Upgrade and Performance Testing of the Benchmark Profiler and the Urban and Low-Speed Profiler

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16. Abstract

This report describes upgrades to the Federal Highway Administration Benchmark Profiler (BP) and the University of Michigan Transportation Research Institute Urban and Low-Speed Profiler (ULSP) and comparison between profiles measured by the two devices. BP and ULSP measurements were compared on six pavement sections at the Illinois Certification and Research Track. The test sections composed a diverse set of macrotexture types. Agreement between profiles was quantified using cross correlation of profile filtered by the International Roughness Index algorithm. Agreement between the two devices and among repeat measurements made by each device exceeded the threshold established for reference quality profilers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic	m^3
	meters NOTE: volumes greater than 1000 L shall be			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ACKNOWLEDGEMENTS

Ken Winzeler, Mich Rasulis, Nicholas Krueger, Dan Huddleson, and Mark Gilbert from the University of Michigan Transportation Research Institute (UMTRI) and Steve Karamihas from Applied Pavement Technology (APTech) contributed heavily to the upgrade and improvement of the Federal Highway Administration Benchmark Profiler (BP) and the UMTRI Urban and Low-Speed Profiler (ULSP). Ken Winzeler, Nicholas Krueger, Steve Karamihas, Mark Gilbert, and Scott Bogard operated both profilers during the experimental work at the Illinois Certification and Research Track (ICART). Abhik Borthakur and Dylan Schmidt from APTech assisted with the BP measurements. John Senger from the Illinois Department of Transportation led the effort to lay out and mark the test sections, and assisted with the operation of the BP.

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data represented in this report. The contents do not necessarily reflect the official views or policies of IDOT. This report does not constitute a standard, specification, or regulation at IDOT.

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LIST OF ABBREVIATIONS

BP	Benchmark Profiler
CPU	Central Processing Unit
DAS	Data Acquisition System
FHWA	Federal Highway Administration
GMSS	Global Mobile Satellite System
GPS	Global Positioning System
ICART	Illinois Certification and Research Track
INS	Inertial Navigation System
IRI	International Roughness Index
LAN	Local area network
NTRIP	Networked Transport of RCTM via Internet Protocol
RAM	Random Access Memory
RCTM	Radio Technical Commission for Maritime (Services)
RTK	Real-Time Kinematic
SSD	Solid State Drive
UDP	User Datagram Protocol
ULSP	Urban and Low-Speed Profiler
UMTRI	University of Michigan Transportation Research Institute
UPS	Uninterrupted Power Supply
WGS84	World Geodedic System 1984

Objective

The objectives of this project were to upgrade the Federal Highway Administration (FHWA) Benchmark Profiler (BP), upgrade the Urban and Low-Speed Profiler (ULSP), establish their repeatability and agreement level on test surfaces at the Illinois Certification and Research Track (ICART), and prepare both devices for use as reference profilers at ICART and other profiler certification facilities.

Background

Pooled Fund Study TPF-5(063) "Improving the Quality of Pavement Profile Measurement" supported the development of a benchmark profile measurement device. (Winkler, et al., 2013) The BP, which was built in 2007-2009, provided longitudinal profiles as a standard for comparison to candidate reference profilers in 2009, 2010, 2013, and 2015 and as a standard for comparison to production high-speed inertial profilers in 2015. (Karamihas, 2009; Karamihas, 2011; Karamihas, et al., 2013; Karamihas and Perera, 2014; Karamihas, et al., 2014; Karamihas, et al., 2015; Perera and Karamihas, 2017a; Perera and Karamihas, 2017b) Output from the BP was deemed "true profile" since other devices were required to reproduce its output in critical wavebands to achieve valid status as a reference device. (Karamihas, 2005) However, the BP operated very slowly, and its operation was labor intensive.

Pooled Fund Study TPF-5(063) also supported the development of the ULSP. The ULSP was an augmented version of a typical high-speed inertial profiler. In addition to the sensors that appear in a standard inertial profiler design, it included GPS, a GPS-based attitude measurement system, gyroscopes, additional inertial sensors, and an optical longitudinal distance measurement system. (Karamihas, 2021a) Specialized algorithms applied to the augmented sensor set overcame some of the inherent limitations in typical inertial profilers, and produced accurate and repeatable profiles at very low speed, during braking, and in stop-and-go operation. (Karamihas, 2021b) Results from the ULSP were sufficiently encouraging to suggest that it may produce profiles with reference-level accuracy at high-speed. If so, use of the ULSP could greatly increase the efficiency of benchmark and reference profile measurement for profiler certification.

The BP and ULSP had last been used for research in 2015. The ULSP was designed and built for temporary use to address a specific set of research questions. Each profiler was upgraded to take advantage of improvements to sensor technology, to bring the software and operating systems up to date, and to bring both devices back into good working order. Some software and hardware upgrades were also made to improve the ease of use of each device in preparation for their potential continued role as reference profilers at ICART.

The goal was to prepare the BP for use one or two times per year for reference measurements, and to prepare the ULSP for use regularly as a surrogate reference measurement system to monitor changes to the test sections and get reference measurements more efficiently throughout a busy certification season. The ULSP could also more readily travel to multiple sites.

