TRACKED AND WHEELED VEHICLE BENCHMARK – A DEMONSTRATION OF SIMULATION MATURITY FOR NEXT GENERATION NATO REFERENCE MOBILITY MODEL

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ABSTRACT

Due to shortcomings in vehicle mobility prediction in the NATO Reference Mobility Model (NRMM), recommendations and requirements for the Next-Generation NATO Reference Mobility Model (NG-NRMM) are under development. The limiting nature of empirically based terramechanics and the recent decades of significant improvements to 3D physics based Modeling and Simulation (M&S) capability call for a process to quantify physics based M&S in meeting the proposed goals of NG-NRMM. A verification and validation (V&V) process is demonstrated to quantify the vehicle mobility prediction capability of current state of the art physics based M&S tools. The evaluation is based upon an M&S maturity scale adopted and modified from corporate simulation governance to fit the specifics of vehicle mobility. The V&V process is demonstrated through a set of benchmarks, one for a tracked and another for a wheeled vehicle. The NG-NRMM benchmark efforts have demonstrated an analytical process for evaluating simulation capability maturity levels for M&S tools. More test data needs to be acquired with this specific purpose in mind. However, current results support the conclusion that current industry standard 3D physics based M&S tools are able to predict expected mobility outcomes that will never be possible with NRMM.

INTRODUCTION

Efforts organized as a research task group 248 under the NATO Advanced Vehicle Technology panel generating recommendations and requirements for the Next-Generation NATO Reference Mobility Model (NG-NRMM) are under development. Existing NRMM mobility prediction is based on 2D quasi-static vehicle modeling and empirically based vehicle - soil interaction, and thereby lacking vehicle mobility performance improvements from current 3D based multibody dynamics vehicle modeling [1]. Advancements such as 3D transient vehicle dynamics, flexible bodies, advanced tire modeling including tire flexibility, and advanced suspension systems are examples of such improvements. Furthermore, the limiting nature of empirically based terramechanics and the recent decades of significant improvements to 3D physics based Modeling and Simulation (M&S) capability call for a process to quantify physics based M&S in meeting the proposed goals of NG-NRMM.

A Verification and Validation (V&V) process [2] is demonstrated to quantify the vehicle mobility prediction capability of current state of the art physics based M&S tools. The evaluation is based on an M&S maturity scale adapted from existing generic M&S V&V process standards, to fit the specifics of vehicle mobility.   The scale is progressive with increasing maturity levels being indicative of models that go beyond verification to ultimately become demonstration of blind validation predictive capability.

V&V BENCHMARKS

The V&V process is demonstrated through a set of benchmarks for a tracked and a wheeled vehicle

platform (WVP). Representations of the two types of benchmarked vehicles are depicted in Figure 1 for the tracked vehicle, and Figure 2 for the wheeled vehicle.
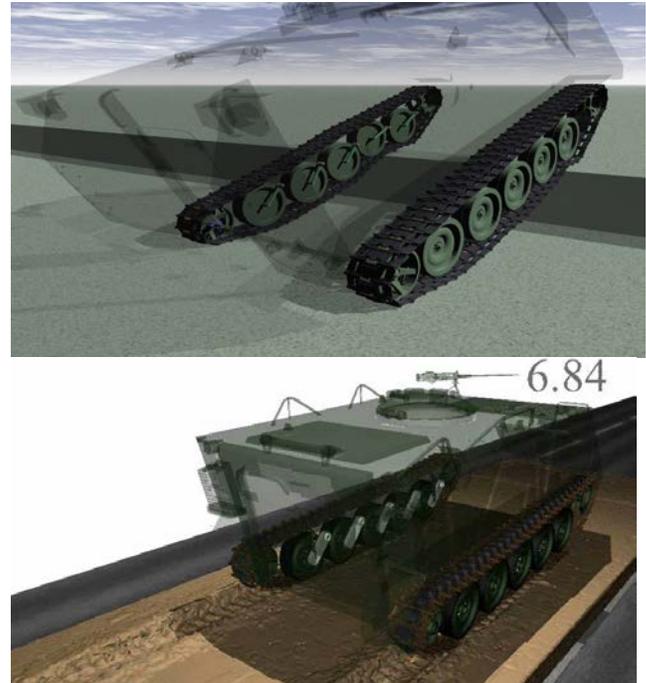
Top: Chrono, Tracked on Step Climb
Bottom: IVRESS, Tracked on Soft Soil
Figure 1: Tracked Vehicle Representation

Figure 2: NATC WVP Representation

Vehicle Sources and Test Events

The tracked vehicle benchmark is based on vehicle and drawbar pull test data made available by Vehicle Systems Development Corporation (VSDC), augmented with two published data points on step climb and gap crossing [3]. All other mobility events do not have test data to support validation.

The WVP benchmark is based on vehicle and test data made available by the Nevada Automotive Test Center (NATC). Several specific test events and corresponding test results are made available for the wheeled vehicle benchmark, as described below.

The NG-NRMM committee focused on several test events for the benchmarks. These and the supporting standards and procedural documents are:

- Steering Performance, including wall-to-wall turn radius in accordance with AVTP 03-30 [12], steady state cornering per SAE J266 [7] and SAE J2181 [16], and double lane change (paved and unpaved) with AVTP 03-160W [8] as a general guideline.
- Side Slope Stability with TOP 2-2-610 [9] as a general guideline, including maneuver on paved and unpaved surfaces.
- Straight Line Acceleration based on TOP 2-2-602 [15] and Grade Climbing with TOP 2-2-610 [9] as a general guideline, including paved and unpaved.
- Ride Quality outlined by TOP 1-1-014 [10]
- Obstacle Crossing, based on TOP 2-2-611 [13], including steps, gaps, and NRMM standard suite of positive and negative trapezoids.
- Off-road trafficability including single and multi-pass soil strengths, drawbar pull in

accordance with TOP 2-2-604 [11] as a general guideline and motion resistance.
- Closed loop traverse including speed made good and fuel economy in partial agreement with AVTP 03-10 [14].

Detailed descriptions of these events and definitions of terms are found in reference [1].

The WVP benchmark based on pre-existing data from NATC focused uniquely on only the events for which test data were available. Some variation from the reference [1] definitions of the events and terminology were required to utilize the NATC data.

The provided event data were specifically:

- Straight Line Acceleration – hard surface
- Grade Climbing – 30% sand slope.
- Steering Performance – wall-to-wall, steady state cornering.
- Ride Quality – hard surface.
- Double Lane Change – hard & gravel surfaces.
- Side Slope Stability – gravel surface.
- Off-road Trafficability – drawbar pull.

Benchmark Participants

Based on response to a request for information set forth in the preceding exploratory work, a number of commercial as well as open source vehicle M&S software developers were invited to the benchmarks. All but one developer participated in both the tracked and wheeled vehicle benchmark. The participating entities, their country of origin and the name of their software codes (bold font) are listed below:

- Advanced Science and Automation Corp., (US), **IVRESS/DIS**
- University of Wisconsin – Madison, (US), **Chrono**
- MSC Software (US), **Adams**
- CM Labs, (Canada), **Vortex** (Wheeled Only)

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- Vehicle Systems Development Corporation, (Canada), **NTVPM, NWVPM**
- FunctionBay, (ROK), **RecurDyn**

Simulation Maturity Scale

The modeling and simulation predictive capabilities of the participating M&S tools are evaluated against a modeling and simulation maturity scale. The concept of a M&S capability maturity scale originated in [4] and was modified for generic purposes in [5]. The latter was dedicated to M&S supporting high volume of production, which does not accurately describe military vehicles or their mobility performance prediction. Therefore, a tailored capability maturity scale, shown in Table 1, was developed for NG-NRMM.

