

ORIGINAL ARTICLE

Agrosystems

Reengineering the Baldree Traffic Simulator for turfgrass wear and traffic research

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Assigned to Associate Editor Manuel Roman Chavarria.

Abstract

Historically, turfgrass researchers utilized the Baldree Traffic Simulator (BTS) to imitate foot traffic for the evaluation of athletic field wear tolerance and performance. Research was conducted to reengineer the BTS “feet” to improve adaptability and compatibility with other aerification units and determine biophysical effects on two native soil turfgrass systems. Inertial measurement unit sensors measured vertical accelerations and derived total force output. Additionally, low (one traffic event week⁻¹) and high (two traffic events week⁻¹) traffic were applied to IronCutter hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy] and Zorro hybrid zoysiagrass [*Zoysia japonica* Steud. × *Z. matrella* (L.) Merr.] for 8 weeks. Average peak vertical accelerations were 280 m s⁻¹ m⁻², which is a total force output of 8221 N per BTS footstrike. Neither the low nor high traffic increased bermudagrass soil bulk density; however, high traffic (1.13 g cm⁻³) increased soil bulk density compared to the non-treated (0.92 g cm⁻³) zoysiagrass. High traffic decreased normalized difference vegetation index (NDVI; 0.75), turfgrass cover (71%), and shear strength (12.3 Nm) of bermudagrass while increasing surface hardness (156 Gmax) compared to low traffic (0.79, 94%, 14.4 Nm, and 141 Gmax, respectively). Both low and high traffic reduced NDVI (0.68–0.69) and turfgrass cover (64%–69%) on zoysiagrass compared to the same plots before traffic (0.86% and 100%, respectively). High traffic (90 Gmax) increased surface hardness compared to low traffic (106 Gmax) on zoysiagrass. The modified BTS can effectively simulate traffic for turfgrass research.

Abbreviations: BTS, Baldree Traffic Simulator; CTS, Cady Traffic Simulator; IMU, inertial measurement unit; NDVI, normalized difference vegetation index; OM, organic matter; TC, turfgrass color; TQ, turfgrass quality; WAIT, weeks after initial treatment.

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Plain Language Summary

The Baldree Traffic Simulator (BTS) is a common piece of research equipment used to mimic athletic field foot traffic. The original design was reengineered in order to increase adaptability for use with other aerification units. Therefore, research was conducted to determine the physical effects of the new design on turfgrass systems. Each “footstrike” of the modified device delivered a total force of 8221 N. High traffic (twice per week) increased bulk density of the soil for zoysiagrass but not bermudagrass. High traffic harmed bermudagrass more than low traffic (once per week), resulting in less greenness, less ground cover, weaker resistance to tearing (shear strength), and a harder surface. Both low and high traffic reduced zoysiagrass greenness and ground cover when compared to measurements taken before traffic was applied. High traffic also increased zoysiagrass surface hardness more than low traffic. In conclusion, the modified BTS is an effective tool for simulating real-world traffic conditions in turfgrass research.

1 | INTRODUCTION

Athletic fields are often exposed to excessive amounts of foot traffic, causing turfgrass wear injury and increases in soil compaction (Beard, 1973; Shearman et al., 2001). Turfgrass wear injury is caused by a combination of crushing, shearing, and/or tearing of the turfgrass surface (Bonos et al., 2001; Shearman et al., 1974). Traffic stress has also been shown to cause increases in soil compaction, which can reduce turfgrass shoot density, root growth, and water infiltration (Beard, 1973; Carrow, 1980; Kowalewski et al., 2013; Matthieu et al., 2011). Historically, turfgrass researchers have utilized equipment designed to consistently provide a combination of shearing and compacting forces to simulate foot traffic for the evaluation of turfgrass wear tolerance and field performance (Morrish & Harrison, 1948; Perry, 1958; Vanini et al., 2007). These devices typically consist of studded rollers that turn at different speeds to provide both shearing and rolling-type compacting forces (Canaway, 1976; Cockerham & Brinkman, 1989; Henderson et al., 2005). While these devices were successful at providing consistent traffic stress and turfgrass wear injury, they lacked the ability to provide dynamic vertical and horizontal forces that are more representative of athletes interacting with the surface.

Henderson et al. (2005) developed the Cady Traffic Simulator (CTS) using recycled tire rubber cleated “feet” attached to a modified walk-behind core aerification unit capable of producing dynamic vertical and horizontal forces along with significant soil compaction and turfgrass wear injury. When compared to a standard studded roller machine, the CTS significantly decreased turfgrass density, shear resistance, and divot resistance while significantly increasing soil bulk density from 1.53 to 1.68 g cm⁻³ over a 6-week period (Vanini et al., 2007). Similarly, Kowalewski et al. (2013) designed the

Baldree Traffic Simulator (BTS), which implemented an analogous concept using an aerification unit with cleated “feet”; however, the BTS contained spring-loaded steel feet with screw-in soccer cleats instead of recycled tire rubber cleated feet utilized by the CTS. This design allowed for increased durability while still implementing similar dynamic forces as the CTS.