The repeatability of each device and their agreement with each other was tested on six surface types at ICART to determine whether they could be used as reference devices for profiler certification. Repeatability of each device and their agreement with each other were established using cross correlation of profile filtered by the International Roughness Index (IRI) algorithm, which is the standard method used for profiler certification. (AASHTO, 2022) Establishing agreement in the measurement of profile was important, because it provided a higher level of confidence in future performance than agreement in summary index values and is less likely to reward compensating error. (Karamihas and Gillespie, 2002). The desired level of cross correlation for reference-quality repeatability and agreement was 0.98. (Karamihas, 2004)

BP Upgrades

This section describes updates made to the BP. All of the updates were tested for safety, operational efficiency, and measurement quality in the University of Michigan Transportation Research Institute (UMTRI) laboratory and on a test section at Mcity before the experiment conducted at ICART.

The BP Field Manual describes its measurement principle in detail. (Winkler et al., 2013) Figure 1 shows the upgraded BP operating at ICART. A stationary tripod with a leveling system houses a laser, which projects a horizontal line to establish a stable reference plane. A self-piloting cart moves along the wheel track of interest using a nylon-coated steel tape as a steering guide. The cart measures its longitudinal position by combining the output of a wheel encoder and detection of landmarks on the guide tape. The cart measures its vertical position and orientation relative to the laser line by detecting the reference laser on a set of targets within a “light tunnel.”

Figure 2 shows a grayscale image of the reference laser on the targets captured by a vision system on the cart. The two outer targets are coplanar, and the inner target is parallel to the others, but offset further from the light tunnel opening. The line across the outer targets establishes the vertical position and roll angle of the cart. Comparison of the line across the outer targets with the line across the inner target establishes the pitch angle of the cart. A RoLine laser, which is hidden under the cart cover, projects a laser line to the road surface directly below the outer targets. The RoLine scans an area that includes the guide tape and a 2.76-inch-wide (7-cm-wide) wheel track of interest beside it.

Under typical conditions, the BP is only able to measure up to 45 ft (13.7 m) along the pavement section before instability of the reference laser line introduces an intolerable level of noise into the measured profile. As a result, measurement of an entire test section requires the use of several tripod setups to capture subsection profiles. Construction of the complete profile requires the use of a rod and level survey to anchor the subsection endpoints in a common coordinate system.

In previous experiments, completion of longitudinal profile measurements on a 528-ft-long (160.9-m-long) test section required up to 4 hours. The upgrades described below have reduced the time for measurement of a 528-ft-long (160.9-m-long) section to about 2.5 hours.

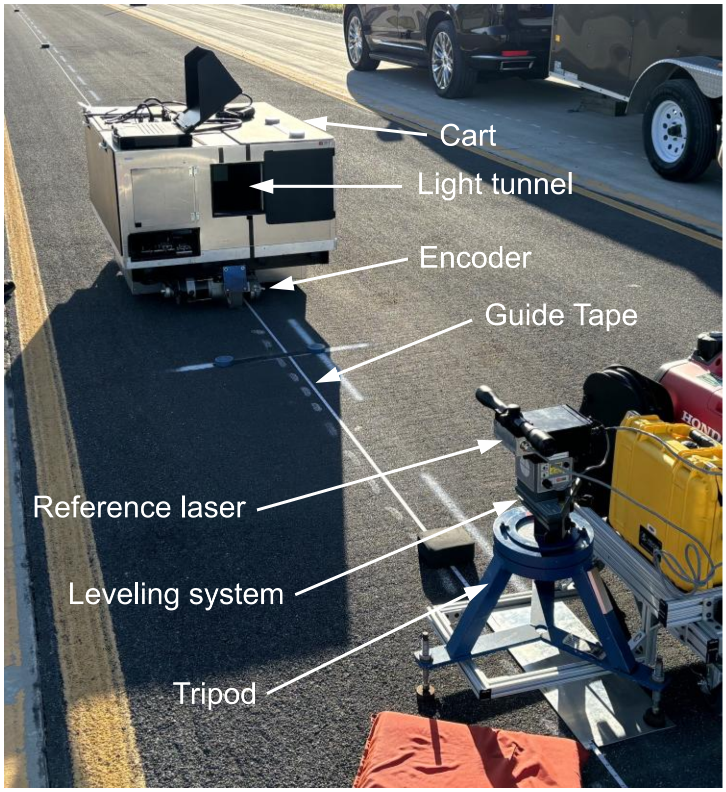

Figure 1. Upgraded BP operating at ICART.

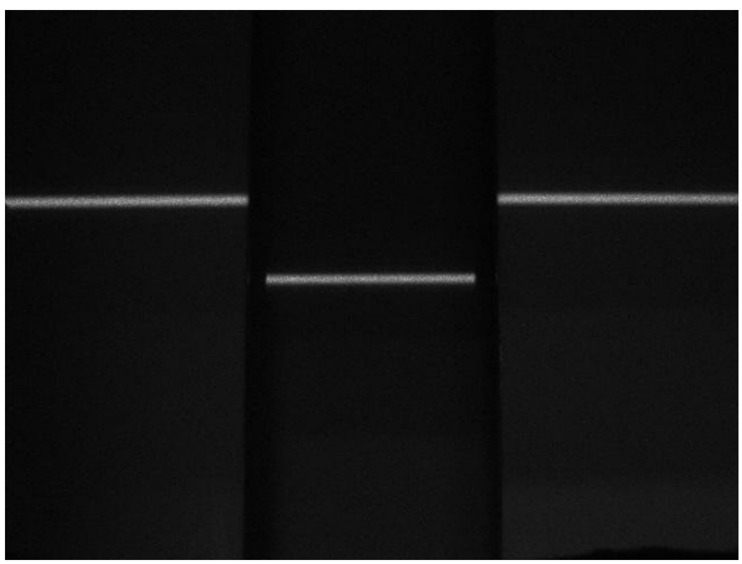

Figure 2. Reference laser line detection on the BP targets.