Table 1: NG-NRMM Modeling and Simulation Predictive Capability Maturity Levels

1. ***DEMONSTRATION:*** Demonstration of a correct implementation of a theoretically and conceptually consistent model.
2. ***PARAMETER SENSITIVITY DEMONSTRATION:*** Verification that performance change with a change in system parameter such as GVW or terrain deformability is consistent with theory and physics principles.
3. ***INDEPENDENT USER VERIFICATION:*** Independent user demonstration and correlation to vendor results
4. ***CROSS CODE VERIFICATION:*** Cross verification with another accepted mobility simulation code
5. ***CALIBRATION:*** Calibration to a real vehicle test data set
6. ***VALIDATION:*** Blind correlation to a real vehicle test data set
7. ***PARAMETER VARIATION VALIDATION:*** Blind correlation to a real vehicle test data set with a change in system parameter(s).

Applying the definitions shown, for any given benchmark mobility event, the achievable maturity level is Level 2 if only one participant provided a simulation result. Level 4 is achieved if two participants independently developed results that correlated well. If calibration data is available such that the model can be tuned to achieve good correlation, Maturity Levels 5 is achieved. If test results are held back and the model is able to predict test results without a priori knowledge of the test results, Level 6 is achieved. Furthermore, if the model is additionally successful in blind prediction of results for a specific test or vehicle parameter variation, then Level 7 is achieved.

Levels 5-7 do not require that all lower levels are explicitly demonstrated if the simulations are able to predict the tested performance. However, from a practical perspective, validation achieved without verification is an improbable random event and all modern M&S software is released with at least a Level 2 verification, without exception. In this benchmark effort Level 0 means no results submitted, and Level 7 demonstration was not requested.

The detailed event level achieved simulation maturity levels for tracked and wheeled benchmarks are presented graphically in spider plots as shown in Figure 7 trough Figure 59. Composite benchmark summary results are provided in Table 2 and Table 3.

It should be noted that for the benchmark maturity levels presented here, the software developers did not have a priori access to the test data for the WVP benchmark, therefore Level 6 is possible for those events where test data was available. The limited performance test data for the tracked vehicle was available a priori (i.e. Level 5 achievement). For a number of the wheeled benchmark tests such as Double Lane Change and Side Slope Stability, steering input was provided from the real vehicle tests to reduce the challenging requirements for prediction of open loop divergent behavior inherent in steering path predictions. This focused the validation challenge on the physics of the vehicle and bypassed issues associated with the myriad of

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ways to include driver steering models that are typically used to "close the path loop".

The submissions are evaluated with scores derived by comparing to test data when available (i.e., Maturity Level 5 or 6 assessment), and otherwise by comparison to the other developer's results, which is a Maturity Level 4, cross code verification. For Level 4, the mean of the results of all submissions is taken as the reference basis for comparsion. Finally, it should be noted that vendor submissions for both of the benchmarks were burdened by first time learning curves for the engineers performing the simulations. It is expected that expert users would fare much better. Additionally, it should be noted that the vendor efforts to iteratively learn more about military mobility simulation and develop improved results based on feedback from first round results were prematurely truncated. This was due to a re-focus driven by the emergence of a more comprehensive benchmark effort sponsored by NATO and TARDEC in the form of a Cooperative Demonstration of Technology (CDT) specifically targeted at collecting data for NG-NRMM validity demonstration. This NATO CDT will occur in September 2018.

TRACKED VEHICLE RESULT DISCUSSION

If test results are held back and the model is able to predict test results without a priori knowledge of the test results, Level 6 is achieved. A Maturity Level of 4 is achievable in most of the tracked vehicle results, where no test data is available. It is judged to have been achieved by the participants who predicted comparable results to a known physical principle, or, in the absence of that, the mean of all submitted results. An industry wide maturity level is assigned based on the maximum achieved across all vendors. A high level summary of all results is provided in Table 2.

Table 2: Tracked Vehicle Benchmark Composite M&S Industry Results

	Max Possible Ranking Score	Max Achievable Maturity Level	Industry Achieved Maturity
Total score	88	4.11	3.89
Score Hard Surface	59	4.10	4.10
Score Soft Soil	29	4.14	3.29

a) Scoring, Composite Maturity and Industry Average

	Participant/Vendor					
SIMULATION EVENTS	NRMM	A	B	C	D	E
Total	44%	67%	58%	49%	89%	9%
Score Hard Surface	50%	81%	78%	71%	92%	0%
Score Soft Soil	32%	40%	20%	7%	85%	27%

b) Individual Results

These results show that at least one vendor was able to demonstrate the maximum maturity level for each event, except for the single pass and multi-pass trafficability as well as motion resistance events. Thus the most significant challenge for most vendors was the soft soil events. Nevertheless, one vendor demonstrated an 85% score on soft soil events. A unit score point was possible for each individual event result on hard surfaces, two points per event for each soft soil result, and double points were awarded for events with test data (Levels 5 - 7).

Figure 3 and Figure 4 show the detailed maturity level achieved by each vendor for each event for the Tracked Vehicle benchmark on hard and soft soil respectively. Figure 5 and Figure 6 show the detailed results for the WVP benchmark on hard and soft soil respectively. Individual plots for each vendor and each event are located in Appendix A through Appendix D. A detailed narrative discussion of results and conclusions for each follow.
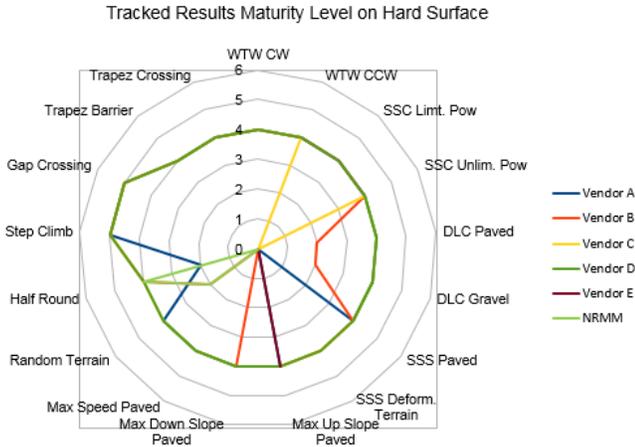
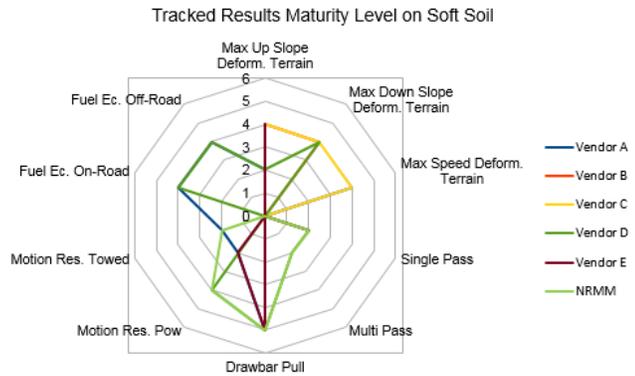**Figure 3:** Detailed Tracked Vehicle Benchmark Results on Hard Soil

Figure 4: Detailed Tracked Vehicle Benchmark Results on Soft Soil

Wall to Wall, WTW
Wall to wall simulation results showed a very significant level of agreement of the diameter traced by the vehicle, resulting in equal Maturity Level of 4. Thus, M&S is judged to be unambiguously capable with respect to this performance parameter. Furthermore, they are likely to achieve Level 6 when test data become available.

