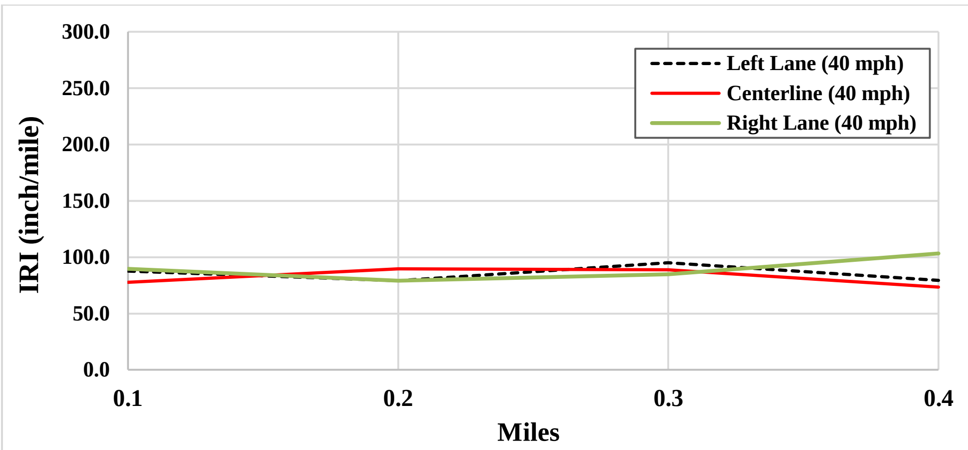
A.12. El Dorado Springs Memorial Airport (El Dorado Springs, MO)

Measurement length: 2,592 ft (0.49 mile)

Figure A.34. Test Location at the El Dorado Springs Memorial Airport (Google)



(a)



(b)

Figure A.35. Plot showing the estimated IRI values for El Dorado Springs Memorial Airport: (a) 30 mph (b) 40 mph

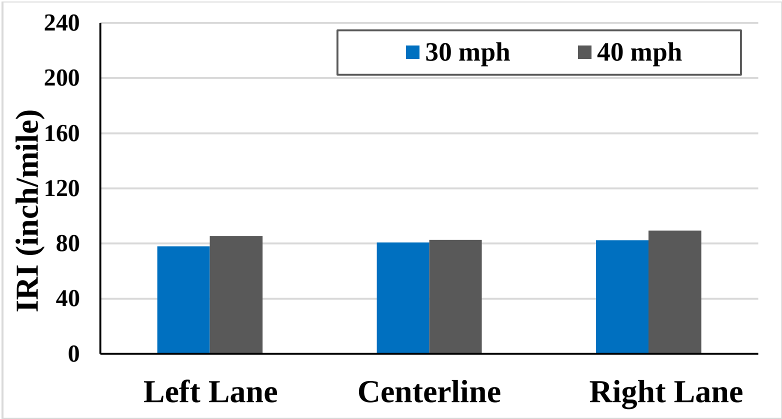
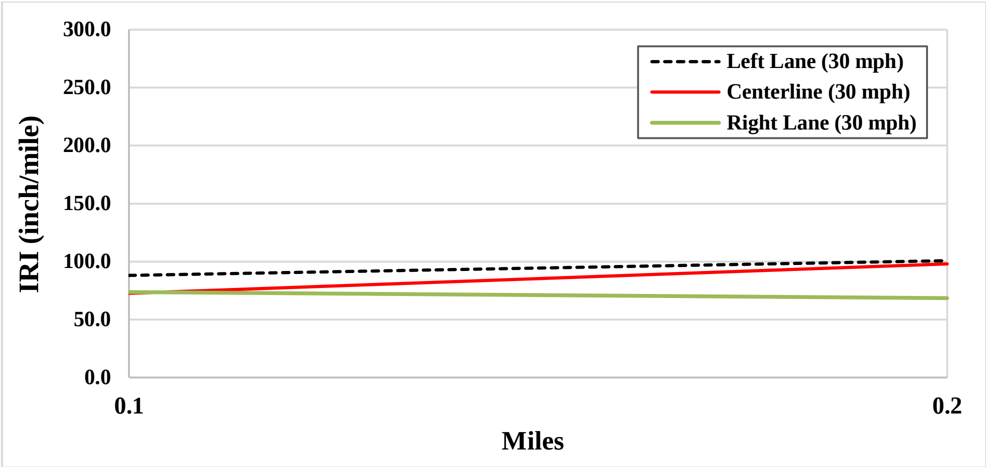


Figure A.36. Estimated average IRI values for El Dorado Springs Memorial Airport

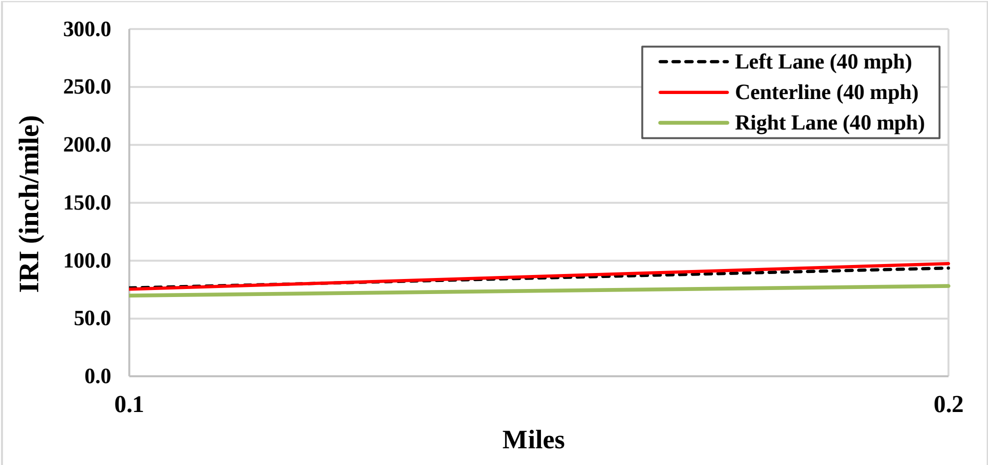
A.13. Excelsior Springs Memorial Airport (Excelsior Springs, MO)

Measurement length: 1,378 ft (0.26 mile)

Figure A.37. Test Location at the Excelsior Springs Memorial Airport (Google)



(a)



(b)

Figure A.38. Plot showing the estimated IRI values for Excelsior Springs Memorial Airport: (a) 30 mph (b) 40 mph

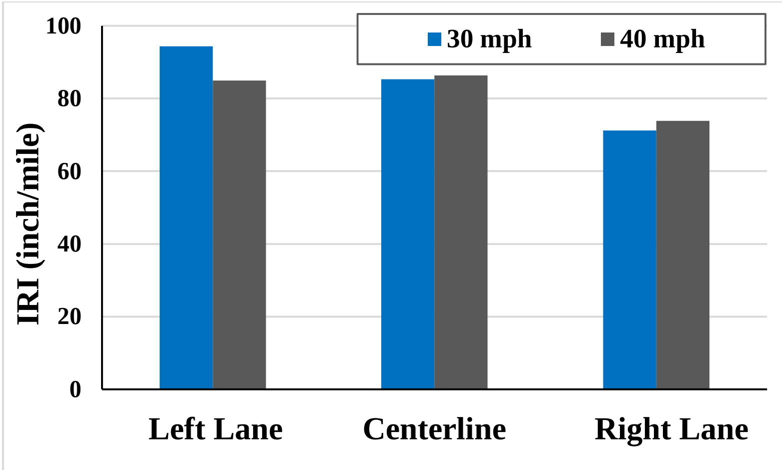
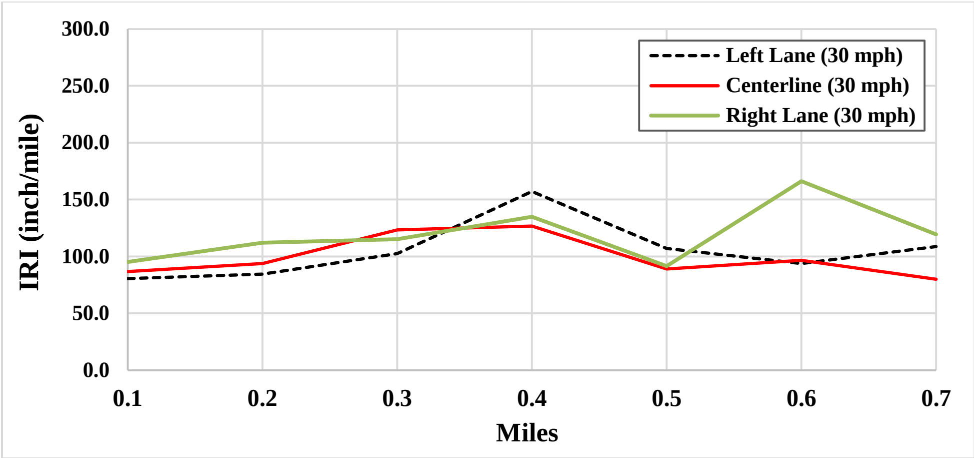