Motor and Drive Control

The motor and drive control was upgraded to allow for more efficient movement of the BP cart between test sections and longer field operation without the need to charge the batteries. The condition of the motor had also degraded since its last use in 2015. The original motor was replaced with a newer, more efficient, higher torque model. (See Figure 3.) The original servo amplifier was also upgraded to a unit with almost double the output current rating. (See Figure 4.)

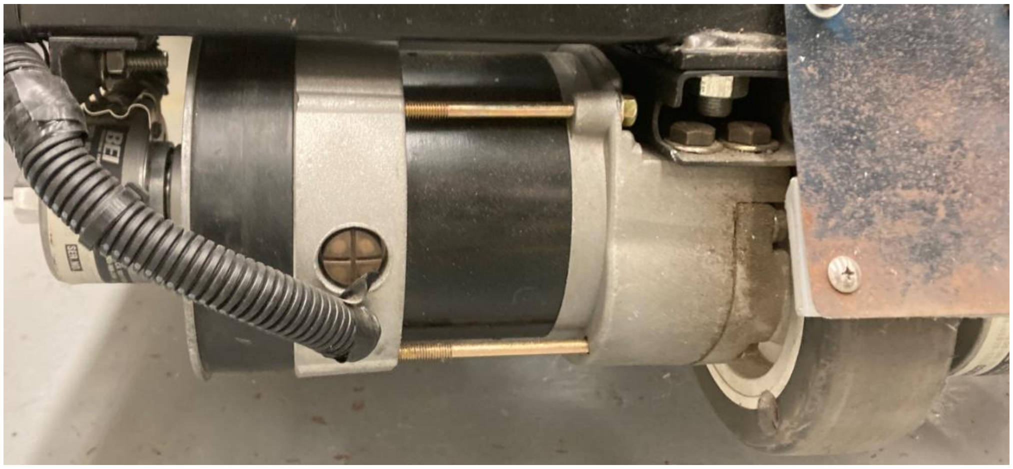

Figure 3. Replacement drive motor.

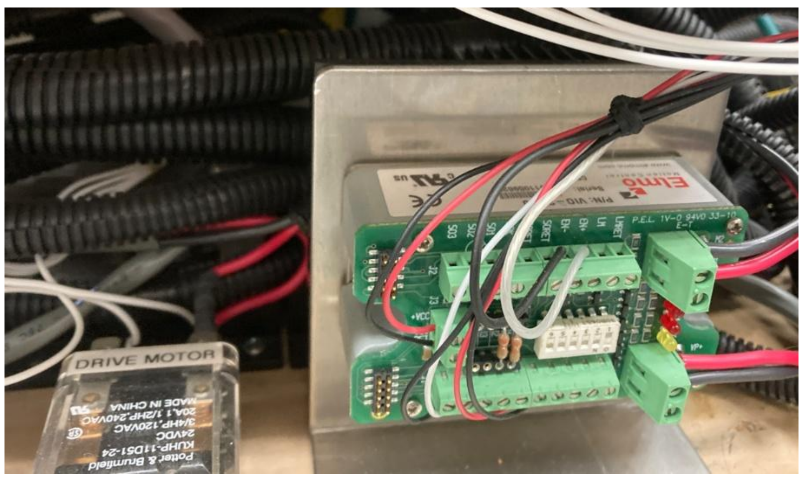

Figure 4. Replacement servo amplifier.

These two hardware upgrades allowed the cart to travel at a higher speed during field operation, and operate longer without battery charging. In addition, the BP is now capable of driving up ramps into the transit trailer without assistance. These upgrades required modifications to the control electronics, motor wiring, servo control software and tuning parameters, and adapter shafts for mounting encoders to the motor. With the higher top speed, it was necessary to retune control parameters for smoother ramp up/ramp down at the start and end of each section.

A compact gasoline generator was purchased for field charging the reference laser, the cart instrumentation, and the cart drive system. The generator rides on the same pushcart that transports the reference laser, the tripod, and the laser leveling hardware. (See Figure 5.) Transporting the generator with the measurement hardware allowed on-site charging of the cart batteries during setup changes and data quality checks, avoiding the previous need to stop work when battery charge levels would drop too low.

Figure 5. Gasoline generator for charging the BP.

Machine Vision Cameras

The machine vision cameras were both replaced. Both In-Sight Micro 1400 (circa 2008) cameras were replaced with Cognex In-Sight 8400 cameras. The cameras were replaced to increase the sampling rate so the BP could conduct measurements at a higher speed with no loss in the spacing between samples.