Steady State Cornering, SSC
The steady state cornering test is specified to be conducted with limited power as well as unlimited power in the powertrain and steering parts of the models. For the unlimited power simulations, the

models predicted very close results, thus achieving Level 4. Due to driver model dependencies in the implementation of the limited power model, the results vary too much to achieve unambiguously a Maturity Level of 4. However, with a more precise definition of tracked vehicle steering system mechanics and the opportunity for all vendors to ask questions, along with test data availability, validation of this mobility event predictive capability is judged to be achievable at Levels 6 or 7.

Double Lane Change, DLC
A double lane change is performed on paved and on gravel surface. All results obtained by the vendors are within acceptable limits, except for vendor B that underestimates the speed compared to the remaining vendors. Thus, the M&S industry capability is judged to have achieved Level 4. Driver model dependencies, and a more precise understanding of the variation in actual test performance will be necessary to perform objective validation and achieve Level 6 or 7.

Side Slope Stability, SSS
Most vendors have conducted the simulation both on paved surface and on sand and the results are comparable, resulting in a Maturity Level of 4 for the participating vendors and thus also the M&S industry as a whole. Likewise, when test data becomes available to validate these models, it also judged to be very achievable at Level 6 or 7.

Grade Climbing
The aim of the grade climbing event is to determine the maximum slope, that the vehicle can maneuver on paved surface and on sand. All vendors that have contributed with a result have obtained a Maturity Level of 4 as their results are in agreement. Thus, the M&S industry as a whole is Level 4. Likewise, when test data becomes available to validate these models, it is also judged to be achievable at Level 6 or 7.

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Maximum Speed on Grades

Three vendors have provided results for the maximum speed obtained on a slope on paved surface. All vendors have achieved a Maturity Level of 4. Only a single participant, vendor C, has performed the simulation on sand, thus only a Maturity Level of 2 is the maximum possible. Test data would permit Level 6 or 7 assessment, but is not available at this time.

Ride Quality on Random Terrain

The random terrain event is performed with three different heights. Most vendors have agreeable results, but the results of vendor B as well as NRMM, are not in agreement. Vendor A, C, and D demonstrate that like models do cross-verify and the known theoretical limitations in the NRMM Vehdyn II simulations are expected. Thus vendors A, C, and D are assessed as representative of the state of the industry and are therefore at Level 4, with expectations of Level 6 or 7 achievement when test data becomes available.

Half Round Obstacles

These simulations are dependent upon much the same vehicle dynamic models as the Random Terrain Ride Quality and similar results are obtained. Five half round obstacle simulations are specified to be performed. Vendor A is an outlier compared to the remaining results, with NRMM Vehdyn II providing a reasonable agreement with the mean of all results. Thus vendors NRMM Vehdyn II, B, C, and D are assessed as representative of the state of the industry and are therefore at Level 4, with expectations of Level 6 or 7 achievement when test data becomes available.

Step and Gap Obstacle Negotiation

The obstacle avoidance tests consist of a step climb and a gap crossing event. Very good agreement with calibration data was obtained thus demonstrating Level 5 across the industry and for each vendor in this category. Expectations of Level 6 or 7 should be achieved when test data becomes available.

Trapezoidal Obstacles

The trapezoidal obstacles tests consist of a trapezoidal fixed barrier and a trapezoidal ditch crossing of various sizes. These are the standard NRMM obstacle definitions. NRMM and the four vendors, that have provided results, are in acceptable agreement of both events resulting in an obtained Maturity Level of 4 for all the vendors and the industry as a whole. Expectations of Level 6 or 7 should be achieved when test data becomes available. When these obstacles are generalized to 3D, NRMM's 2D methods will be obsolete.

Off-Road Trafficability

For the maturity levels achieved by the vendors for a single pass and a multi pass on soft soil, the vendors have reported the soil strength limit. Only NRMM has been capable of producing a limit, while vendor E and vendor G attempted the exercise and have not been capable of obtaining a limit therefore resulting in a maximum achievable Maturity Level of 2. NRMM uses an empirical model. Physics based models for predicting this performance are possible but not yet demonstrated. This particular soft soil for this event was very strong making this particular performance parameter difficult to predict as it is likely very large or near infinite. This event will be re-framed in the future to ensure consistency with available test data and only use relevant limiting soil conditions wherein the metric becomes more meaningful.

Drawbar Pull

The drawbar pull event is performed to determine the net traction of the vehicle on the LETE sand of reference [3]. All provided results are within a reasonable limit compared to the calibration data, hence all vendors have obtained a Maturity Level of 5. Vendor E actually calibrated their model

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with the test data and therefore judged as Level 5. Because no particular model adjustments were required for calibration, blind predictions are likely to be successful, hence this event is likely a Level 6 candidate when validation test data becomes available to conduct blind predictions.

Motion Resistance

The motion resistance event is specified to be performed powered and towed. The overall industry assessment of powered motion resistance is identical with the drawbar pull event above since this motion resistance is a natural result of the drawbar pull test event. Towed motion resistance is a lower priority but deemed to be equally achievable.

Closed Loop Traverse/Fuel Economy

The fuel economy events are conducted both on-road and off-road. Only two vendors, vendor A and vendor D, have provided results and since they are very comparable, the achieved Maturity Level is 4.

WHEELED VEHICLE RESULT DISCUSSION

A Maturity Level of 6 is obtained by a vendor who has achieved blind correlation to test data. A Maturity Level of 4 is obtained when the results obtained by multiple vendors are comparable. A Maturity Level of 2 is the maximum possible where the test data were inadequate and only one vendor produced a simulation, or if a vendor was judged to be an outlier (>100% difference from the mean of all other vendors). An industry wide maturity level is assigned based on the maximum achieved across all vendors for the individual event. The composite industry maturity for the whole WVP benchmark is based on the average across the events. A high level summary of all results is provided in Table 3.

Table 3: NATC WVP Benchmark Composite M&S Industry Results

	Max Possible Ranking Score	Max Achievable Maturity Level	Industry Achieved Maturity
Total Score	36	5.11	5.00
Score Hard Surface	22	4.92	4.92
Score Soft Soil	14	5.60	5.17

a) Scoring, Composite Maturity and Industry Average

	Participant/Vendor						
	NRMM	A	B	C	D	E	G
Total Score	17%	58%	57%	82%	51%	5%	76%
Score Hard Surface	28%	62%	78%	78%	67%	0%	84%
Score Soft Soil	0%	52%	24%	87%	26%	12%	64%

b) Individual Results

These results show that at least one vendor was able to demonstrate the maximum maturity level for each event, except for the locked differential drawbar pull event. Thus, the most significant challenge for most vendors was the soft soil events. Nevertheless, one vendor demonstrated an 87% score on soft soil events. However, it should be recalled that this WVP benchmark was for a limited subset of events, and counted hardpack gravel conditions as "soft soil" and did not include soft soil trafficability or motion resistance (i.e., the unachieved events in the Tracked Benchmark).

Based on a review of the individual results:
a) Paved surface events were generally successful at Level 6 for events with reported test data.
b) Gravel surface turning and side slope events were also successful at Level 6.
c) Traction (drawbar pull) validations were partially successful at Level 6 demonstrating the need for further soft soil model development for simulation implementation. Nevertheless, good agreement among the vendors supported a strong Level 4 assessment, and though not

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explicitly demonstrated, Level 5 (model calibration) should also be very achievable.

d) Sand slope gradeability results demonstrated reasonable agreement at Level 4 but also highlighted this area as the most significant technical challenge for both consistent test procedures and repeatability as well as simulation and modeling.