While effective, the spring-loaded cleated feet of the current BTS were specifically designed for a Ryan GA 30 aerification unit and not directly transferrable to other aerification units (Kowalewski et al., 2013). Other turfgrass researchers have modified the current BTS feet to fit on additional aerification units, such as the Toro ProCore 648 (The Toro Company; Dalsgaard et al., 2020; Dickson et al., 2018; Lindsey et al., 2021; Thoms et al., 2011, 2023); however, the specification changes made to the BTS design to accommodate other aerification devices have not been officially documented. Anecdotal evidence also suggests that different aerification units provide different amounts of vertical and/or horizontal dynamic force per footstrike than the Ryan GA 30 aerification unit described by Kowalewski et al. (2013), although research documenting these differences in dynamic force between aerification units is limited. Additionally, several versions of BTS feet have been created since the original BTS testing by Kowalewski et al. (2013) to further improve function and durability (L. Baldree, personal communication, March 8, 2023). Consequently, there is a need to provide documented updates and improvements to the design of the BTS feet that can be made compatible with different aerification units.

Therefore, the objectives of this research were to (1) reengineer the BTS feet with readily available parts, (2) design the BTS feet to fit a John Deere Aerocore 800 (Deere & Company) aerification device with flexibility for adaptation

to other aerification units, and (3) evaluate the biophysical responses of two native-soil turfgrass systems following traffic stress applied with the modified John Deere Aerocore 800 BTS.

2 | MATERIALS AND METHODS

2.1 | Modified BTS “foot” construction

The original BTS foot designed by Kowalewski et al. (2013) included two steel plates attached with four Grade 8 bolts and springs, with the bottom plate studded with screw-in soccer cleats. A prototype modified BTS foot was constructed in Athens, GA, during 2023–2024 (Figures 1 and 2). The original BTS foot was reengineered with materials that are regularly available and easily replaceable if broken. The following modifications were made for the prototype BTS foot:

1. The four Grade 8 bolts were moved out toward the perimeter of the steel plates (2.7 cm closer to the corner of the steel plates).
2. Grade 8 bolts were replaced with Grade 8 alloy steel shoulder screws (McMaster-Carr Part #: 91259A850) that thread into the bottom of the steel plate.
3. Shoulder screws were housed in press-fit drill bushings with heads (McMaster-Carr Part #: 8492A302) that are machined and press-fit into the top plate. Graphite powder lubricant was periodically added to shoulder screws to prevent binding.
4. A perpendicular steel plate was welded to the top plate and fabricated to fit onto the aerator arm assembly of a John Deere Aerocore 800 unit. This perpendicular plate can be substituted out to accommodate other aerification unit assemblies.
5. Cleat count expanded from 17 to 21 foot⁻¹.
6. Spring specifications were matched from the original BTS foot and purchased from Lee Spring (Part #: LHC 156 M 04S).
7. A single washer (0.3 cm thick) was placed between the spring and the top plate.
8. Steel plate thickness was expanded to 1 cm.

Once the prototype was completed and tested on the John Deere BTS device, four additional, identical modified BTS feet were constructed and used throughout the field evaluation study.

2.2 | Acceleration experiment

Research was conducted in Athens, GA (33° 54' 19.7892" N, 83° 22' 26.1228" W) on August 19, 2024, to determine the

Core Ideas

- The modified Baldree traffic simulator has a potential force output of 8221 N per footstrike.
- High traffic increased soil bulk density of zoysiagrass when compared to non-trafficked plots.
- High traffic decreased normalized difference vegetation index (NDVI), cover, and shear strength while increasing surface hardness of bermudagrass.
- Both low and high traffic reduced NDVI and cover of zoysiagrass.
- The modified Baldree Traffic Simulator can effectively apply traffic for use in turfgrass research.

potential force output for a single modified BTS foot attached to a John Deere Aerocore 800 aeration unit. To derive the potential force output, a Vicon Blue Trident (Vicon Motion System) inertial measurement unit (IMU) sensor was attached to the perpendicular steel plate of two of the four modified BTS feet, one on the middle-left assembly and one on the far-right assembly if viewed posteriorly. The two aerator arm assemblies were selected at random and assumed to be representative of the four aerator arm assemblies on the John Deere Aerocore 800 aeration unit. Blue Trident IMUs contain two accelerometers (± 16 g at 1125 Hz and ± 200 g at 1600 Hz), a magnetometer (± 4900 μ T at 112 Hz), and a gyroscope ($\pm 2000^\circ$ s⁻¹ at 1125 Hz). Sensors were attached using double-sided tape and secured with duct tape. The John Deere Aerocore 800 was placed on a vertical lift, and the vertical acceleration was measured during a stationary aeration motion for approximately 6 s. A region of interest was created within the IMU software (Capture.U 1.4.1; Vicon Motion System) on a 10th generation iPad (Apple) that connects to the IMUs via Bluetooth to allow for data processing and analysis. The raw ± 200 g acceleration data measured by each IMU were exported at 1600 Hz and filtered using a Butterworth fourth-order zero-phase shift filter with a cutoff frequency of 50 Hz using the “butfilt_vbz_xla_v2.xla” add-in (created by Sam Van Wassenbergh, University of Antwerp, June 6, 2007 in “Microsoft Visual Basic for Applications” for Microsoft Excel 2000; Erer, 2007) within Microsoft Excel (Microsoft Corporation). Once filtered, peak accelerations were extracted from the vertical plane (*x*-axis of each IMU) for analysis. Preliminary visual inspection of the aeration motion of the John Deere BTS device indicated a brief period (approximately 1 s) of time during the lowering and lifting of the aeration unit where the BTS feet were not in contact with the surface. Therefore, the middle 50% of vertical acceleration peaks during the trial were extracted for analysis to remove any potential