Figure A.39. Estimated average IRI values for Excelsior Springs Memorial Airport

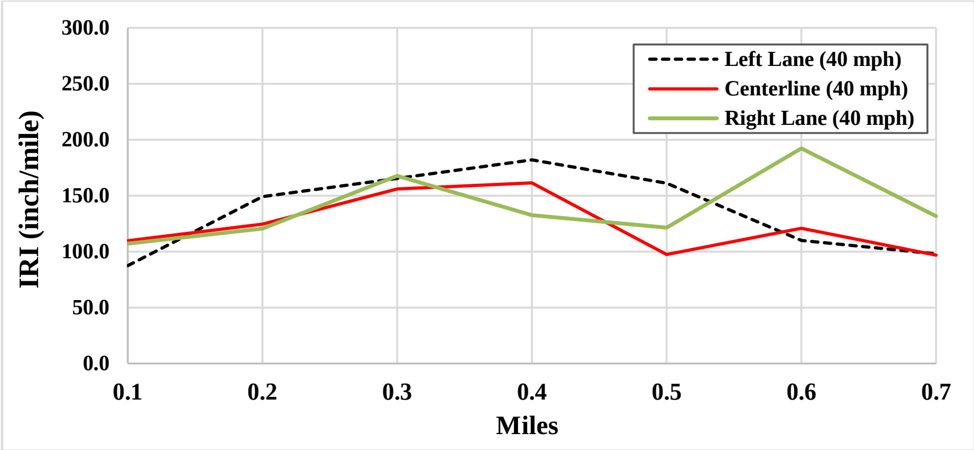
A.14. Gideon Memorial Airport (Gideon, MO)

Measurement length: 3,848 ft (0.73 mile)

Figure A.40. Test Location at the Gideon Memorial Airport (Google)



(a)



(b)

Figure A.41. Plot showing the estimated IRI values for Gideon Memorial Airport: (a) 30 mph (b) 40 mph

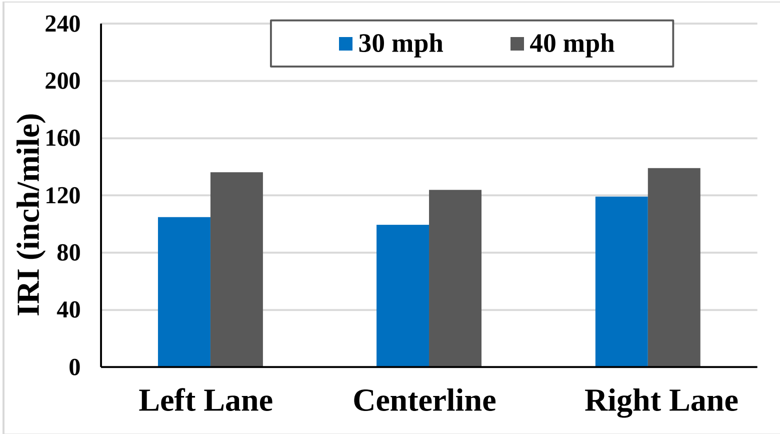
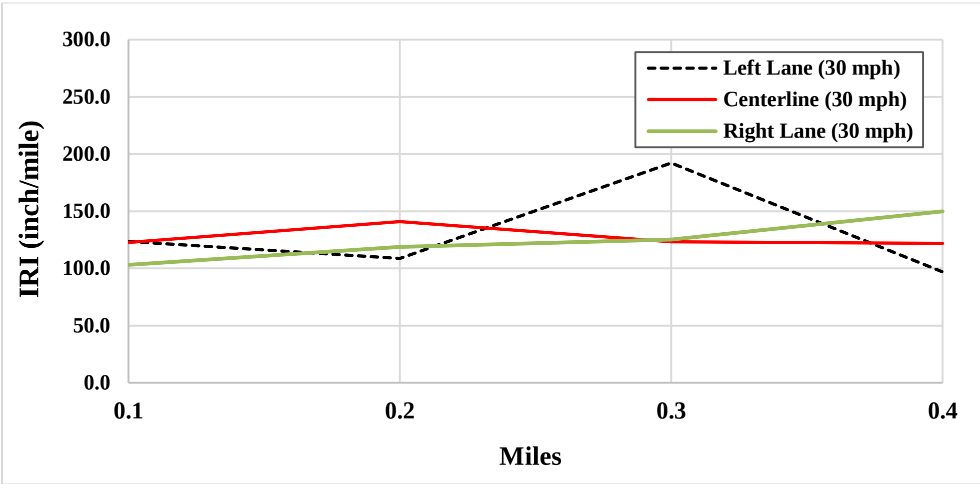


Figure A.42. Estimated average IRI values for Gideon Memorial Airport

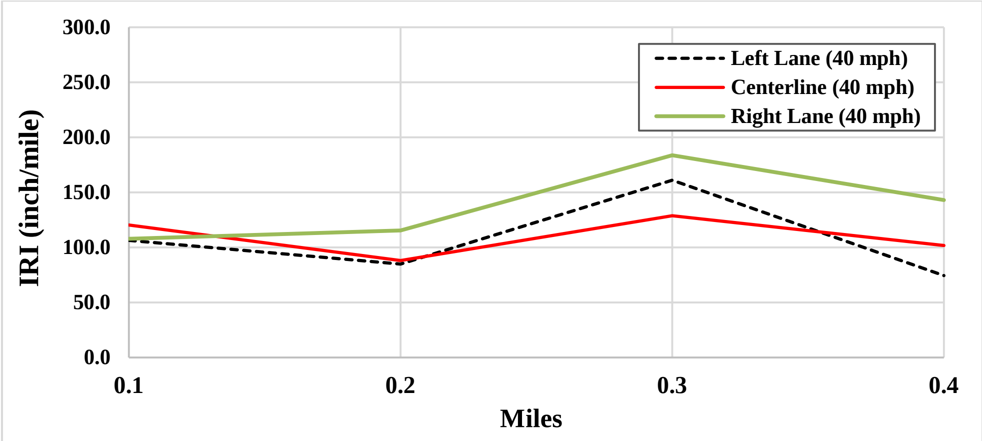
A.15. Hermann Municipal Airport (Rhineland, MO)

Measurement length: 2,305 ft (0.44 mile)

Figure A.43. Test Location at the Hermann Municipal Airport (Google)



(a)



(b)

Figure A.44. Plot showing the estimated IRI values for Hermann Municipal Airport: (a) 30 mph (b) 40 mph

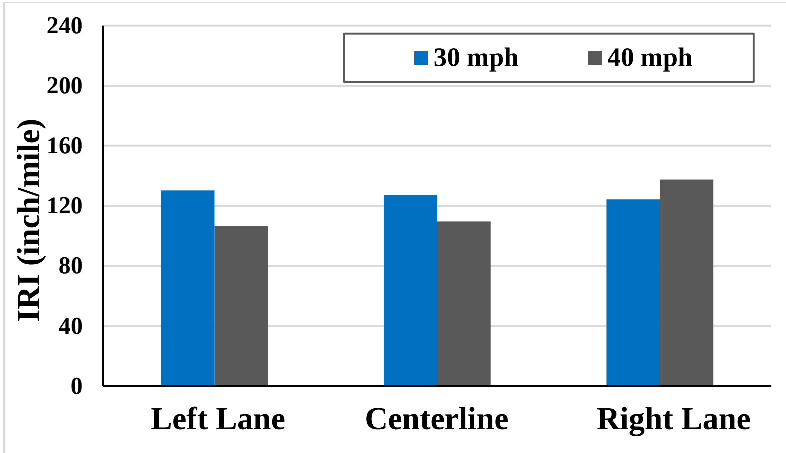
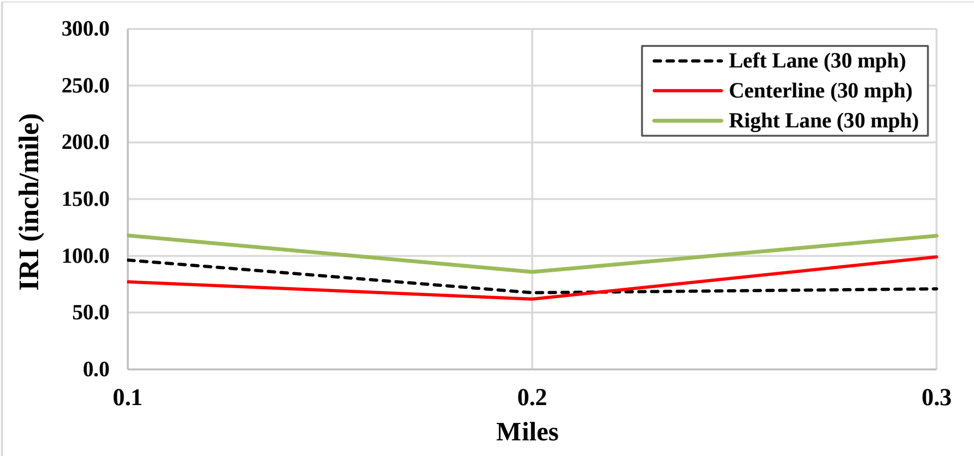