A summary of maturity levels achieved across all events, by vendor, is shown in Figure 5 and Figure 6.

Figure 5: WVP Maturity Levels Achieved on Hard Soil

Figure 6: WVP Maturity Levels Achieved on Soft Soil

Straight Line Acceleration, SLA
Several vendors have obtained a Maturity Level of 6, due to the similarity between test data (actual time to max speed ~ 50sec) and simulation data. Though not shown, the vendors have produced simulation time history plots that resemble the test plots in both shape and magnitude.

Wall To Wall, WTW
Test data is not available for the wall to wall simulation, resulting in a maximum achievable Maturity Level of 4. The vendors, that have performed both the clockwise and the counter clockwise simulation, perform equally in both. Industry is judged as Level 4 with Level 6 and Level 7 very achievable.

Steady State Cornering, SSC
The steady state cornering test is performed both clockwise and counter clockwise. Test data is only available for the clockwise event.

Vendors C and G have obtained blind correlation and thus achieved a Maturity Level of 6. The blind correlation is estimated based on correlation to the steering wheel angle versus the lateral acceleration plot of test data. Industry is judged as Level 6 with Level 7 very achievable.

Double Lane Change, DLC
The double lane change simulation is specified to be performed both on paved and gravel surface. RTF indicated Right Turn First. Due to driver response model dependencies results were predicted with actual steering wheel input from test given as an option.

The vendors, that have succeeded in performing the double lane change using the given steering input, achieved Level 6, based on the fact that the shape of peak roll, pitch and yaw angles and rates closely resembles the test data (see Figure 5) for at least two vendors.
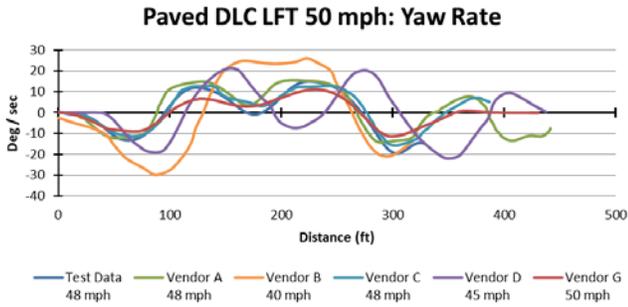
Figure 5: Double Lane Change Comparison to Test Data

For the Right Turn First event no vendors performed the simulation due to limited time and resources and similarity of the event to the Left Turn First.

Side Slope Stability, SSS

The side slope stability event is specified to be performed left side down and right side down both by using a given steering input as well as by using the vendors own driver model steering controller. When the steering wheel input is provided, Vendors A, B and C comparisons between the test data and the simulation conducted at the same speed shows good correlation between roll rate, yaw rate and lateral acceleration. Therefore, Level 6 is achieved. Without using the actual steering input, no vendor achieved good correlation to test data.

Sand Slope Gradeability

Test data exists of a successful 30 percent slope climb, but not a full suite of data demonstrating slope climb limits. Thus for this benchmark resulting in a maximum Maturity Level of 4. Some vendors predicted limits below the 30 percent achieved in test. Driver input to the throttle is one of the primary issues but this event demonstrates the need for improved terramechanics data and models for trafficability up sand slopes, as well as test procedures that include varying slopes.

Ride Quality

The ride quality is determined by conducting a series of tests over random profile courses at RMS roughness levels of 1in, 1.2in, 2.4in and 3.6in. A reduced results plot of 6 watt limiting speed vs roughness level comparison shows that all vendors that have contributed with a result have obtained a Maturity Level of 6. This remains a complex mobility evaluation event for which significant coordination of test procedure and analysis procedure are required to eliminate driver influences and subtle data reduction misinterpretation. Nevertheless, industry maturity is judged a Level 6 because at least one vendor matched results for each terrain roughness.

Drawbar Pull

The final event was the drawbar pull simulation for net tractive effort. The test is specified to be performed with both locked and open differentials. Similar results for simulations with the same assumptions result in a minimum Level 4 assessment. Test data were eventually made available which yielded a Maturity Level of 6.

CONCLUSIONS

The overall goal of the tracked and wheeled vehicle benchmarking exercise has been to establish the framework for judging the maturity level of Modeling and Simulation tools to be compliant with requirements for Next Generation NRMM evaluation criteria. The process involved a number of efforts:

- Selection and detailed definition of a set of benchmark events suitable for tracked and wheeled vehicles to capture the vehicle performance essential to NG-NRMM.
- Establish benchmark data sets for tracked and wheeled vehicles, including test data if available.
- Establish the maturity scale for judging the M&S tools capability to fulfill the

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requirements for NG-NRMM compliance.

The general conclusion is that the vehicle dynamics M&S vendors, as an industry, do have the mature capability to predict most of the required events identified by the NG-NRMM effort. Furthermore, by virtue of it's 2D theoretical basis, the NRMM model falls short on the events requiring 3D modeling for maneuvering. It is also noted that soft soil modeling for the 3D transient dynamics simulation is in need of tailored soil characterization data dedicated to this purpose, in order to rigorously demonstrate Maturity Level of 6 and above. This is seen as a major future work component to evaluate the advanced capabilities of NG-NRMM M&S software. Furthermore, the 3D simulation capability allowing for simulation campaigns to estimate the minimum time through a complex terrain requiring transient maneuvering is an area in need of evaluation metrics. Utilizing these capabilities in guiding acquisition, design and operations planning calls for renewed attention to the way mobility maps are presented.

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APPENDIX A: Tracked Vehicle: Maturity Achieved for All Vendors on Each Individual Events

Vendor A

Figure 7 displays the maturity level of vendor A in the hard surface events, shows that vendor A in general achieves a high maturity level, and that the vendor has performed most of the hard surface events. Figure 8 displays the maturity level of vendor A in the soft soil events reveals that vendor A has conducted less of the soft soil events, indicating that the vendor is stronger in hard surface than on soft soil.

Figure 8: Tracked Maturity Levels for Vendor A on soft soil

Vendor B

The observations made regarding vendor A are likewise valid for vendor B, that has performed most of the soft soil events with a high maturity level, but lacks results of the soft soil events.