The “tape camera” faces downward, and monitors a nylon-coated steel guide tape for steering control and measurement of longitudinal travel distance. Figure 6 shows the tape camera installed on the BP with the cover off. (During normal operation, the tape camera is shrouded.) Figure 7 shows an image of the guide tape captured by the tape camera. The tape camera seeks a reference pattern, which is shown in green, within the image to establish the position of the guide tape under the cart.

Figure 6. Tape camera.

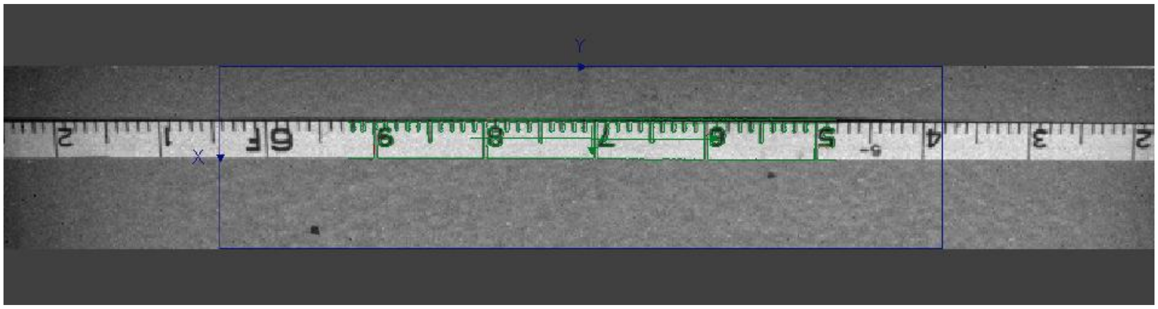

Figure 7. Tape camera image of the guide tape. (Winkler, et al., 2013.)

The tape camera program was modified as follows:

- Imbedded the steering controller algorithm into the cart control program and removed it from the camera's on-board processing. Imbedding the steering algorithm directly into the cart control program allows the operator to make field adjustments to the steering behavior more efficiently.
- Upgraded the system for establishing a reference pattern on the guide tape. This upgrade provides a more convenient way to reprogram the BP for use with a different guide tape.
- Added a system for establishing a physical coordinate origin in the camera images and providing physical position and orientation of the cart relative to the guide tape as output.

The "target camera" measures the reference laser position and orientation on a target screen on the cart. Figure 8 shows a close-up of the new target camera. The target camera is mounted at the bottom of the light tunnel just inside the light tunnel opening.

Figure 8. Target camera.

The target camera program was modified as follows:

- Reprogrammed the camera to detect a line of constant laser light. The previous system detected a laser dot as it swept across the target, and required precise control of exposure timing and duration.

- Removed the external trigger for camera exposure. The updated target program runs in an open loop mode to maximize the sampling rate.

- Added a system for establishing a physical coordinate origin in the camera images and providing physical position and orientation of the cart relative to the guide tape as output.

Replacement of both cameras required the lenses to be replaced to optimize their field of view and insensitivity to ambient light. The narrow bandpass optical filter on the target camera was replaced to match the wavelength of the new line laser. Both cameras were intrinsically calibrated. Intrinsic calibration is a standard method of relating pixels within an image to physical coordinates. For the tape camera and target camera, intrinsic calibration was needed remove the effects of lens distortion and infer physical position from position within each captured image. To facilitate intrinsic calibration of each camera, custom calibration targets were fabricated with dots that appear in a grid, as shown in Figure 9.

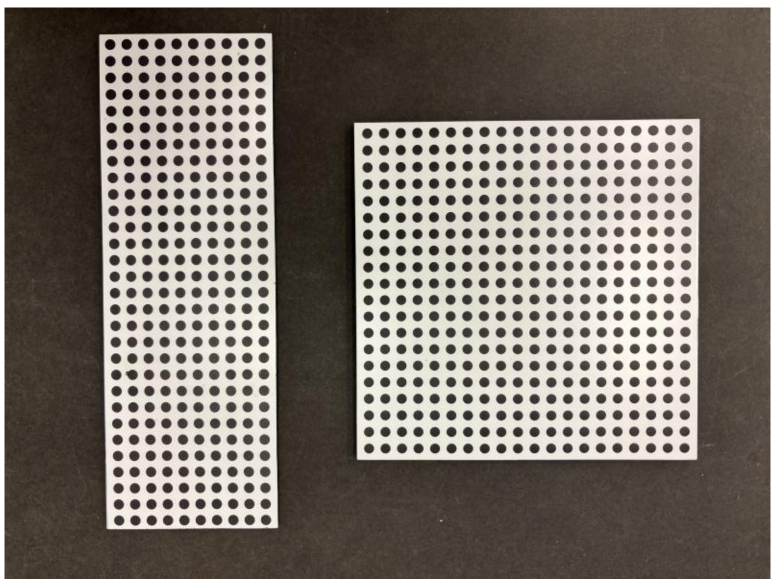

Figure 9. Camera intrinsic calibration targets.

Reference Laser and Tripod Design

Movement and placement of the reference laser tripod and leveling of the laser is a painstaking process, and has a major influence on the quality of the BP measurements. The tripod and the pushcart used to move it between reference points were redesigned to improve quality and convenience. (See Figure 5.)