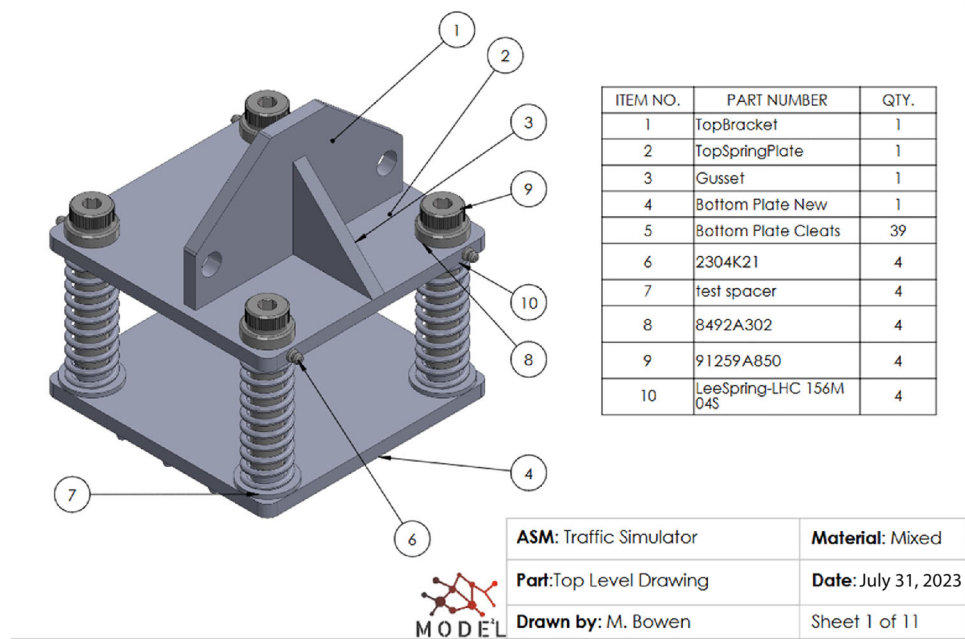


FIGURE 1 Prototype schematic of the reengineered Baldree Traffic Simulator foot. QTY, quantity.

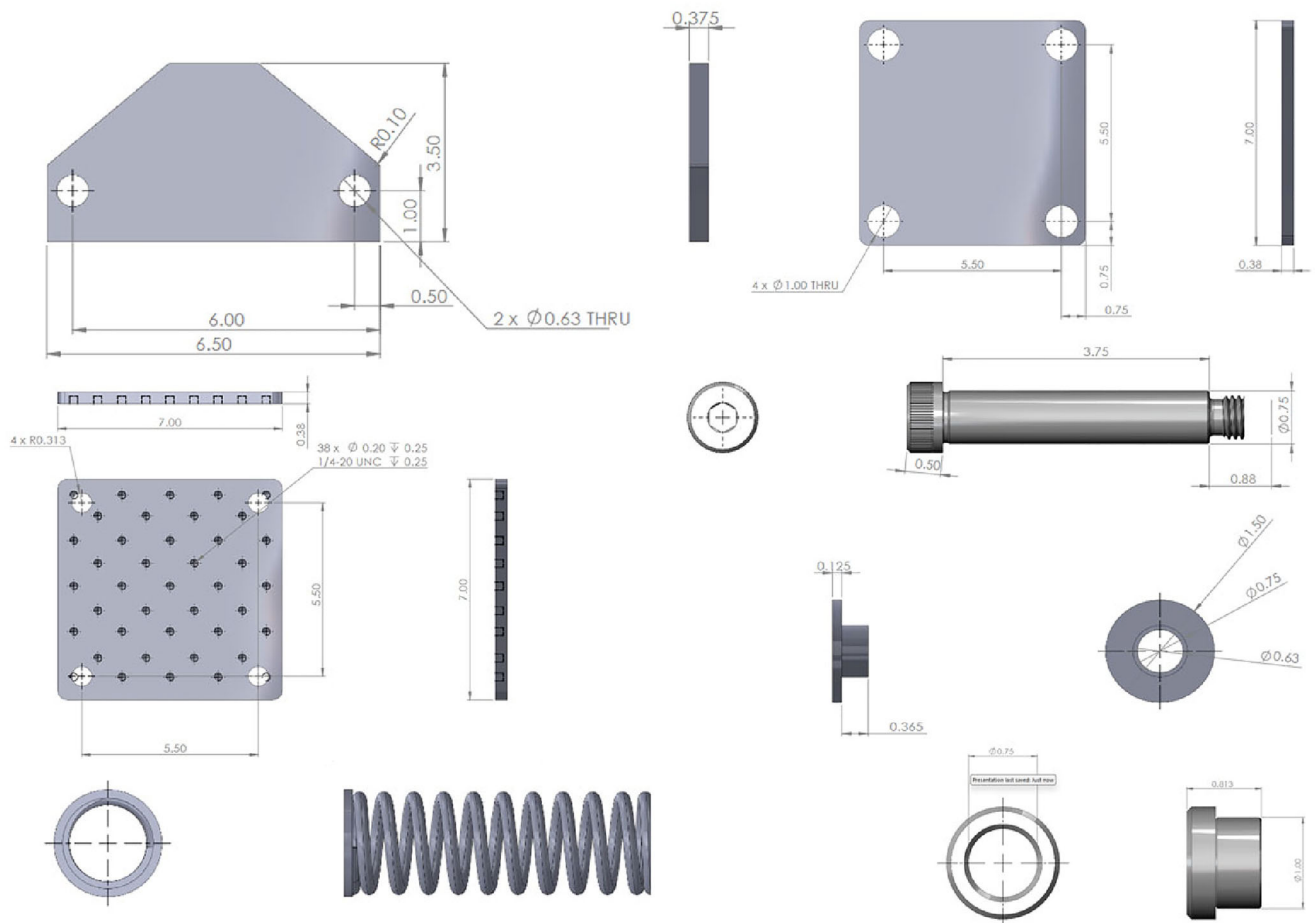


FIGURE 2 Schematic of materials utilized for the construction of the reengineered Baldree Traffic Simulator feet.