Figure 7: Tracked Maturity Levels for Vendor A on hard surface
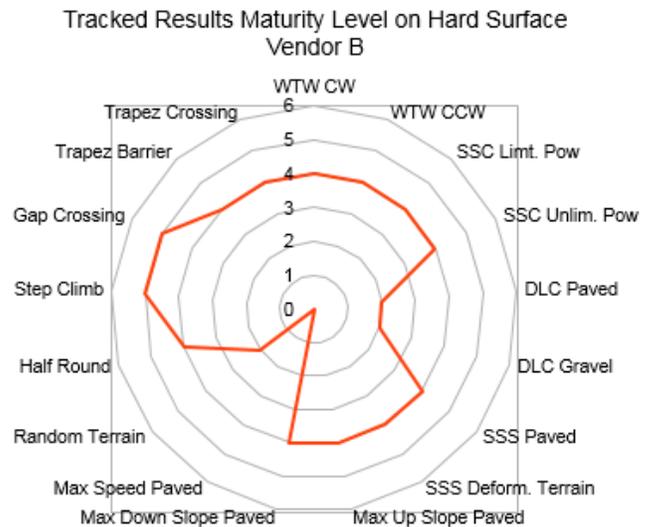
Figure 9: Tracked Maturity Levels for Vendor B on hard surface

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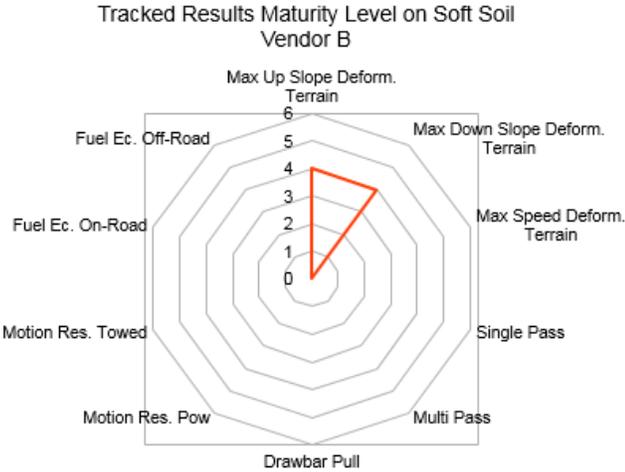
Figure 10: Tracked Maturity Levels for Vendor B on soft soil
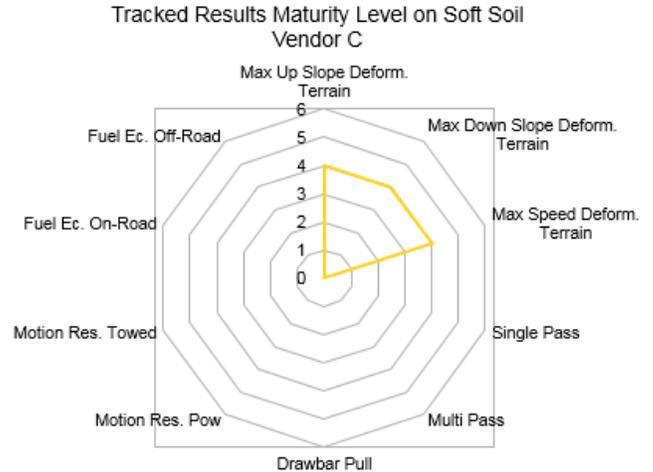
Figure 12: Tracked Maturity Levels for Vendor C on soft soil

Vendor C

A repetition of the two previous vendors. Vendor C shows a high level of maturity in the hard surface events in Figure 11, but has only conducted few of the soft soil events, shown in Figure 12.

Vendor D

Vendor D has performed all the hard surface events and has achieved the maximum obtainable Maturity Level of 4 and 5 in all hard surface events. From Figure 14 it is evident, that vendor D also has performed well in the soft soil events, and is the vendor, that has conducted most of the soft soil events.
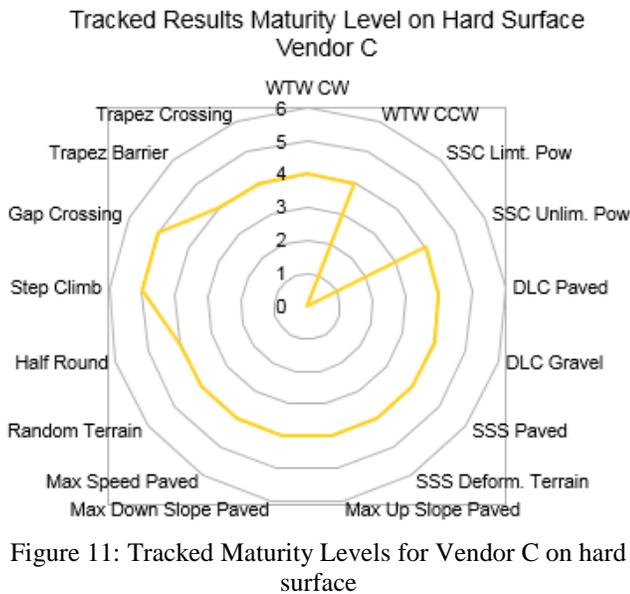
Figure 11: Tracked Maturity Levels for Vendor C on hard surface
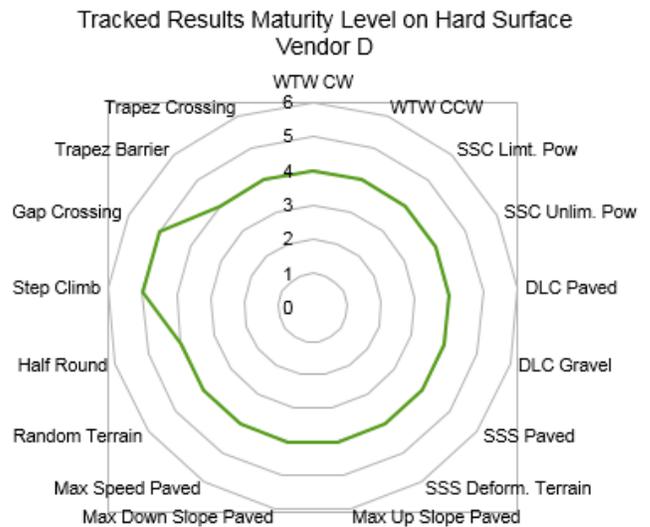
Figure 13: Tracked Maturity Levels for Vendor D on hard surface
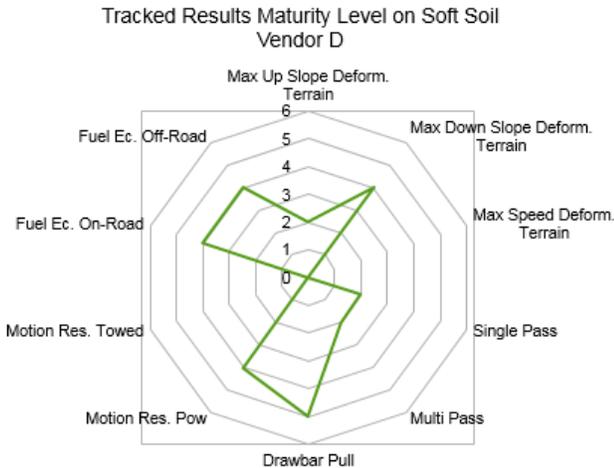
Figure 14: Tracked Maturity Levels for Vendor D on soft soil
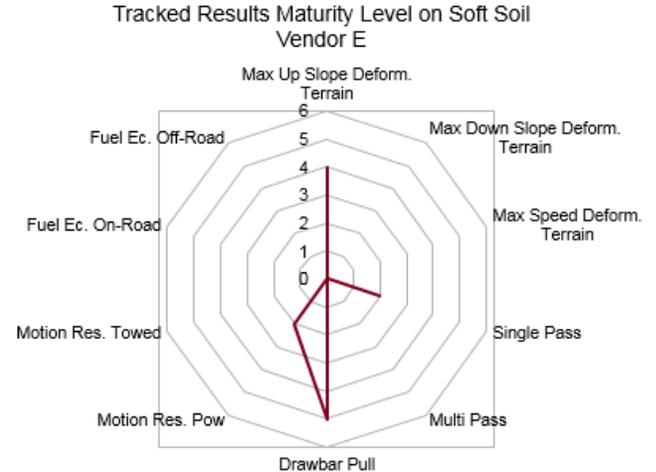
Figure 16: Tracked Maturity Levels for Vendor E on soft soil

Vendor E

Vendor E has only conducted a single hard surface event, the grade climbing up slope event, hence no general comments on the performance of vendor D can be made. The vendor has conducted two of the soft soil events with varying success.