- The pushcart for transporting the tripod was retrofitted with a lift mechanism and brakes.

- Modifications were made to the pushcart so the lift mechanism was used to position the tripod for each setup and lift it for transport to the next location, which avoids the need for the operator to place the tripod and pick it up manually for each setup.

- Racks were installed on the pushcart to transport the generator, the tripod, the laser battery, cart guide plates, and tripod leveling tools.

- The new constant-line reference laser was installed on the leveling mechanism.
- The laser battery pack was modified to support the voltage required by the new constant-line reference laser.

Update of the DAS to Windows 10

The BP DAS operating system was updated to Windows 10 to improve the data processing and transfer pipeline, and to facilitate on-board data processing. To support the newer operating system and accommodate the increased processing demand, the original Advantech PCM-9562 DAS motherboards were replaced with Versalogic EBX-38 units, which have higher performance CPUs, and support double the RAM. The system disk was upgraded from a rotating unit to a larger SSD.

The changes described above required the BP control and data collection program to be recompiled and tested. All offline programs for setup of subsystems (e.g., the machine vision cameras, the steering system servo controller, the RoLine configuration program, etc.) still function. Testing was also done to: (1) check the operation of the drive and steering systems in all modes, (2) verify data from each sensor, and (3) verify data mover and database loader programs over a local area network (LAN).

Updates to the BP Control and Data Collection Program

The cart control program was revised to incorporate the steering and speed control loops and tuning parameters. This moved them from the camera programs, allowing for more efficient tuning. As noted in the camera upgrade section, this also included a more gradual ramp up/ramp down in speed, which could be tuned from within the DAS, instead of in the camera firmware.

A uBlox GPS receiver was added to the BP. The positioning data from this receiver provides a ground truth for identifying which test section is being measured, and which area within a test section. The DAS application was updated to incorporate this data and synchronize it with other measurements.

ULSP Upgrades

This section describes updates made to the ULSP. All of the updates were tested for safety, operational efficiency, and measurement quality in the UMTRI laboratory and on a test section at Mcity before the experiment conducted at ICART.

The ULSP includes sensors that would appear in a typical inertial profiler and additional sensors to help improve measurement quality and to measure valid profile at low speed, during braking, and through stops. Figure 10 shows a rear view of the ULSP. A rigid plate mounted directly to the frame at the rear of the host vehicle provides a system backbone, and rigid sensor pods are attached to it on each side and at the center.

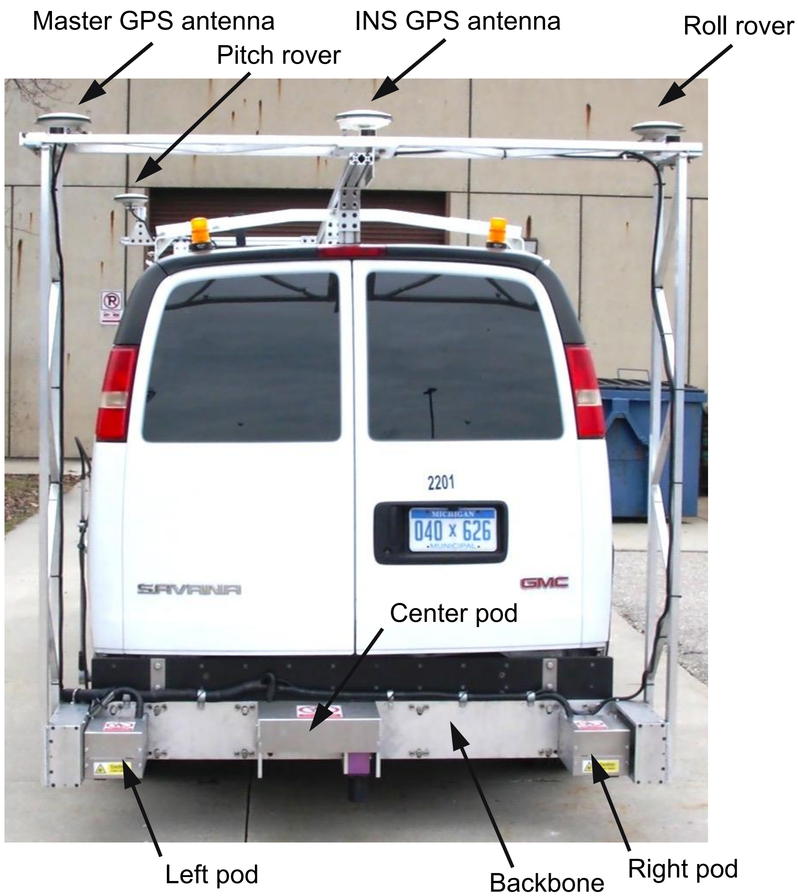

Figure 10. ULSP rear view.

The left and right pod each include a vertical accelerometer, a longitudinal accelerometer, a Gocator line laser, and a point laser. The left pod also includes a lateral accelerometer. The center pod includes gyroscopes for measurement of pitch and roll rate, an inertial navigation system (INS), and an optical distance measurement instrument.