deviations due to starting and stopping of the aeration motion of the John Deere BTS device. The potential total force output (F) was derived from the following novel equation:

$$F = ma + 4Ds, \quad (1)$$

where m is the mass of all aerator arm components plus the mass of BTS foot, a is the average peak vertical acceleration measured from the IMUs, D is the aerating depth set on the John Deere Aerocore 800, and s is the spring load rate for each individual spring.

2.3 | Field experiment

Research was conducted at two locations in Athens, GA, to determine the biophysical effects of the traffic device on two native soil turfgrass systems. The first location consisted of IronCutter hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] plots (1.5 m × 3 m) maintained at 2 cm on a Cecil clay loam (fine, kaolinitic, thermic Typic Kanhapludults) (3.14% organic matter [OM], 6.01 pH). The second location consisted of Zorro hybrid zoysiagrass [*Zoysia japonica* Steud. × *Z. matrella* (L.) Merr.] plots (1.5 m × 2.4 m) maintained at 1.3 cm on a modified Cecil clay loam with a Wakulla sand (siliceous, thermic Psammentic Hapludults) (approximately 2:1 mixture) (3.27% OM, 6.52 pH). Hybrid bermudagrass and hybrid zoysiagrass plots received 49 kg N ha⁻¹ of 25N-0P₂O₅-3K₂O fertilizer (The Andersons, Inc.) on September 13, 2024, and September 24, 2024, respectively. Treatments were initiated on August 20, 2024, for hybrid zoysiagrass plots and August 23, 2024, for hybrid bermudagrass plots. Treatments included two rates (low rate = one traffic event week⁻¹ for eight total traffic events, high rate = two traffic events week⁻¹ for 16 total traffic events) of simulated traffic applied weekly using the modified BTS with the John Deere Aerocore 800 for eight consecutive weeks. The John Deere BTS was initially set to an aerating depth of 7 cm and a spacing of 7.4 cm (approximately 1450 cleat marks m⁻² per traffic event) for the first 2 weeks of the study, but due to apparent wear on the John Deere BTS device, the settings were adjusted to an aerating depth of 6.25 cm and spacing of 5 cm to apply (approximately 2100 cleat marks m⁻² per traffic event) for the remainder of the study. These settings supplied a similar number of cleat marks per simulated traffic event as two to three National Football League games (667 cleat marks m⁻² game⁻¹) between the hashmarks at the 40-yard line (Henderson et al., 2005). The experimental design was a modified 2 × 2 strip-plot design with four replications, with location (hybrid bermudagrass or hybrid zoysiagrass) being the whole-plot factor

TABLE 1 Soil bulk density measurements recorded from soil cores obtained on November 1, 2024, following 8 weeks of simulated traffic events.

Traffic rate ^b	Turfgrass species ^a	
	Hybrid bermudagrass (g cm ⁻³)	Hybrid zoysiagrass (g cm ⁻³)
None	1.38	0.92b ^c
Low	1.43	1.07ab
High	1.43	1.13a
LSD _{0.05}	ns	0.15

Abbreviations: LSD, least significant difference; ns, non-significant.

^aIronCutter hybrid bermudagrass was grown on a Cecil clay loam (fine, kaolinitic, thermic Typic Kanhapludults) with 3.14% organic matter (OM) while Zorro hybrid zoysiagrass was grown on a modified Cecil clay loam with a Wakulla sand (approximately 2:1 mixture) with 3.27% OM.

^bSimulated traffic was applied weekly using the modified BTS with the John Deere Aerocore 800 for eight consecutive weeks. The low rate consisted of 1 traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^cMeans followed by the same letter within a column are not significantly different at the $\alpha = 0.05$ significance level.

and simulated traffic rate (low or high) being the sub-plot factor.

Response variables included soil bulk density, normalized difference vegetation index (NDVI), % turfgrass cover, turfgrass color (TC), turfgrass quality (TQ), surface hardness, shear strength, soil moisture, and penetration resistance. Soil cores (6.25 cm diameter × 10 cm deep measured from the soil surface) were removed using an AMS Soil Core Sampling Kit, consisting of a slide hammer, soil core cup, and cap (AMS Inc.) on November 1, 2024, following the last traffic event to evaluate changes in soil bulk density. Soil cores were also obtained from adjacent non-trafficked plots at both locations for comparison. Samples were air-dried for 1 week before thatch and turfgrass residues were removed. Remaining material was crushed with a pestle to eliminate all soil structure. Soil was passed through a 2-mm sieve (No. 10 USA Standard Testing Sieve; Fisher Scientific Company) to remove all plant residue and inorganic parent material. Samples were placed in a 105°C oven for 72 h before weighing to determine dry mass per unit volume (g cm⁻³).