Figure 15: Tracked Maturity Levels for Vendor E on hard surface

NRMM

The NRMM has only conducted two hard surface events, showing the limitations of the model in 3D events. In the soft soil events, Figure 18, the NRMM has conducted more of the events, and is the only vendor, that has been able to present a soil strength limit.
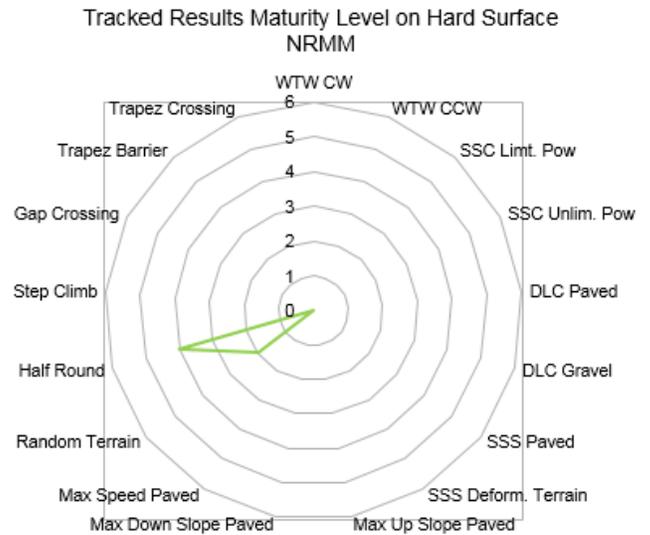
Figure 17: Tracked Maturity Levels for NRMM on hard surface

A demonstration of simulation maturity for Next Generation NATO Reference Mobility Model, Balling et al.
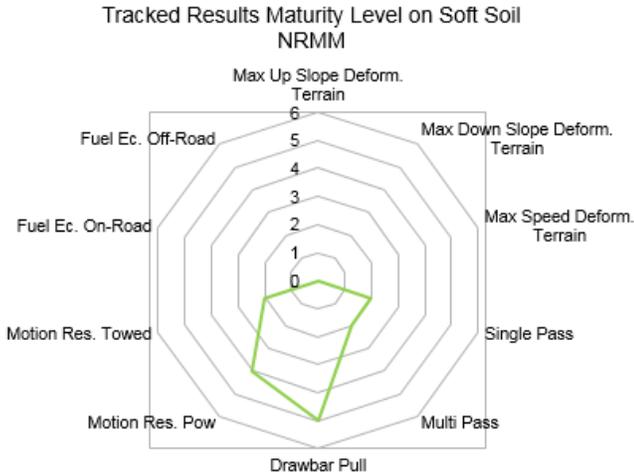
Figure 18: Tracked Maturity Levels for NRMM on soft soil

APPENDIX B: Tracked Vehicle: Maturity Achieved for All Vendors Presented by Each Individual Event

Wall To Wall, WTW

The wall to wall simulation shows a very significant level of agreement for the diameter traced by the vehicle for the vendors, that have performed the event, resulting in equal maturity level for the participating vendors, see Figure 19.
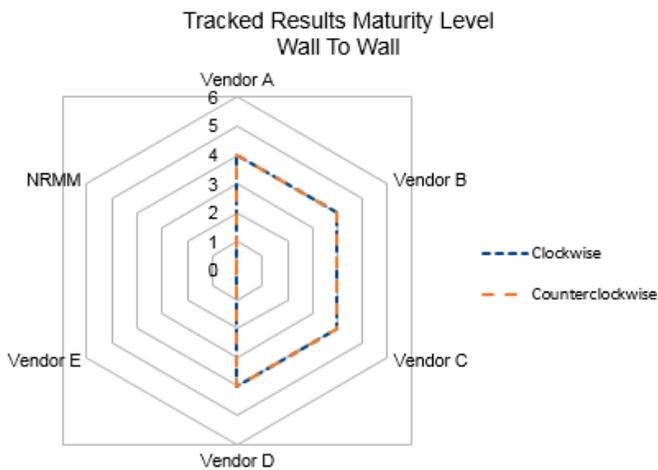
Figure 19: Tracked Maturity Levels for Wall to Wall

Steady State Cornering, SSC

The vendors, that have conducted the steady state cornering event, has achieved a high maturity level for the unlimited power event.
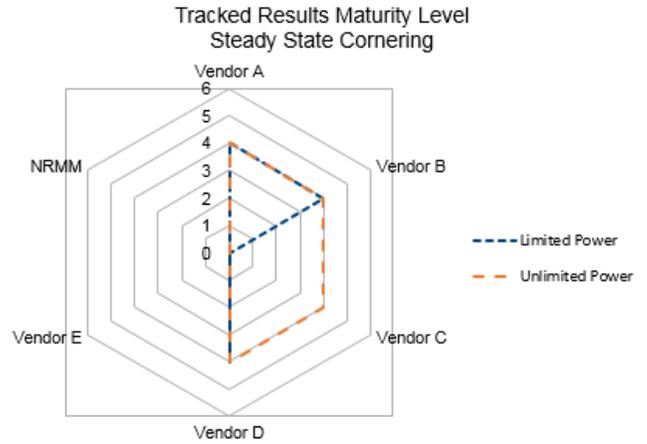
Figure 20: Tracked Maturity Levels for Steady State Cornering

Double Lance Change, DLC

The double lance change events have been conducted by four vendors, all, except vendor B, that deviates more than 50% compared to the average, achieving the maximum maturity Level of 4, since no test data is available.
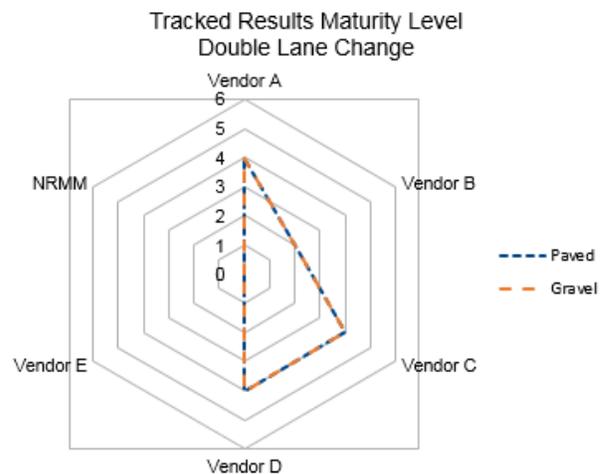
Figure 21: Tracked Maturity Levels for Double Lane Change

Side Slope Stability, SSS

The side slope stability results obtained by the vendors are comparable.
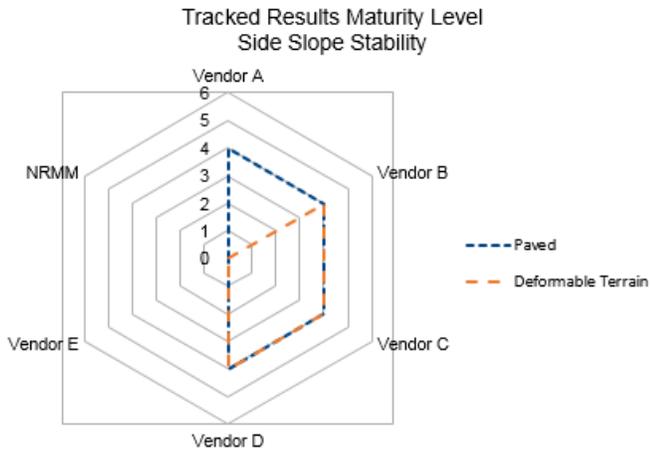
Figure 22: Tracked Maturity Levels for Side Slope Stability