Figure A.45. Estimated average IRI values for Hermann Municipal Airport

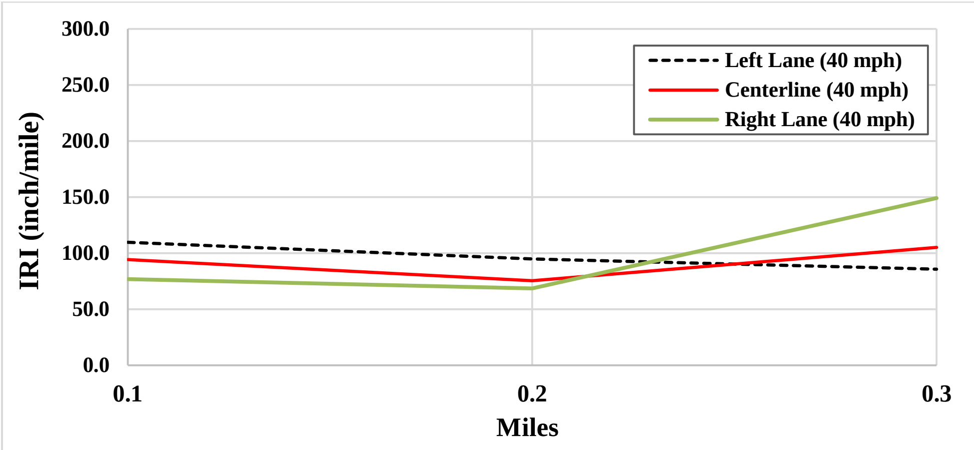
A.16. Hornersville Memorial Airport (Hornersville, MO)

Measurement length: 1,941 ft (0.37 mile)

Figure A.46. Test Location at the Hornersville Memorial Airport (Google)



(a)



(b)

Figure A.47. Plot showing the estimated IRI values for Hornersville Memorial Airport: (a) 30 mph (b) 40 mph

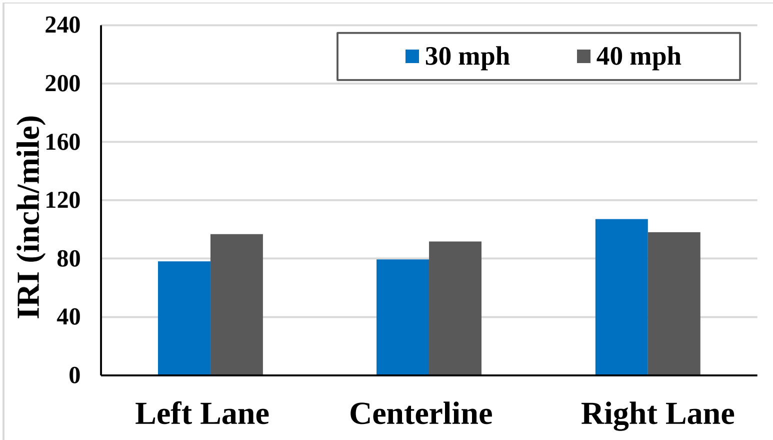
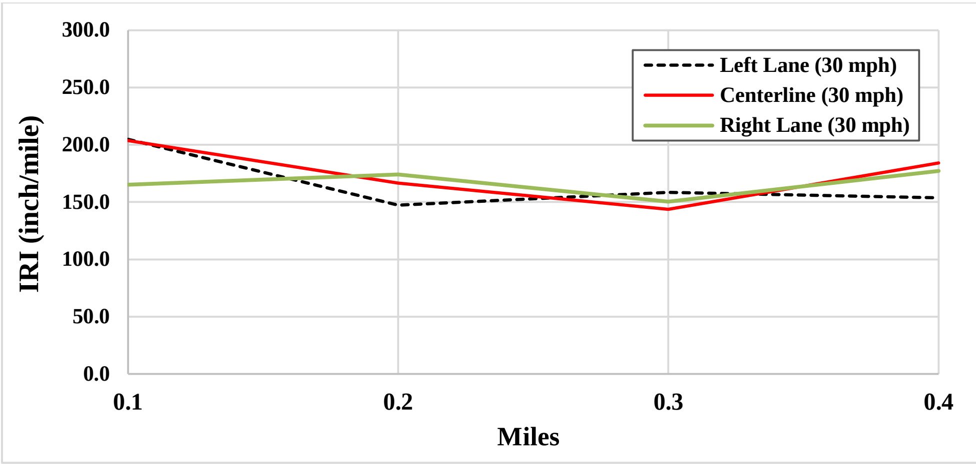


Figure A.48. Estimated average IRI values for Hornersville Memorial Airport

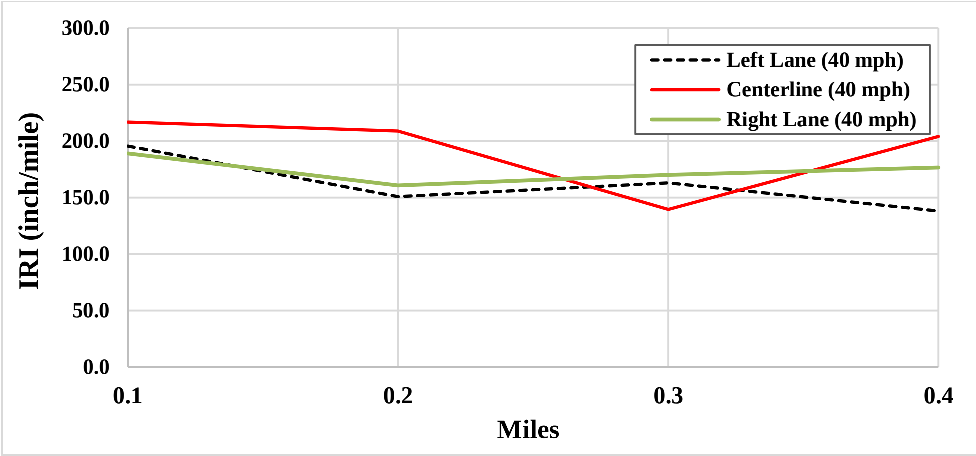
A.17. Mansfield Municipal Airport (Mansfield, MO)

Measurement length: 1,941 ft (0.37 mile)

Figure A.49. Test Location at the Mansfield Municipal Airport (Google)



(a)



(b)

Figure A.50. Plot showing the estimated IRI values for Mansfield Municipal Airport: (a) 30 mph (b) 40 mph

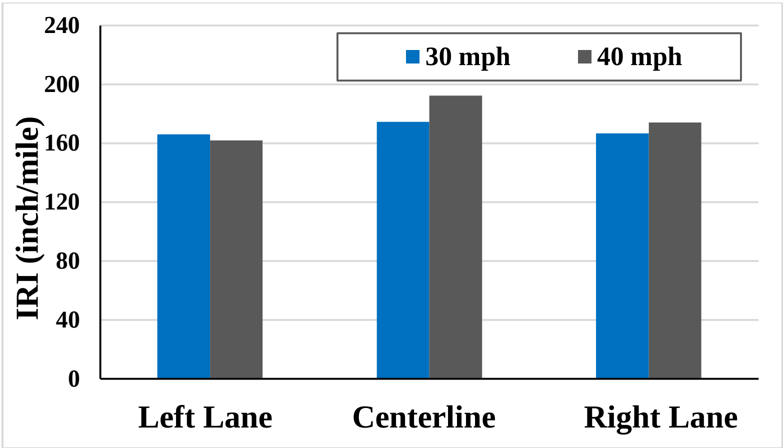
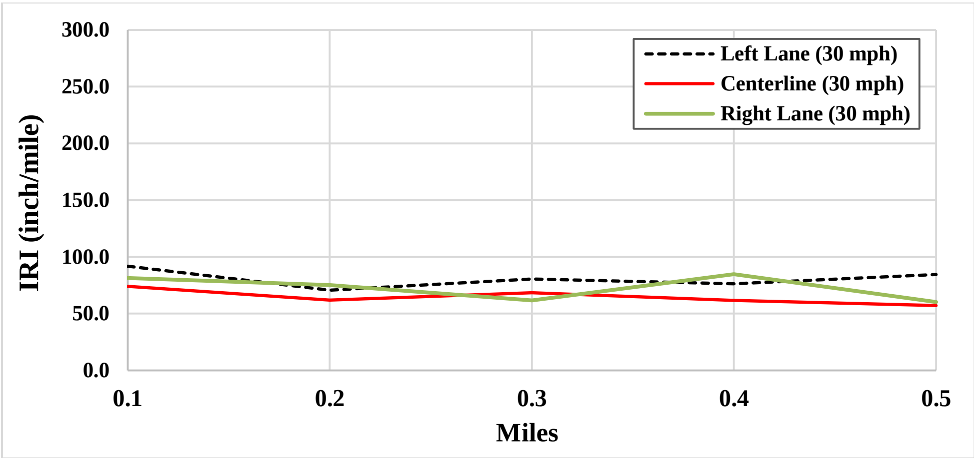