All other response variables were assessed before the first traffic event and weekly throughout the experiment. A FieldScout CM1000 NDVI Meter (Spectrum Technologies, Inc.) was used to measure the relative greenness of the leaf canopy (five averaged readings). Percent turfgrass cover, TC, and TQ were visually assessed. A scale of 1–9 with a rating of ≥6 considered acceptable was implemented for TC and TQ assessment. A Clegg Impact Tester (Lafayette Instrument Co.) equipped with an accelerometer inside a 2.25 kg missile was used to measure surface hardness. The missile was dropped

TABLE 2 Normalized difference vegetation index (NDVI) and visual % turfgrass cover in response to simulated traffic from the modified Baldree Traffic Simulator on the John Deere Aerocore 800.

		WAIT ^a								
		0	1	2	3	4	5	6	7	8
Turfgrass species ^b	Traffic rate ^c	NDVI ^d								
Hybrid bermudagrass	Low	0.82	0.84a ^e	0.83a	0.84a	0.81a	0.84a	0.82a	0.84	0.79a
	High	0.80	0.79b	0.78b	0.78b	0.76b	0.82b	0.79b	0.83	0.75b
	LSD _{0.05}	ns	0.03	0.03	0.05	0.02	0.01	0.02	ns	0.03
Hybrid zoysiagrass	Low	0.86	0.88a	0.84a	0.82a	0.81a	0.84a	0.81a	0.77	0.69
	High	0.86	0.84b	0.81b	0.78b	0.76b	0.79b	0.76b	0.78	0.68
	LSD _{0.05}	ns	0.01	0.02	0.03	0.02	0.03	0.02	ns	ns
Turfgrass species	Traffic rate	Visual % turfgrass cover								
Hybrid bermudagrass	Low	100	100	100	100	100	100a	99a	99a	94a
	High	100	100	100	100	100	95b	95b	93b	71b
	LSD _{0.05}	ns	ns	ns	ns	ns	0.1	3.1	4.7	6.6
Hybrid zoysiagrass	Low	100	100	100	100	100	98a	95a	80	69
	High	100	100	100	100	100	90b	80b	71	64
	LSD _{0.05}	ns	ns	ns	ns	ns	6.1	5.0	ns	ns

^aAbbreviations: LSD, least significant difference; ns, non-significant; WAIT, weeks after initial traffic event.

^bIronCutter hybrid bermudagrass and Zorro hybrid zoysiagrass were evaluated.

^cThe low rate consisted of one traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^dNDVI was assessed by averaging five subsample measurements per plot using a FieldScout CM1000 NDVI Meter measured on a -1 to 1 scale.

^eMeans followed by the same letter within a column within the same species for each response variable are not significantly different at the $\alpha = 0.05$ significance level. The hybrid bermudagrass NDVI data measured 5 WAIT were only significant at the $\alpha = 0.1$ significance level.

TABLE 3 Visual turfgrass color (TC) and turfgrass quality (TQ) in response to simulated traffic from the modified Baldree Traffic Simulator on the John Deere Aerocore 800.

		WAIT ^a							
		0	1	4	5	6	7	8	
Turfgrass species ^b	Traffic rate ^c	TC ^d							
Hybrid bermudagrass	Low	6.6	6.6a ^e	6.5a	6.6a	6.0a	7.1a	6.4a	
	High	6.5	6.1b	5.6b	5.5b	5.5b	5.8b	4.8b	
	LSD _{0.05}	ns	0.4	0.6	0.8	0.1	0.5	0.5	
Hybrid zoysiagrass	Low	7.9	7.6a	6.3a	7.0a	5.6a	5.3	4.8	
	High	7.8	6.3b	5.4b	5.3b	3.9b	4.5	4.6	
	LSD _{0.05}	ns	0.8	0.5	0.8	0.7	ns	ns	
Turfgrass species	Traffic rate	TQ							
Hybrid bermudagrass	Low	7.0	6.8a	6.5a	6.6a	6.9a	7.0a	6.9a	
	High	6.9	6.0b	5.6b	5.7b	6.0b	5.5b	5.3b	
	LSD _{0.05}	ns	0.4	0.6	0.8	0.3	0.6	0.5	
Hybrid zoysiagrass	Low	8.0	7.1	6.3a	6.8a	5.9a	5.9a	5.4	
	High	7.9	6.8	5.3b	5.8b	4.6b	5.0b	4.9	
	LSD _{0.05}	ns	ns	0.7	0.9	0.4	0.8	ns	

^aAbbreviations: LSD, least significant difference; ns, non-significant; WAIT, weeks after initial traffic event.

^bIronCutter hybrid bermudagrass and Zorro hybrid zoysiagrass were evaluated.

^cThe low rate consisted of one traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^dTC and TQ were rated on a scale of 0–9 scale with a rating of ≥ 6 considered acceptable.

^eMeans followed by the same letter within a column within the same species for each response variable are not significantly different at the $\alpha = 0.05$ significance level.

TABLE 4 Surface hardness, shear strength, and soil moisture in response to simulated traffic from the modified Baldree Traffic Simulator on the John Deere Aerocore 800.