As shown in Figure 10, a sensor rack mounted above the system backbone supports a master GPS antenna on the left side and a rover GPS antenna on the right side. The master antenna provides absolute position, and it receives corrections from a base station. The rover antenna provides a means to measure host vehicle roll angle using its position relative to the master antenna. An additional rover antenna is mounted near the front of the vehicle on the left side to measure host vehicle pitch angle. An antenna mounted to the center of the rack is a component of the INS in the center pod.

The ULSP also includes rotational encoders mounted to both rear wheels.

CPU and Motherboard Replacement

Like the BP, the ULSP's dual CPUs were older Advantech units, which were both upgraded to high performance Versalogic units. As in the BP, the operating system on both the new ULSP CPUs was updated to Windows 10. The system motherboard was rebuilt; incorporating updates to further lower the noise floor of analog sensors. The new CPU's additional Ethernet ports allowed each Gocator to have the full bandwidth of port. This eliminated the issue with the old system where occasionally UDP (User Datagram Protocol) packets transmitted by the Gocator packets were dropped. The Gocator data acquisition code was updated to monitor the rate of data packet flow and provide feedback to the operator in real time.

Charging System Upgrade

The ULSP includes a large lead-acid battery, which, along with an isolation module, serves as a UPS for the DAS and sensors. This system was upgraded with a new onboard charger, inverter, and a disconnect switch under the hood for both the vehicle electrical system and the DAS.

Mobile GPS Base Station

The portable GPS base station was built, which serves as an NTRIP server providing RTCM correction data to the ULSP. This allows the ULSP GPS receivers to provide positioning solutions accurate to 0.4-0.8 inches (1-2 cm). It can be set up in 30 minutes or less, and operates using its internal battery for several days of testing without the need for charging. The base station incorporates a GNSS receiver capable of computing RTCM corrections, a cellular modem, battery/power supply, and an embedded computer running an NTRIP server that can support multiple clients. Figure 11 shows the base station at a reference marker at ICART.

Figure 11. Mobile GPS base station.

Lateral Tracking

The ULSP van was equipped with a camera mounted to the hood and a compact monitor mounted on the dashboard. This provided the driver a fixed frame of reference for piloting. A dry erase marker was used to place a reference mark on the monitor where the longitudinal reference mark on the pavement appeared. Figure 12 shows the dashboard display.

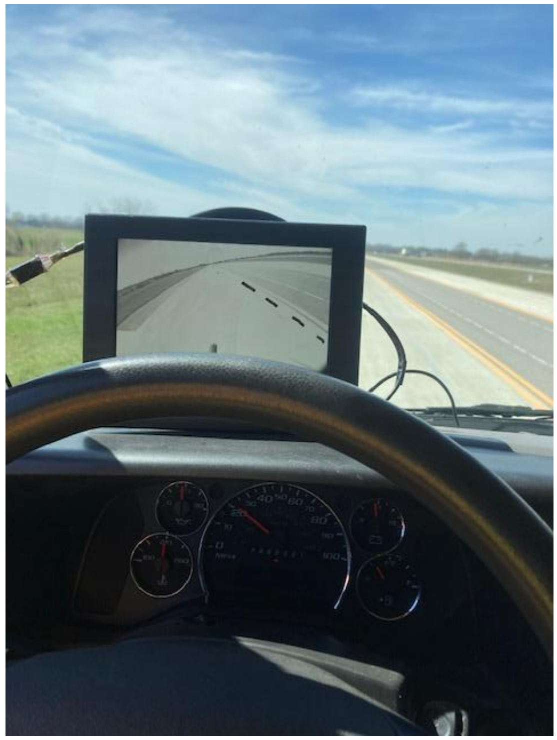

Figure 12. Dashboard monitor for lane tracking feedback.

An application on the main CPU processed the results of each run to examine the lateral tracking error. The processing program used RTK corrected GPS coordinates of the starting and ending point of the left wheel track as input, and used ULSP sensors to produce a record of tracking error versus distance over the length of the test section. Typically, the driver used mean lateral offset as a measure of tracking error, and standard deviation of offset as a measure of wander.

The ULSP estimated the position of the left profiler laser projection into the road surface using the master GPS antenna, roll angle from the INS, and the layout of sensor rack. The analysis program converted longitude and latitude measurements from the master GPS antenna to longitudinal and lateral position on the wheel track of interest using the test section endpoints as a reference. Lateral position was corrected to account for roll angle and the lateral offset between the master GPS antenna and the profiler, as shown in Figure 13. The calculation did not account for variations in host vehicle ride height or cross slope.

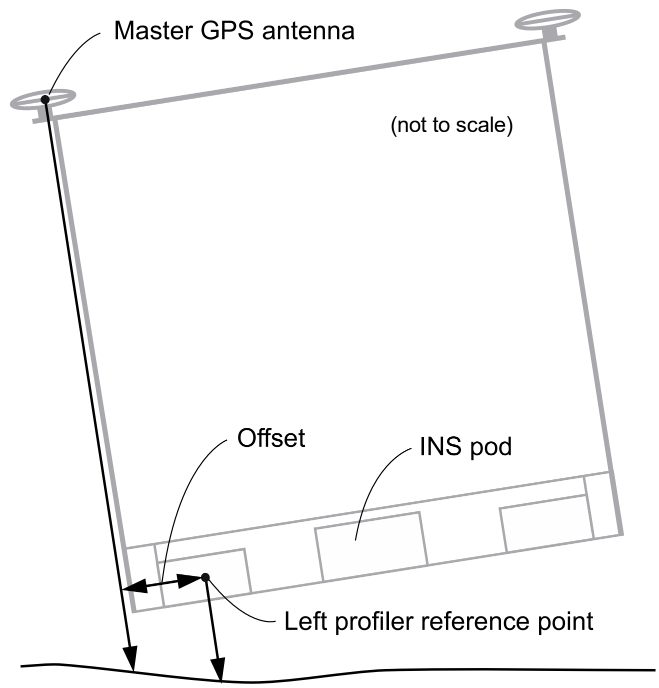

Figure 13. Projection of GPS measuerments to profiler footprint position.