Figure A.51. Estimated average IRI values for Mansfield Municipal Airport

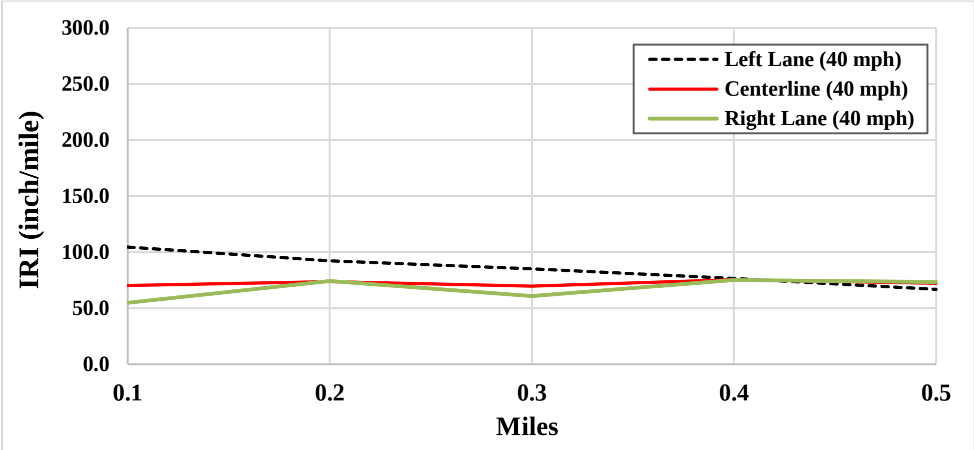
A.18. M. Graham Clark Downtown Airport (Branson, MO)

Measurement length: 2,750 ft (0.52 mile)

Figure A.52. Test Location at the M. Graham Clark Downtown Airport (Google)



(a)



(b)

Figure A.53. Plot showing the estimated IRI values for M. Graham Clark Downtown Airport: (a) 30 mph (b) 40 mph

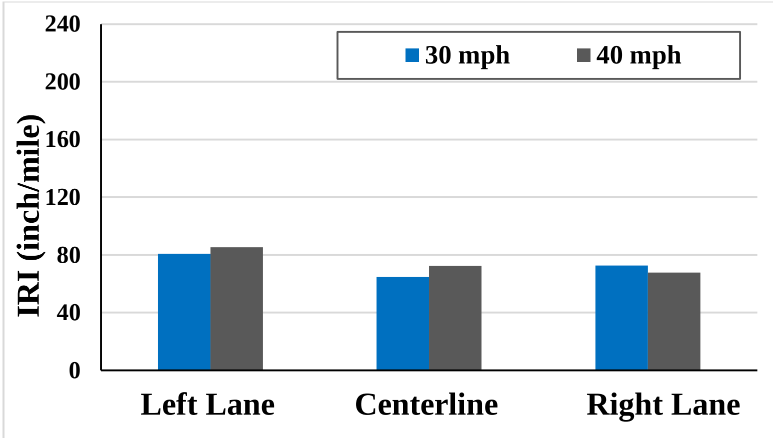
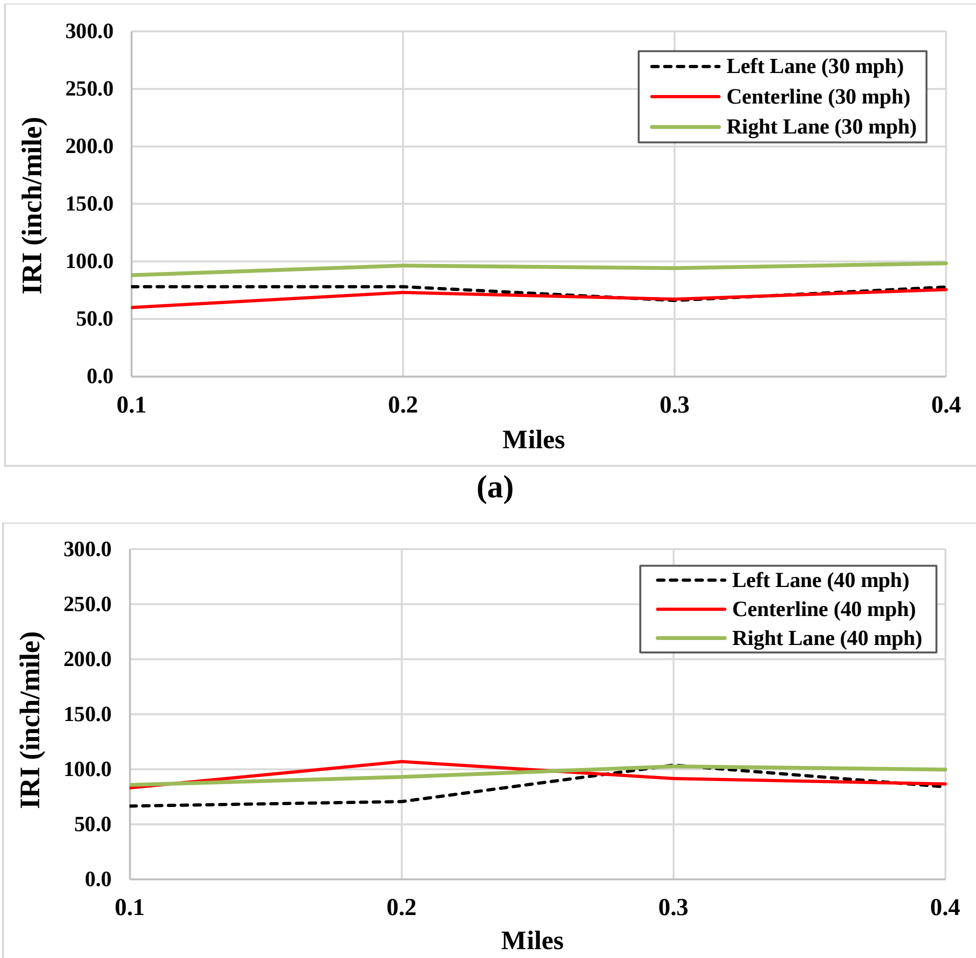


Figure A.54. Estimated average IRI values for M. Graham Clark Downtown Airport

A.19. Mississippi County Airport (Mississippi County, MO)

Measurement length: 2,181 ft (0.41 mile)

Figure A.55. Test Location at the Mississippi County Airport (Google)



(a)

(b)

Figure A.56. Plot showing the estimated IRI values for Mississippi County Airport: (a) 30 mph (b) 40 mph

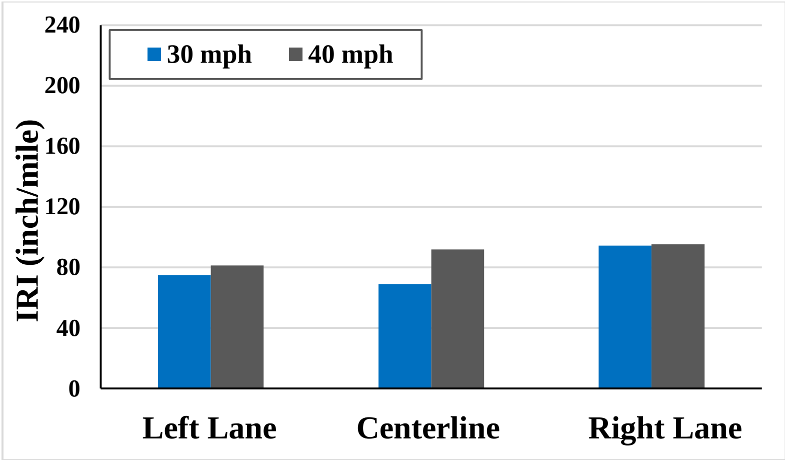
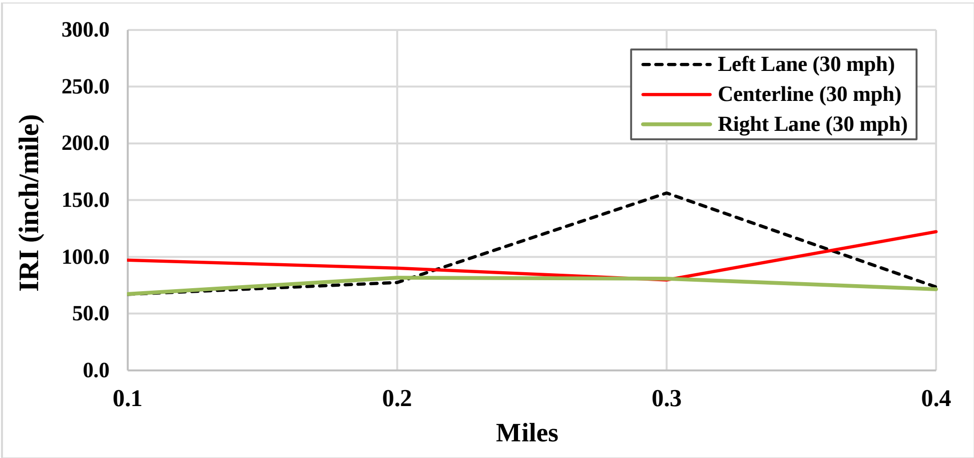