		WAIT ^a								
		0	1	2	3	4	5	6	7	8
Turfgrass species^b	Traffic rate^c	Surface hardness (Gmax)^d								
Hybrid bermudagrass	Low	75	77	71	63	71	68	65b ^e	86b	141b
	High	65	84	75	73	80	79	81a	106a	156a
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	15	12	10
Hybrid zoysiagrass	Low	57	55	62	55	66	54	54	61b	90b
	High	53	56	60	59	69	61	57	72a	106a
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	ns	9	15
Turfgrass species	Traffic rate	Shear strength (Nm)								
Hybrid bermudagrass	Low	–	10.6	11.1	20.5	14.9	15.1	15.5	18.0	14.4a
	High	–	11.1	12.3	19.2	14.5	16.4	14.9	14.5	12.3b
	LSD _{0.05}	–	ns	ns	ns	ns	ns	ns	ns	2.0
Hybrid zoysiagrass	Low	–	24.0	23.3	16.6	25.4	30.0a	23.1	24.4	22.0b
	High	–	22.1	23.6	15.3	23.5	25.4b	24.8	24.5	27.4a
	LSD _{0.05}	–	ns	ns	ns	ns	2.1	ns	ns	5.1
Turfgrass species	Traffic rate	Soil moisture (%VWC)								
Hybrid bermudagrass	Low	30.2	32.6	30.3	26.3	28.1	29.9a	30.2	23.5a	16.5
	High	27.9	30.6	27.5	27.8	25.7	25.9b	26.5	18.8b	13.4
	LSD _{0.05}	ns	ns	ns	ns	ns	3.8	ns	4.6	ns
Hybrid zoysiagrass	Low	30.0	35.7	31.3	29.4	27.2	33.2	35.6b	24.9b	15.2
	High	30.1	39.4	32.5	29.9	28.8	36.5	39.6a	29.9a	16.5
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	3.6	4.0	ns

^aAbbreviations: LSD, least significant difference; ns, non-significant; VWC, volumetric water content; WAIT, weeks after initial traffic event.

^bIronCutter hybrid bermudagrass and Zorro hybrid zoysiagrass were evaluated.

^cThe low rate consisted of one traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^dSurface hardness was measured using a Clegg Soil Impact Tester. Shear strength was measured using the Turf-Tec Shear Strength Tester. Soil moisture was assessed using a Field Scout TDR 300 Soil Moisture Meter.

^eMeans followed by the same letter within a column within the same species for each response variable are not significantly different at the $\alpha = 0.05$ significance level. The 6 WAIT bermudagrass surface hardness data, 8 WAIT zoysiagrass surface hardness data, 8 WAIT zoysiagrass turfgrass shear strength data, and 6–7 WAIT zoysiagrass soil moisture data were significant at the $\alpha = 0.1$ significance level.

through a guide tube from a height of 45 cm three times in a single spot per plot and the final Gmax (a unitless ratio of maximum deceleration of the missile upon impact with the surface in units of gravities relative to the acceleration due to gravity) reading on the third drop was recorded for analysis (American Society for Testing and Material [ASTM F1702-10, 2010]). Shear strength was measured using the Turf-Tec Shear Strength Tester (Turf-Tec International), which measures the rotational force required to tear the turfgrass. This instrument contains a torque wrench handle that is attached to a shear vane foot that is inserted into the surface and turned steadily until tearing. The highest torque (Nm) measurement determined using the torque wrench handle during the turning motion was recorded for analysis. A Field Scout time-domain reflectometry (TDR) 300 Soil Moisture Meter (Spectrum Technologies, Inc.) containing two probes (5 mm diameter, 7.6-cm depth) spaced 3.3 cm apart that are inserted

into the soil recorded % volumetric water content using TDR (five averaged readings). A Field Scout SC 900 Soil Compaction Meter (Spectrum Technologies, Inc.) was used to measure penetration resistance in the top 10 cm of the soil profile. The instrument uses a 9.8 mm diameter shaft with a cone tip (30° angle and 12.8 mm base) that is manually inserted into the soil profile and measures the penetration resistance in pounds per square inch (later converted to MPa) at soil depth increments of 2.5 cm. All response variables were subjected to analysis of variance ($\alpha = 0.05$) within R version 4.3.2 (RStudio, Inc.) to determine significance. If traffic rate was considered significant, Fisher's protected least significant difference provided means separation. All response variables other than soil bulk density were analyzed separately by rating date. Soil bulk density was only measured after all traffic events had occurred to determine the cumulative effect of the BTS device on soil compaction.

TABLE 5 Soil compaction (penetration resistance) in response to simulated traffic from the modified Baldree Traffic Simulator on the John Deere Aerocore 800.

		WAIT ^a								
		0	1	2	3	4	5	6	7	8
Turfgrass species^b	Traffic rate^c	Penetration resistance (0 cm) (MPa)^d								
Hybrid bermudagrass	Low	0.36a ^e	0.43a	0.20	0.16	0.13	0.00b	0.31	0.40	0.44
	High	0.18b	0.15b	0.39	0.13	0.34	0.51a	0.36	0.64	0.80
	LSD _{0.05}	0.18	0.26	ns	ns	ns	0.47	ns	ns	ns
Hybrid zoysiagrass	Low	0.09	0.09	0.29	0.20	0.41	0.38	0.4	0.13	0.30
	High	0.07	0.20	0.15	0.11	0.35	0.44	0.44	0.41	0.38
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	ns	ns	ns
Turfgrass species	Traffic rate	Penetration resistance (2.5 cm) (MPa)								
Hybrid bermudagrass	Low	0.54	0.55	0.41	0.51	0.37	0.37b	0.51	0.81	1.10
	High	0.25	0.59	0.43	0.60	0.39	0.75a	0.72	1.03	1.40
	LSD _{0.05}	ns	ns	ns	ns	ns	0.23	ns	ns	ns
Hybrid zoysiagrass	Low	0.32	0.55	0.50	0.43	0.54	0.77	0.65	0.56	1.08
	High	0.25	0.48	0.52	0.34	0.81	0.67	0.72	0.63	0.97
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	ns	ns	ns
Turfgrass species	Traffic rate	Penetration resistance (5.0 cm) (MPa)								
Hybrid bermudagrass	Low	0.23b	0.48	0.35	0.57	0.42	0.42b	0.64	0.67b	1.44b
	High	0.53a	0.53	0.50	0.74	0.53	0.66a	0.67	0.90a	2.00a
	LSD _{0.05}	0.27	ns	ns	ns	ns	0.22	ns	0.19	0.49
Hybrid zoysiagrass	Low	0.32	0.34	0.30	0.68	0.46	0.36	0.43	0.43b	0.76
	High	0.28	0.43	0.41	0.42	0.55	0.47	0.48	0.55a	0.92
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	ns	0.11	ns