Grade Climbing

Only NRMM has not conducted the grade climbing up slope event. Since no test data exists, the maximum maturity level achievable is 4. This has been obtained by most of the vendors in both the up and down slope event showing promising result for the soft soil event.
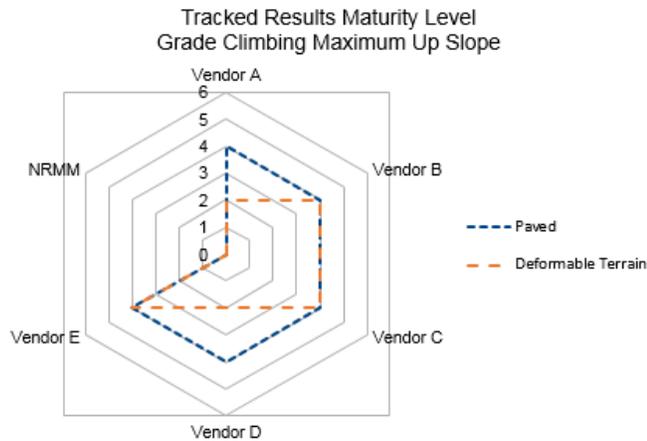
Figure 23: Tracked Maturity Levels for Grade Climbing Up Slope
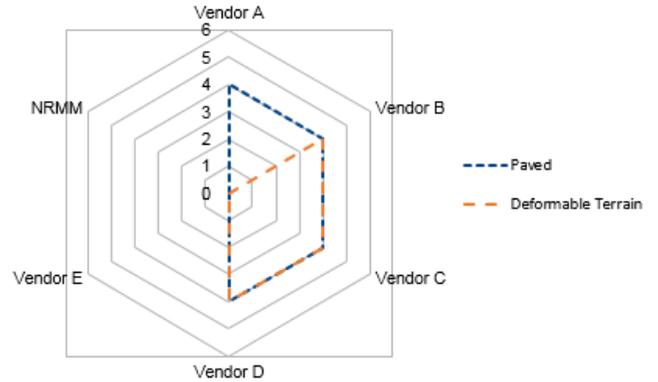
Figure 24: Tracked Maturity Levels for Grade Climbing Down Slope

Maximum Speed on Grades

The maturity level obtained by the vendors is shown in Figure 25. The event on sand has been conducted by less vendors, than the soft soil event, implying that the hard surface event is easier for the vendors to perform.
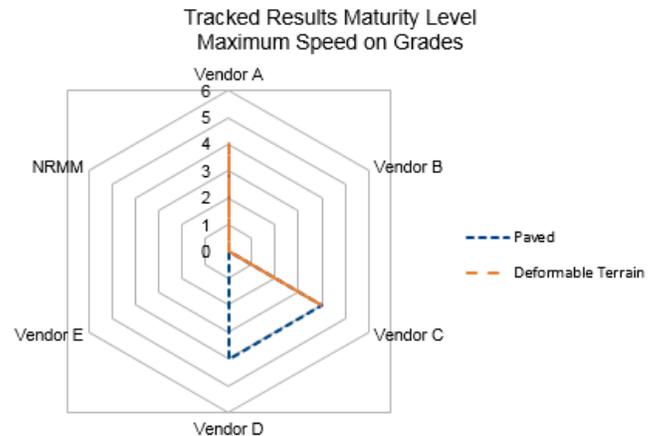
Figure 25: Tracked Maturity Levels for Maximum Speed on Grades

Ride Quality on Random Terrain

The vendors, that have conducted the random terrain event, have presented varying limiting speeds, as reflected in Figure 26, but three of the

vendors presented curves, that was within 50 % of the mean curve, resulting in a Maturity Level of 4.
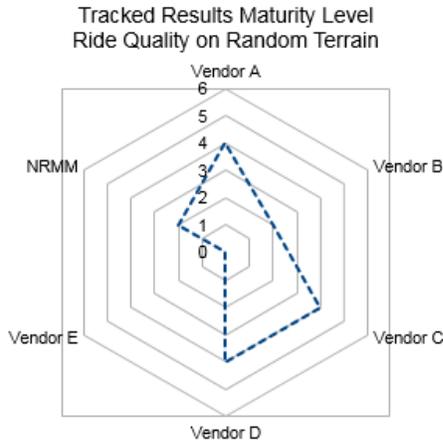
Figure 26: Tracked Maturity Levels for Random Terrain

Half Round Obstacles
Four vendors have presented a half round obstacle curve and all four vendors was within the limit, resulting in a Maturity Level of 4 for all four vendors.
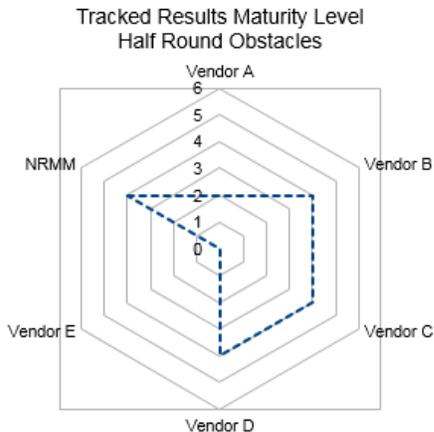
Figure 27: Tracked Maturity Levels for Half Round Obstacles

Step and Gab Obstacle Negotiation
Four vendors have conducted a step and a gab obstacle negotiation and have achieved a Maturity Level of 5 due to the calibration data available.
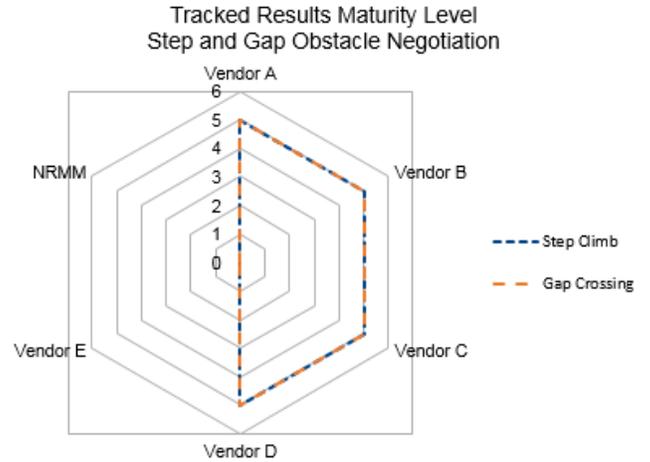
Figure 28: Tracked Maturity Levels for Obstacle Avoidance

Trapezoidal Obstacles
The same four vendors have also performed the trapezoidal obstacles and been able to achieve a Maturity Level of 4, since the results are comparable.
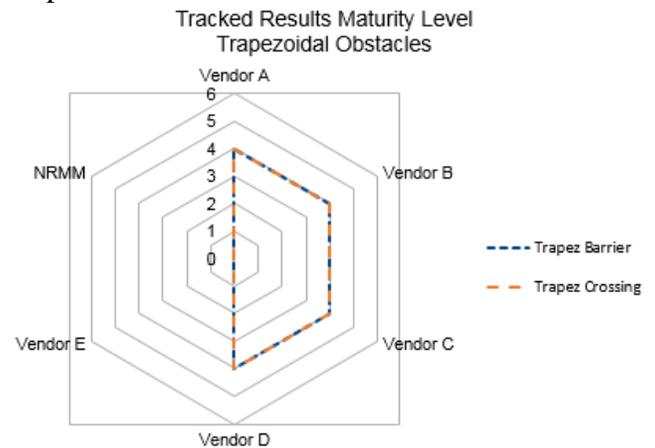
Figure 29: Tracked Maturity Levels for Trapezoidal Obstacles

Off-Road Trafficability
Only vendor NRMM was able to present a soil strength limit. The two other vendors have presented a result of no limit, hence the maximum Maturity Level possible is 2 achieved by the three vendors.