Figure A.57. Estimated average IRI values for Mississippi County Airport

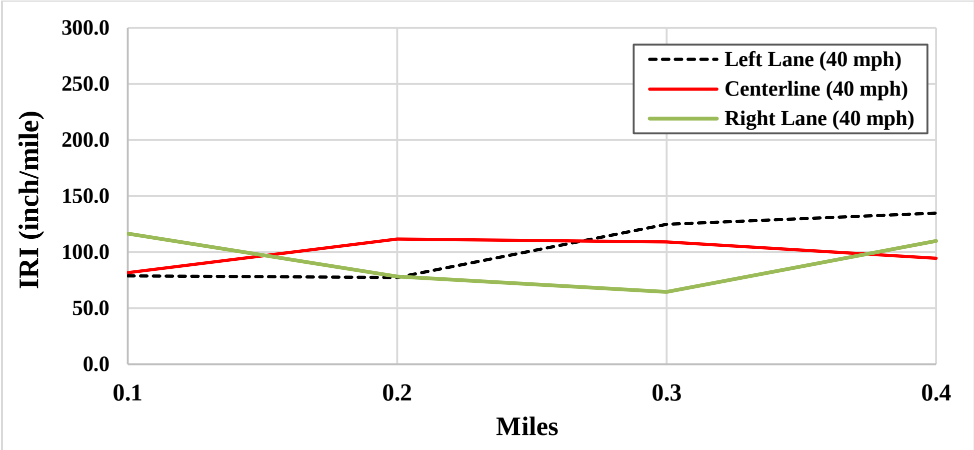
A.20. Mount Vernon Municipal Airport (Mount Vernon, MO)

Measurement length: 2,529 ft (0.48 mile)

Figure A.58. Test Location at the Mount Vernon Municipal Airport (Google)



(a)



(b)

Figure A.59. Plot showing the estimated IRI values for Mount Vernon Municipal Airport: (a) 30 mph (b) 40 mph

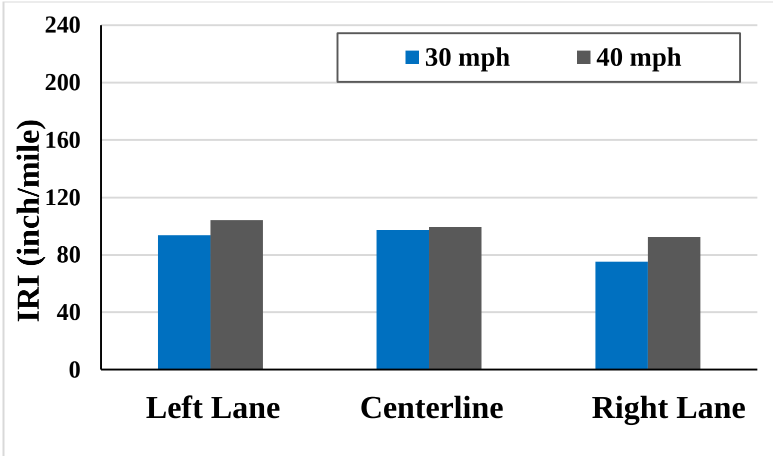
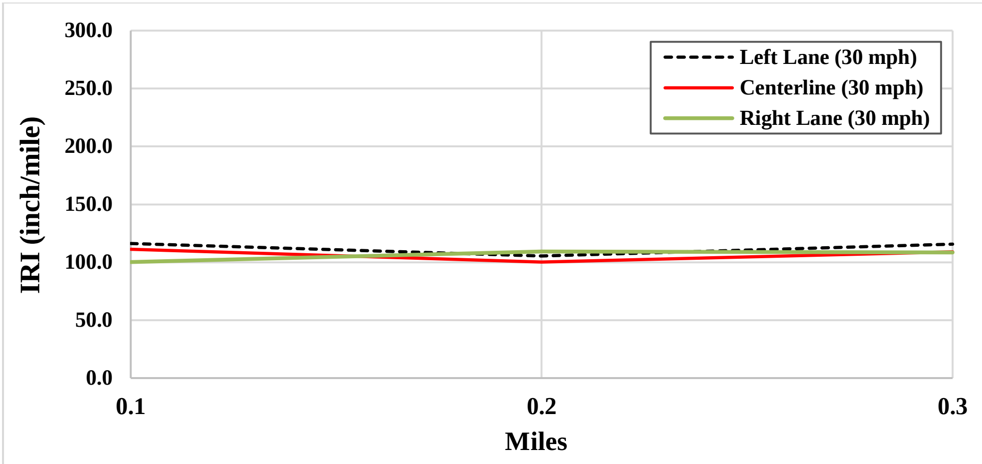


Figure A.60. Estimated average IRI values for Mount Vernon Municipal Airport

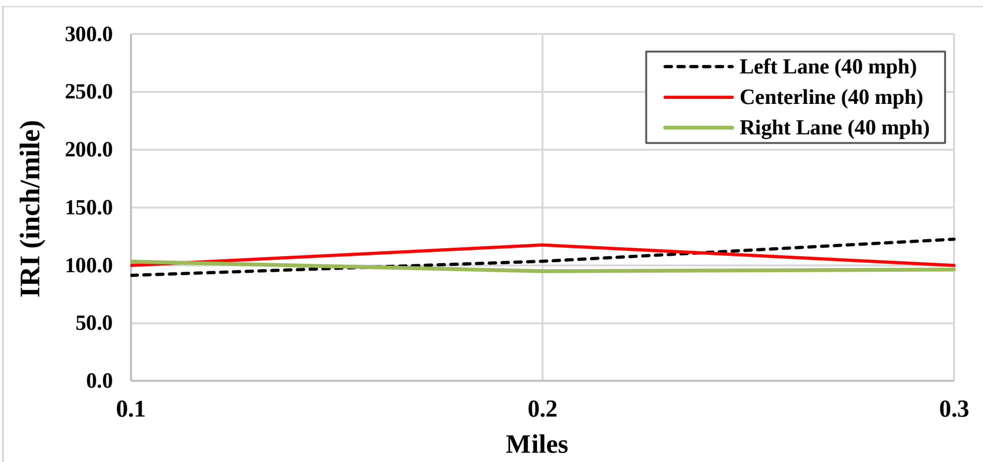
A.21. Richland Municipal Airport (Richland, MO)

Measurement length: 2,102 ft (0.39 mile)

Figure A.61. Test Location at the Richland Municipal Airport (Google)



(a)



(b)

Figure A.62. Plot showing the estimated IRI values for Richland Municipal Airport: (a) 30 mph (b) 40 mph

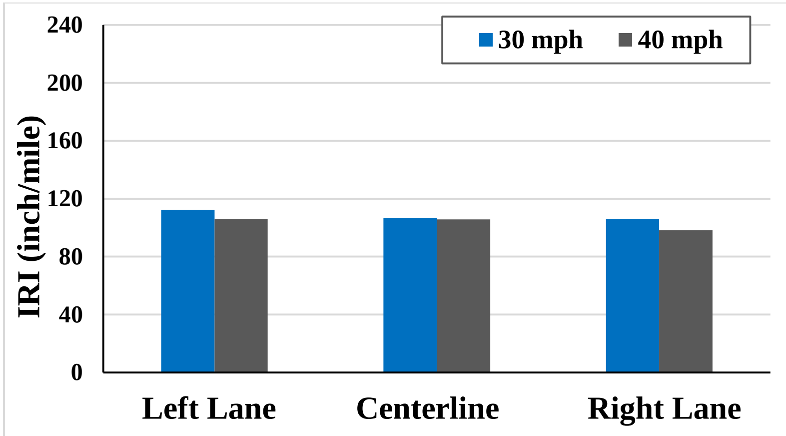
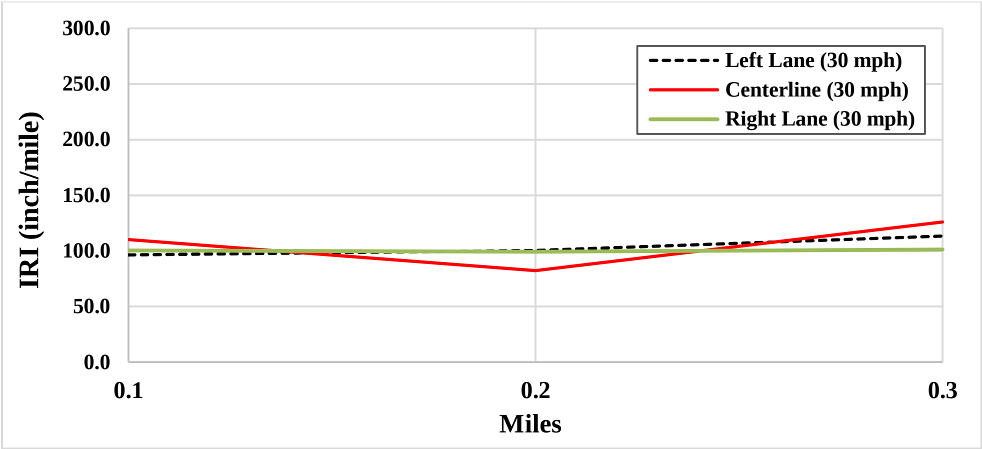