BP and ULSP Comparison Experiment

Comparison testing of the BP and ULSP was performed October 21 through October 23, 2024.

Test Sections

Testing took place at the ICART facility in Clinton, Illinois. ICART is a closed test facility with three lanes of pavement on a tangent section that is ¾ miles (1.2 km) long. The testing included six surface types: (1) dense-graded hot-mix asphalt (HMA), (2) stone matrix asphalt (SMA), (3) microsurface, (4) diamond ground, (5) diamond grooved, and (6) transversely tined. The test sections were selected to provide a broad range of macrotexture types, including positive, negative, isotropic, and directional. Table 1 lists the GPS coordinates of the test section endpoints in the WGS84 datum. Table 1 provides the length of each test section as measured by a steel tape and adjusted for ambient temperature. The HMA and SMA surfaces were adjacent to each other, and were combined into a single, long test section.

Table 1. Test section endpoints.

Test Section	Start Longitude (deg)	Start Latitude (deg)	End Longitude (deg)	End Latitude (deg)	Length (ft)
SMA/HMA	-89.6437649	38.6159336	-89.6401782	38.6158698	1025.3
Microsurface	-89.6391967	38.6158522	-89.6379164	38.6158295	366.0
Diamond Ground	-89.6394067	38.6158732	-89.6412072	38.6159054	514.7
Diamond Grooved	-89.6425021	38.6159285	-89.6442226	38.6159591	491.6
Transversely Tined	-89.6393863	38.6158065	-89.6411049	38.6158373	491.2

(1 ft = 0.3048 m)

Markings

Dashed longitudinal guide marks to were painted along each test section to assist with lateral tracking. The markings were placed 7 inches (17.78 cm) to the right of the left wheel track of interest. The wheel tracks of interest were placed approximately 33 7/8 inches (86.04 cm) from the lane center on each test section, because the lateral spacing between the profiler footprints on the ULSP was 67 ¾ inches (172.09 cm). A transverse marking was also placed at the start and end of each test section. Figure 14 shows a downstream view at the start of the SMA section.

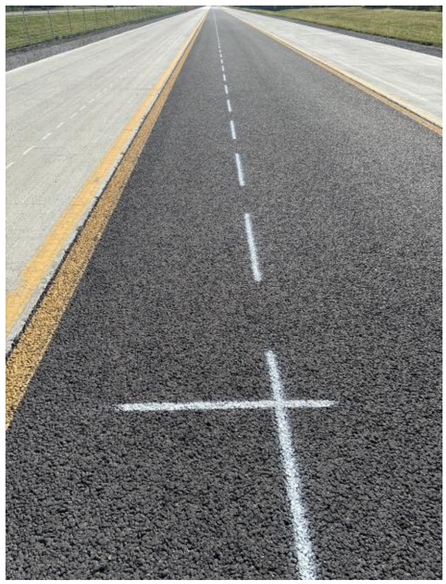

Figure 14. Test section markings.

Figure 15 shows the lateral layout of the painted guide stripe, the BP guide tape, and the wheel track of interest. The BP guide tape was placed 4 7/8 inches (12.38 cm) to the right of the painted guide stripe using painted guide dots placed 20-30 ft (6-9 m) apart along the test section.

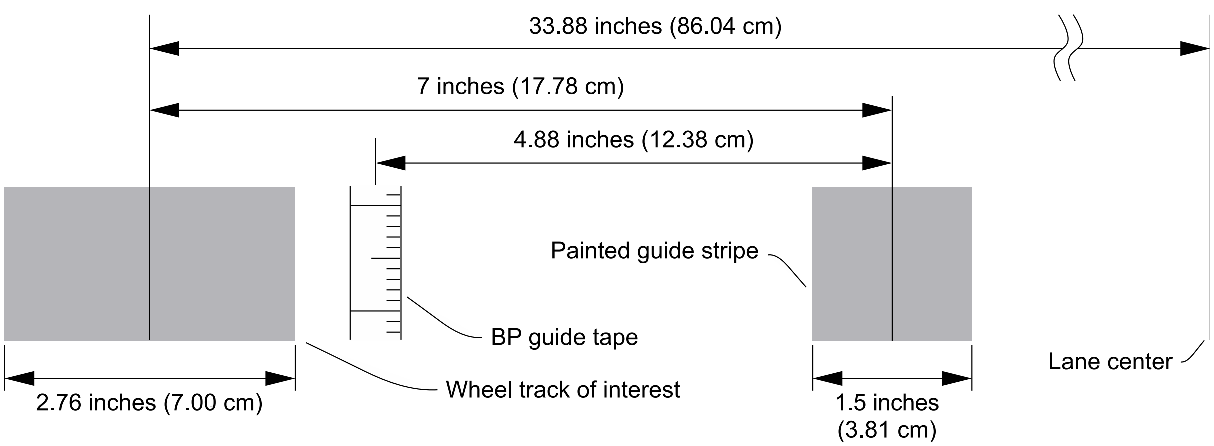

Figure 15. BP guide tape layout.