^aAbbreviations: LSD, least significant difference; ns, non-significant; WAIT, weeks after initial traffic event.

^bIronCutter hybrid bermudagrass and Zorro hybrid zoysiagrass were evaluated.

^cThe low rate consisted of one traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^dA Field Scout SC 900 Soil Compaction Meter was used to measure penetration resistance in the top 10 cm of soil in increments of 2.5 cm.

^eMeans followed by the same letter within a column within the same species for each response variable are not significantly different at the $\alpha = 0.05$ significance level. The 0 cm 0 WAIT bermudagrass data and 5 cm 7 WAIT bermudagrass and zoysiagrass data were significant at the $\alpha = 0.1$ significance level.

3 | RESULTS AND DISCUSSION

3.1 | Acceleration experiment

The mass of one aerator arm assembly on the John Deere Aerocore 800 was measured as 11.25 kg, the mass of one modified BTS foot was 7.23 kg, making the total mass (m) 18.48 kg. The spring load (s) for each individual spring (determined from spring specifications) is 118.84 N cm⁻¹, and the aerating depth (D) used in the current trial was set to 6.4 cm. The average peak vertical acceleration measured from the IMU on the middle-left BTS foot measured 278.34 m s⁻¹ s⁻² and the IMU on the far-right BTS foot measured 282.08 m s⁻¹ s⁻², providing an overall average of the two IMUs (a) of 280.21 m s⁻¹ s⁻². When these values are inserted into Equation (1), the total average potential force output (F) was measured as 8221 N. This observed value is similar to that observed by Kowalewski et al. (2013) with the original Ryan GA 30 BTS device (9155 N). This value can be influenced

by adjusting the aeration depth set on the aerator device; however, due to the violent nature of the traffic procedure, increasing the aeration depth places additional strain on the aeration device itself and is not recommended.

3.2 | Field experiment

No differences in soil bulk density were observed in the hybrid bermudagrass plots (Table 1). The high bulk density (1.38 g cm⁻³) measured in the non-trafficked hybrid bermudagrass may indicate that penetration resistance of this site was too great to further influence with the addition of traffic treatments. The high traffic rate significantly increased bulk density compared to the non-treated in the hybrid zoysiagrass plots; however, no significant difference was observed between the low and high traffic rates (Table 1). The high traffic rate significantly reduced NDVI (0.75) and visual % turfgrass cover (71%) compared to the low traffic rate in

TABLE 6 Soil compaction (penetration resistance) in response to simulated traffic from the modified Baldree Traffic Simulator on the John Deere Aerocore 800.

		WAIT ^a								
		0	1	2	3	4	5	6	7	8
Turfgrass species^b	Traffic rate^c	Penetration resistance (7.5 cm) (MPa)^d								
Hybrid bermudagrass	Low	0.66	0.63	0.46b ^e	0.74	0.45b	0.45b	0.53	0.96	1.76
	High	0.66	0.71	0.81a	0.90	0.71a	0.78a	0.91	0.97	2.03
	LSD _{0.05}	ns	ns	0.29	ns	0.23	0.26	ns	ns	ns
Hybrid zoysiagrass	Low	0.29	0.37	0.37	0.36b	0.61	0.43	0.51	0.49b	0.91
	High	0.48	0.41	0.52	0.44a	0.66	0.54	0.55	0.71a	1.14
	LSD _{0.05}	ns	ns	ns	0.07	ns	ns	ns	0.17	ns
Turfgrass species	Traffic rate	Penetration resistance (10.0 cm) (MPa)								
Hybrid bermudagrass	Low	1.04	0.71	0.80	0.99	0.92	1.01	0.66b	1.17	1.94
	High	0.79	0.76	0.79	1.06	0.90	0.97	0.99a	1.03	1.73
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	0.31	ns	ns
Hybrid zoysiagrass	Low	0.68	0.66	0.72	0.59	1.01	0.63	0.70	0.67	1.28
	High	0.59	0.63	0.70	0.61	0.84	0.69	0.88	0.83	1.27
	LSD _{0.05}	ns	ns	ns	ns	ns	ns	ns	ns	ns

^aAbbreviations: LSD, least significant difference; ns, non-significant; WAIT, weeks after initial traffic event.

^bIronCutter hybrid bermudagrass and Zorro hybrid zoysiagrass were evaluated.

^cThe low rate consisted of one traffic event week⁻¹ for eight total traffic events, and the high rate consisted of two traffic events week⁻¹ for 16 total traffic events.