Figure A.63. Estimated average IRI values for Richland Municipal Airport

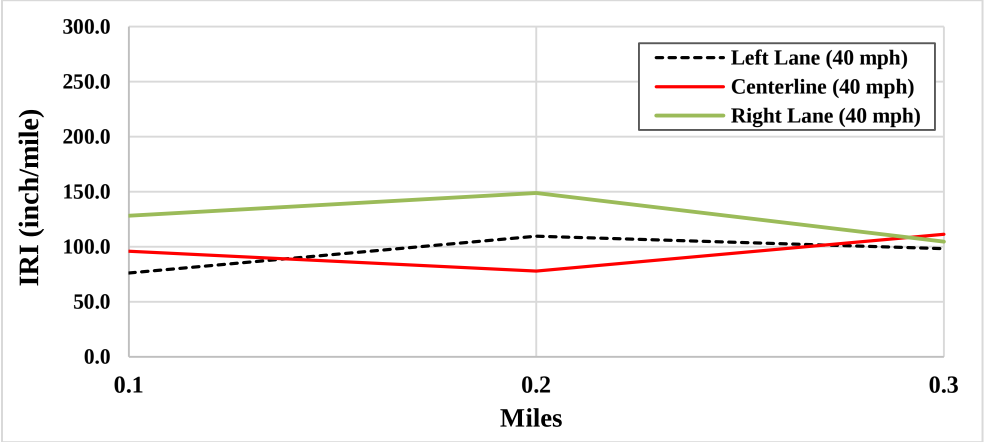
A.22. Roy Otten Memorial Airfield (Versailles, MO)

Measurement length: 2,529 ft (0.48 mile)

Figure A.64. Test Location at the Roy Otten Memorial Airfield (Google)



(a)



(b)

Figure A.65. Plot showing the estimated IRI values for Roy Otten Memorial Airfield: (a) 30 mph (b) 40 mph

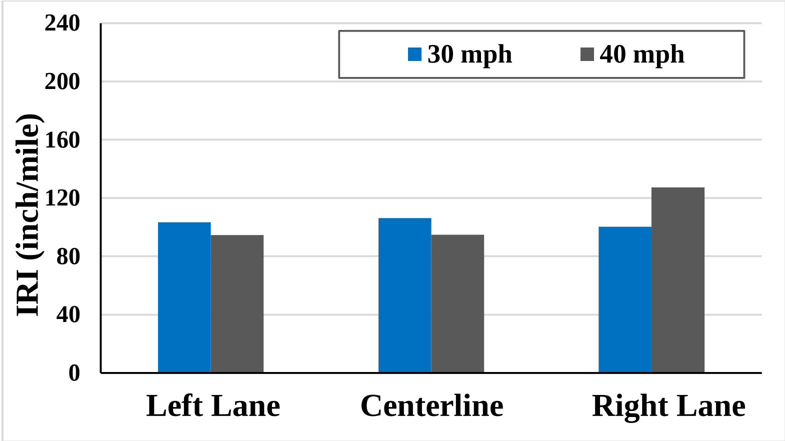
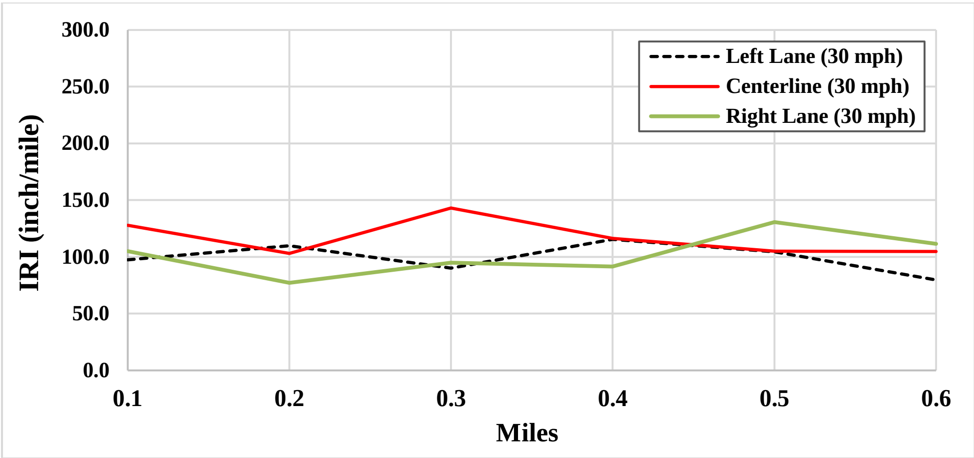


Figure A.66. Estimated average IRI values for Roy Otten Memorial Airfield

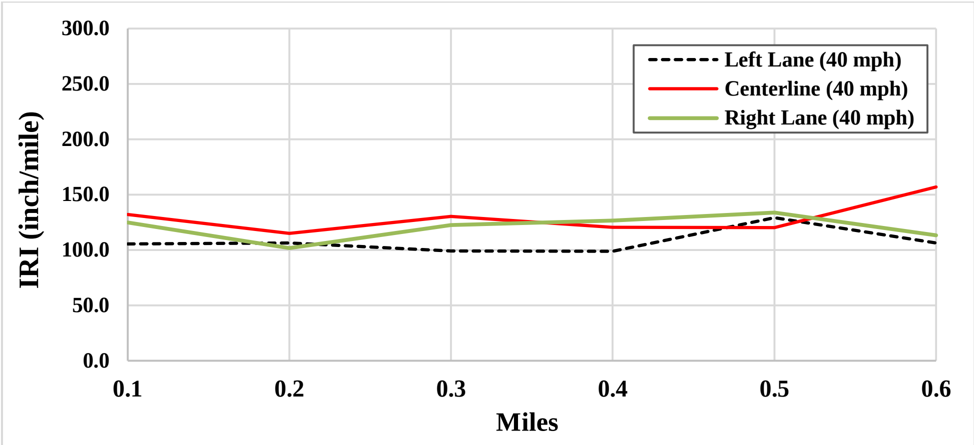
A.23. Steele Municipal Airport (Steele, MO)

Measurement length: 3,176 ft (0.6 mile)

Figure A.67. Test Location at the Steele Municipal Airport (Google)



(a)



(b)

Figure A.68. Plot showing the estimated IRI values for Steele Municipal Airport: (a) 30 mph (b) 40 mph

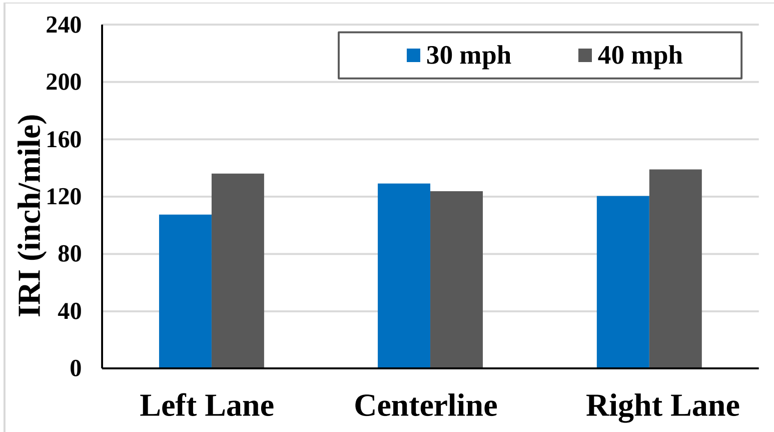
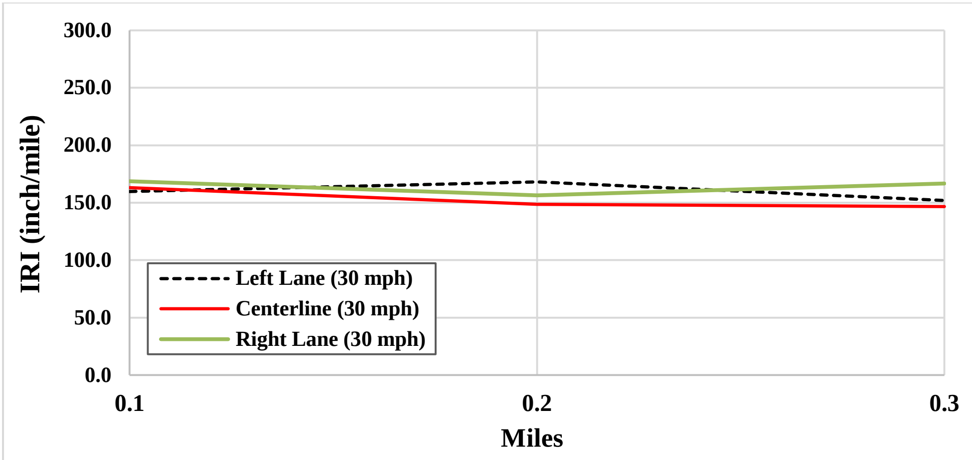