Test Conditions

The asphalt test sections ran eastbound, and the concrete test sections ran westbound. To avoid difficulty with sunlight directed into the BP light tunnel, eastbound test sections were measured in the morning and westbound test sections were measured in the afternoon. The BP measures each segment of each section in three passes. Typically, the complete profile is constructed using the pass for each segment with the best agreement to the other two. The results reported here used the first pass for each segment to construct a complete profile, the second pass from each segment to construct a second complete profile, and the third pass from each segment to construct a third complete profile

The ULSP passes over each section multiple times in an effort to capture at least three runs with acceptable lateral tracking. Typically, a few practice runs were required to mark the dashboard monitor and help the driver develop a piloting strategy. Three runs over each test section with acceptable tracking statistics were selected for analysis. Any run with average absolute tracking error of less than 1.25 inches (3.18 cm) was considered acceptable. In several runs, absolute tracking error of less than 1 inch (2.54 cm) was achieved.

Results

Table 2 presents results for cross correlation of IRI filter output for repeatability of each device and agreement between them. Repeatability results are the average of the three possible comparisons among the three repeat measurements over each test section. Agreement results are the average of the nine possible comparisons of each of three profiles measured by the BP to each of three profiles measured by the ULSP. The HMA and SMA surfaces were combined into a single test section that was 1025.3 ft (312.5 m) long. Results are also reported for the first 488.8 ft (149.0 m) of the test section, which was SMA, and the last 488.8 ft (149.0 m) of the test section, which was HMA.

Table 2. Cross correlation results.

Surface	BP Repeatability	BP vs. ULSP Agreement	ULSP Repeatability
SMA/HMA	0.994	0.984	0.988
HMA	0.987	0.980	0.993
SMA	0.995	0.990	0.986
Microsurface	0.993	0.989	0.990
Diamond Ground	0.993	0.980	0.981
Diamond Grooved	0.995	0.981	0.975
Transversely Tined	0.996	0.988	0.990

All the averaged BP repeatability scores and averaged agreement scores between the BP and ULSP reached or exceeded the reference-level target of 0.98. With one exception, the averaged ULSP repeatability scores exceeded the reference-level target of 0.98.

Interpretation

The agreement level between the BP and the ULSP suggests that they can be deployed as interchangeable reference-level profilers. For example, the BP could serve as the primary reference device to ensure the validity and health of the ULSP, and the ULSP could provide more frequent reference measurements throughout a certification season.

Three observations may affect the implementation of the BP in conjunction with a version of the ULSP as reference devices at ICART.

First, the diamond-grooved surface interacted with the profile data processing algorithms in a manner that may have hindered the agreement level between repeat measurements and between the two devices. The height sensors in the BP and ULSP project lines on the pavement surface that are about 4 inches (10 cm) wide. A bridging algorithm reduces the readings within a 2.76-inch-wide (7-cm-wide) area of the footprint into a single value of range to the pavement surface, as described by Karamihas (2005). The bridging algorithm disregards grooves or other negative texture within the footprint in areas that are unlikely to contact a passing vehicle tire, and determines range using the remaining readings.

On the diamond-grooved surface, the grooves are 0.75 inches (1.91 cm) apart. As a result, a small deviation from perfect tracking parallel to the grooves may change the number of grooves that appear within the 2.76-inch-wide (7-cm-wide) area from three to four, or vice versa. Application of the bridging filter mitigates the effect of the number of grooves on the height sensor range values, but not entirely. To further reduce the variability caused by lateral wander, the center of the 2.76-inch-wide (7-cm-wide) area was adjusted in the ULSP data processing to a position as close to the wheel track of interest as possible. However, even with expert drivers the ULSP host vehicle typically wandered more than the margin available within the footprint of the height sensors for adjustment.

Second, cross correlation levels between profiles measured on the HMA surface were more sensitive to deviations in lateral tracking than expected. To achieve reference-level cross correlation (of 0.98 and above), a more stringent specification on average absolute lateral wander than 1.25 inches (3.18 cm) may be required. Reducing average absolute tracking error below 1 inch (2.54 cm) may require a larger number of passes or robotic steering control.

Third, profiles measured on the transversely tined section included periodic roughness at wavelengths that correspond to the joint spacing and integer fractions of the joint spacing (1/2, 1/3, etc.). To avoid the potential confounding effects of changes in curl and warp, the BP and ULSP measured the transversely tined section under similar environmental conditions.

If the ULSP, or a version of the ULSP with similar agreement to the BP, is implemented as a more efficient surrogate to the BP, it is recommended that it be used to characterize changes with time and sensitivity to lateral tracking errors, which will help assist candidates for profiler certification and to develop standards for the timing and tracking accuracy of reference measurements.

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