^dA Field Scout SC 900 Soil Compaction Meter was used to measure penetration resistance in the top 10 cm of soil in increments of 2.5 cm.

^eMeans followed by the same letter within a column within the same species for each response variable are not significantly different at the $\alpha = 0.05$ significance level. The 7.5 cm 2, 4, and 5 WAIT bermudagrass data were only significant at the $\alpha = 0.1$ significance level.

the hybrid bermudagrass plots (0.79 and 94%, respectively) 8 weeks after initial treatment (WAIT). However, the NDVI values were not extremely different from the NDVI values measured before any simulated traffic was applied (0.80 and 0.82, respectively), despite the reduction in visual % turfgrass cover (Table 2). Similarly, the high traffic rate significantly reduced TC (4.8) and TQ (5.3) in the hybrid bermudagrass plots 8 WAIT compared to the low traffic rate (6.4 and 6.9, respectively; Table 3). However, these same trends in NDVI, visual % turfgrass cover, TC, and TQ were not observed in the hybrid zoysiagrass plots. Despite the lack of similar trends, the difference in values from before and after all traffic events was more extreme for the hybrid zoysiagrass plots than for hybrid bermudagrass. This suggests that the hybrid zoysiagrass plots were more sensitive to a single traffic event week⁻¹, but an additional traffic event per week did not significantly affect hybrid zoysiagrass. Conversely, hybrid bermudagrass was more resilient to single traffic events week⁻¹, but the addition of a second traffic event week⁻¹ caused significantly more injury to hybrid bermudagrass. Therefore, traffic rates for future studies will need to be adjusted based on species and/or soil types, among other variables.

Traffic rate had a significant effect on surface hardness observed for both species 8 WAIT (Table 4). The high traffic rate hybrid bermudagrass plots (156 Gmax) were significantly harder than the low traffic rate plots (141 Gmax). Similar

trends were observed in the hybrid zoysiagrass plots, with the high traffic rate (106 Gmax) demonstrating a significantly harder surface than the low traffic rate plots (90 Gmax). Additionally, the surface hardness values increased from 65 to 156 Gmax for the high traffic rate hybrid bermudagrass plots and 53 to 106 Gmax for the high traffic rate hybrid zoysiagrass plots throughout the duration of the trial, suggesting that the traffic stress had a cumulative effect on surface hardness across all plots with the high traffic rate increasing surface hardness at a faster rate than the low traffic rate (Table 4).

The high traffic rate hybrid bermudagrass plots (12.3 Nm) also demonstrated less rotational resistance compared to the low traffic rate plots (14.4 Nm; Table 4). However, the opposite trend was observed for the hybrid zoysiagrass plots (27.4 Nm for the high traffic rate plots and 22.0 Nm for the low traffic rate plots). While unexpected, the force provided by the John Deere BTS was primarily vertical; therefore, it did not radiate extreme amounts of horizontal force onto the surface. Consequently, it is possible that hybrid bermudagrass shear strength is affected more by a vertical crushing force while hybrid zoysiagrass shear strength is affected more by tearing and other horizontal forces. No significant differences were observed in soil moisture 8 WAIT for either species, clearly indicating an alteration in soil structure.

Minimal significant differences in penetration resistance were observed between traffic rates for either species

(Tables 5 and 6). However, the general trends in the data suggest that there were cumulative increases in penetration resistance in both species throughout the duration of the trial. This is most evident at the 5- and 7.5-cm depths, where there were increases from 0.53 to 2.00 MPa (Table 5) and 0.66 to 2.03 MPa (Table 6) in the high traffic rate hybrid bermudagrass plots from trial initiation to 8 WAIT. This suggests that although there were minimal differences between traffic rates, the applied simulated traffic has a cumulative effect on soil compaction regardless of traffic rate.

4 | CONCLUSION

Results from the current study indicate that the reengineered BTS feet designed for a John Deere Aerocore 800 are effective at providing simulated traffic stress for turfgrass performance research. Although not evaluated in the current study, the inclusion of the specific parts used in the design process along with the newly engineered attachment mechanism allows for the adaptation of our BTS feet to be used with other aerification units. However, further work needs to be conducted to fine-tune the exact aerification settings to accomplish adequate turfgrass traffic stress without causing too much strain on each individual device. The settings used at the beginning of the current study caused extreme stress to the lifting mechanism of the John Deere Aerocore 800, ultimately leading to required repairs of the aerification machine. Therefore, further research should be directed at establishing these settings and specifications for the John Deere Aerocore 800 aerification unit and others. Additional research should also be conducted to evaluate the effects of traffic on water infiltration and other soil physical parameters.

AUTHOR CONTRIBUTIONS

Erick G. Begitschke: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; writing—original draft. **Matthew Bowen:** Conceptualization; resources. **Larry M. Baldree:** Conceptualization; methodology. **Nandita Gaur:** Conceptualization; resources; supervision; writing—review and editing. **Robert C. Lynall:** Conceptualization; resources; supervision; writing—review and editing. **Gerald M. Henry:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The authors would like to thank Kevin Tucker, Audrey Young, Julie Wang, Alberto Novello, and all of the undergraduate student employees for their technical support during this research.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Begitschke, E. G., Bowen, M., Baldree, L. M., Gaur, N., Lynall, R. C., & Henry, G. M. (2026). Reengineering the Baldree Traffic Simulator for turfgrass wear and traffic research. *Agrosystems, Geosciences & Environment*, 9, e70360. <https://doi.org/10.1002/agg2.70360>