Figure A.69. Estimated average IRI values for Steele Municipal Airport

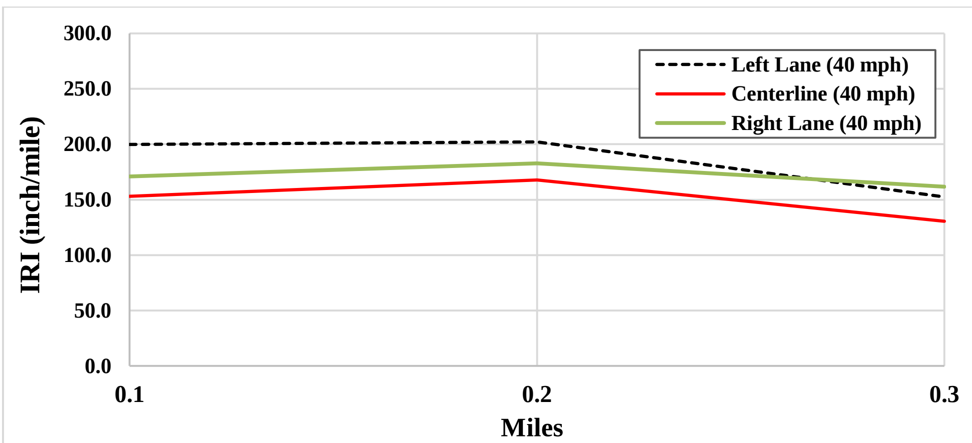
A.24. Stockton Municipal Airport (Stockton, MO)

Measurement length: 2,050 ft (0.39 mile)

Figure A.70. Test Location at the Stockton Municipal Airport (Google)



(a)



(b)

Figure A.71. Plot showing the estimated IRI values for Stockton Municipal Airport: (a) 30 mph (b) 40 mph

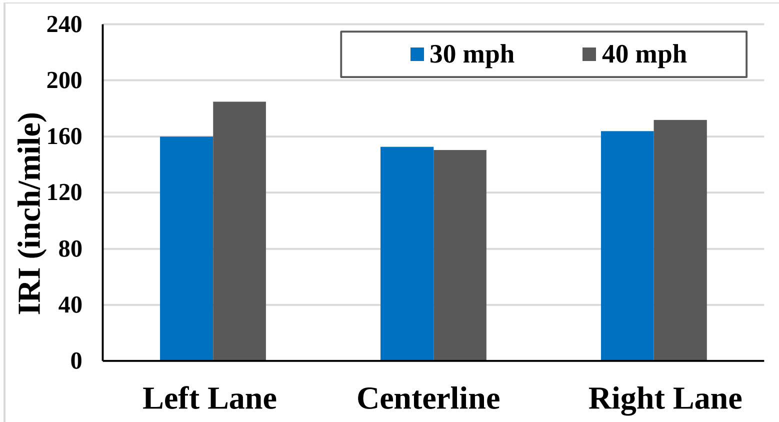
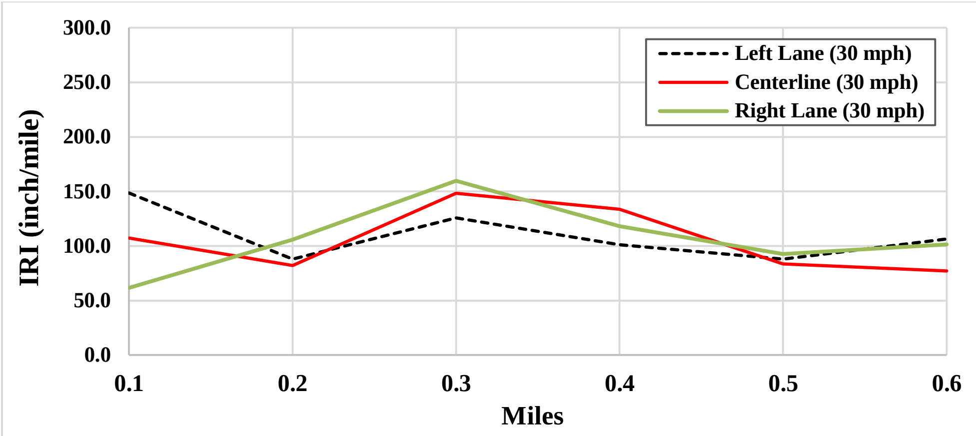


Figure A.72. Estimated average IRI values for Stockton Municipal Airport

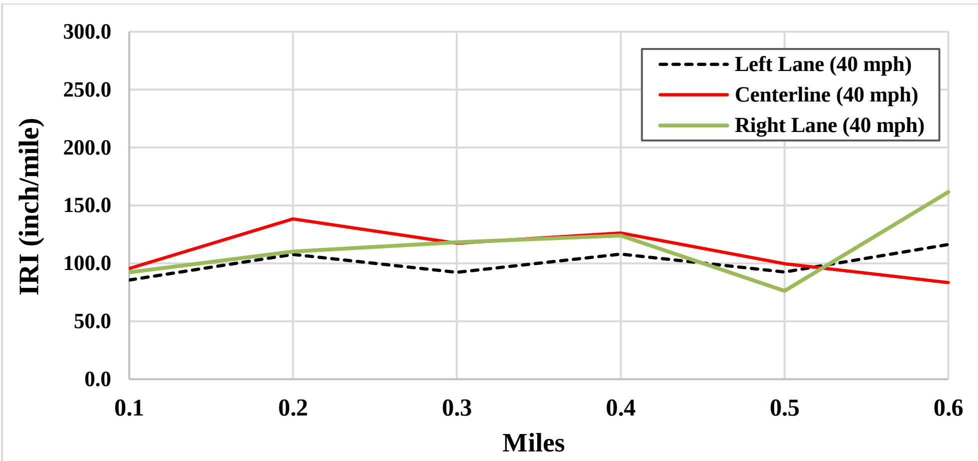
A.25. Thayer Memorial Airport (Thayer, MO)

Measurement length: 3,534 ft (0.67 mile)

Figure A.73. Test Location at the Thayer Memorial Airport (Google)



(a)



(b)

Figure A.74. Plot showing the estimated IRI values for Thayer Memorial Airport: (a) 30 mph (b) 40 mph

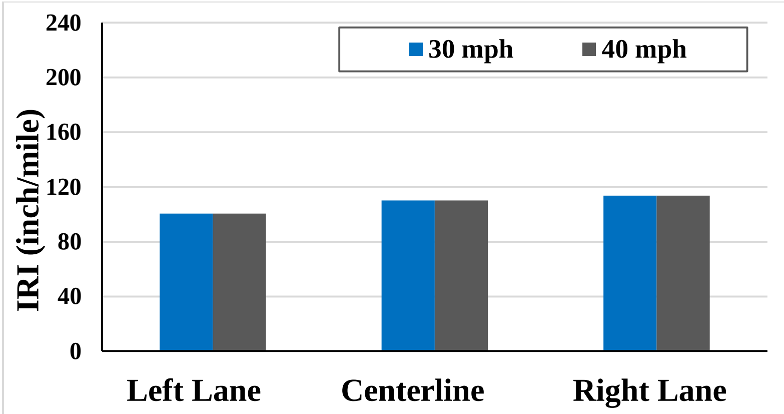


Figure A.75. Estimated average IRI values for Thayer Memorial Airport

A.26. Unionville Municipal Airport (Unionville, MO)

Measurement length: 2,175 ft (0.41 mile)

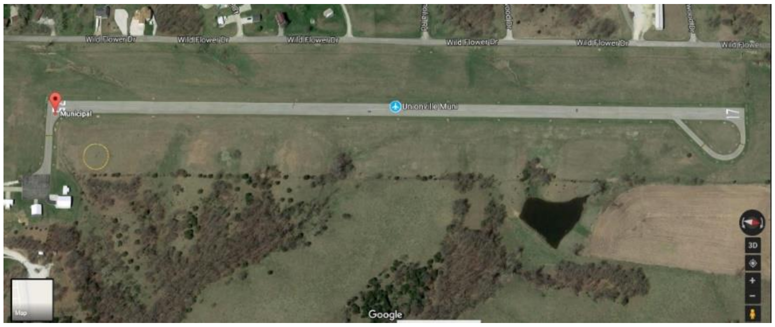
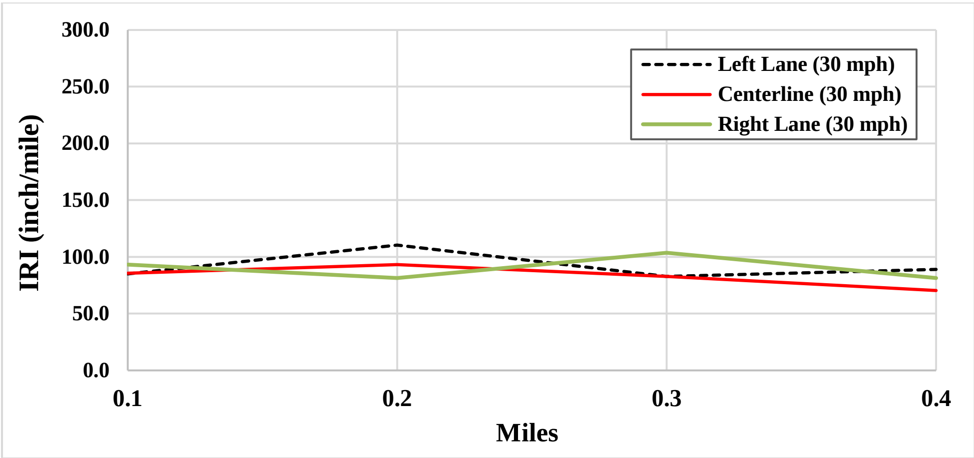
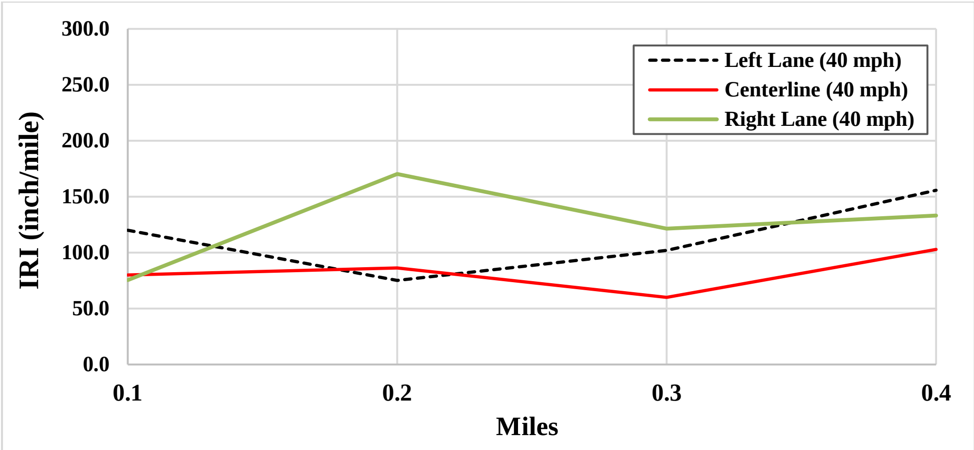


Figure A.76. Test Location at the Unionville Municipal Airport (Google)



(a)



(b)

Figure A.77. Plot showing the estimated IRI values for Unionville Municipal Airport: (a) 30 mph (b) 40 mph

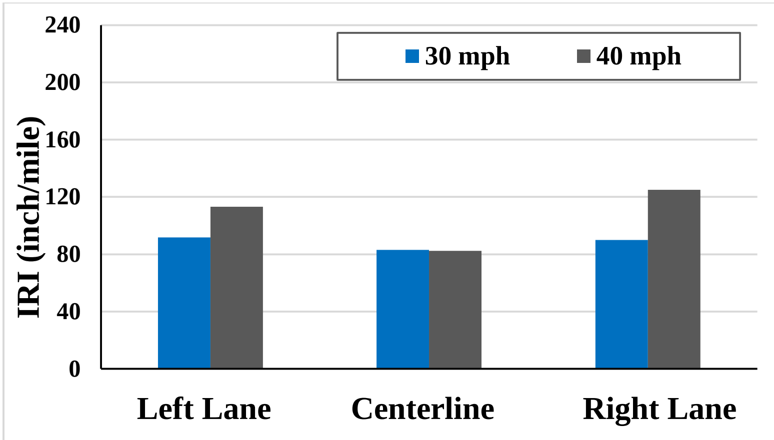
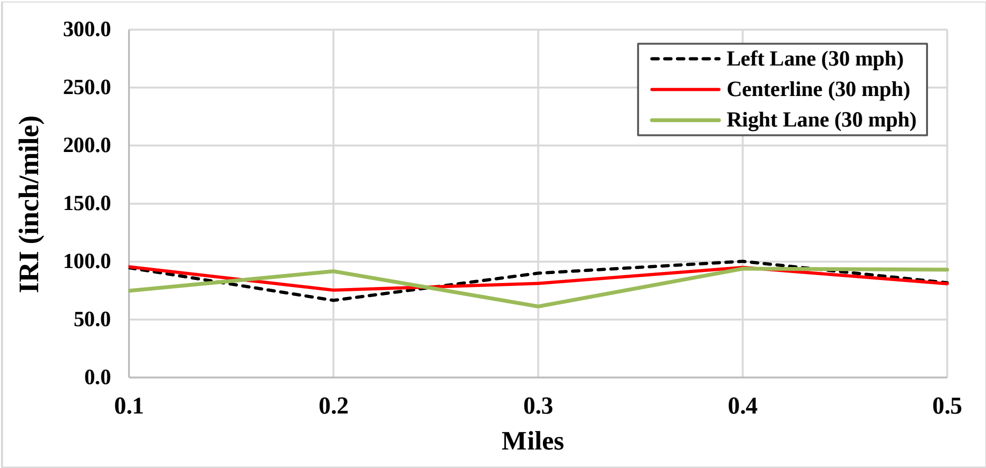


Figure A.78. Estimated average IRI values for Unionville Municipal Airport

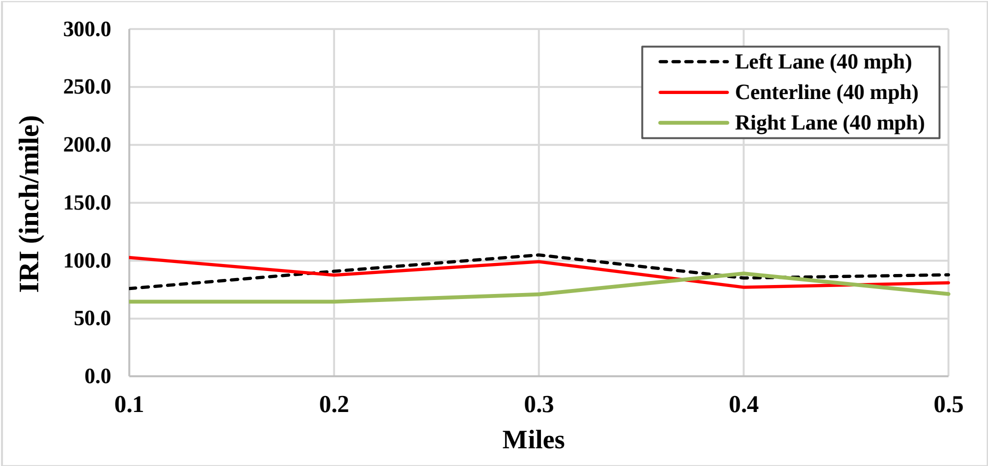
A.27. Willow Springs Memorial Airport (Willow Springs, MO)

Measurement length: 2,892 ft (0.55 mile)

Figure A.79. Test Location at the Willow Springs Memorial Airport (Google)



(a)



(b)

Figure A.80. Plot showing the estimated IRI values for Willow Springs Memorial Airport: (a) 30 mph (b) 40 mph

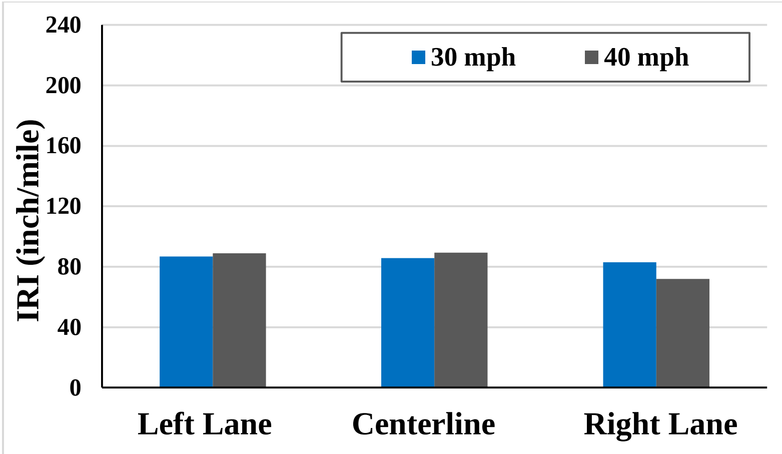


Figure A.81. Estimated average IRI values for Willow Springs Memorial Airport