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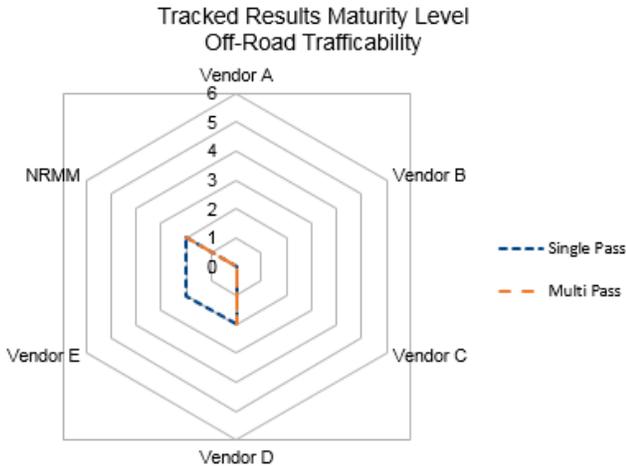
Figure 30: Tracked Maturity Levels for Off-Road Trafficability

Drawbar Pull

Test data of the drawbar pull event is available resulting in a maximum achievable Maturity Level of 5 based on the calibration data. This has been obtained by all the vendors presenting a result.
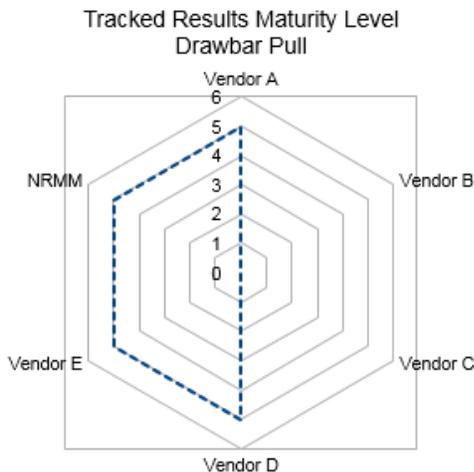
Figure 31: Tracked Maturity Levels for Drawbar Pull

Motion Resistance

The four vendors, that have conducted the motions resistance events, have presented varying results as can be obtained from Figure 32.

Figure 32: Tracked Maturity Levels for Motion Resistance

Closed Loop Traverse/Fuel Economy

Only two vendors have presented a fuel economy results, but these two vendors have obtained similar results, resulting in a Maturity Level of 4.
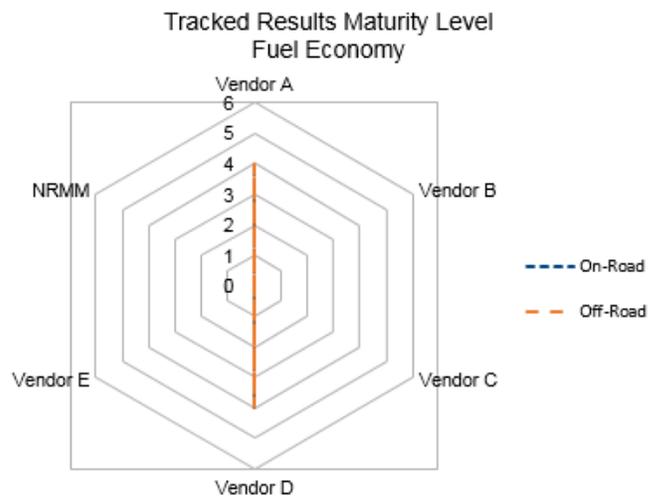
Figure 33: Tracked Maturity Levels for Fuel Economy

APPENDIX C: Wheeled Vehicle: Maturity Achieved for All Vendors on Each Individual Events

Vendor A

Where vendor A performed most of the hard surface with the tracked vehicle, the number of

wheeled events conducted by vendor A is much less. The vendor has obtained a high level of maturity in the events, that have been conducted and most of the results are comparable with test data. For the wheeled vehicle vendor A has conducted all the soft soil event and achieved a Maturity Level of minimum 4 for all events.

vehicle results. The vendor achieves a high maturity level in the hard surface events, but the vendor has not been able to conduct any of the soft soil events.
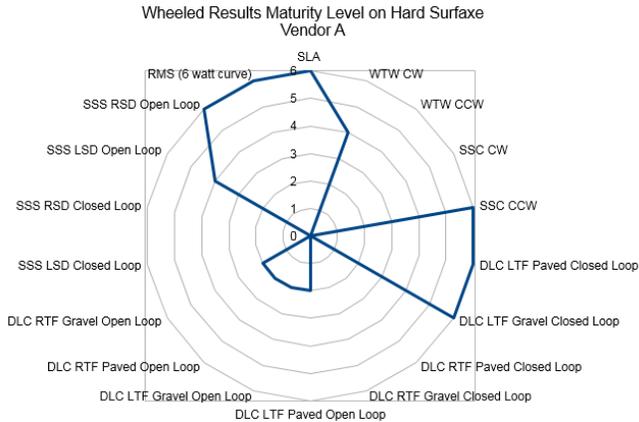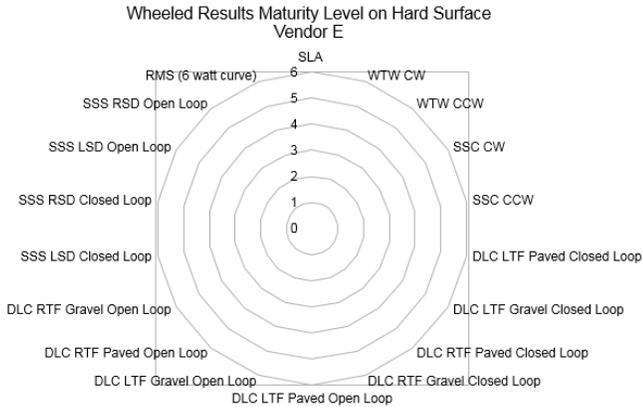

Figure 34: Wheeled Maturity Levels for Vendor A on hard surface
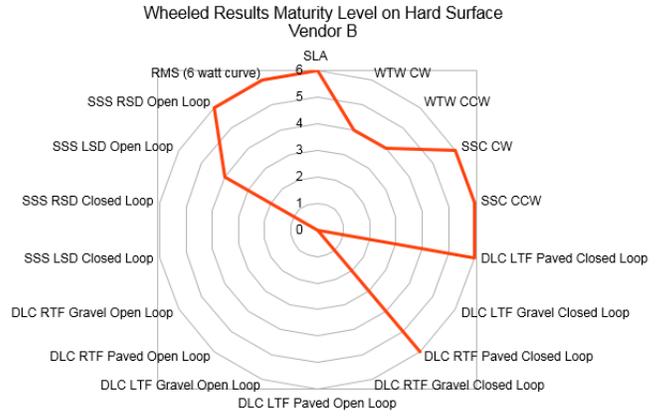
Figure 36: Wheeled Maturity Levels for Vendor B on hard surface
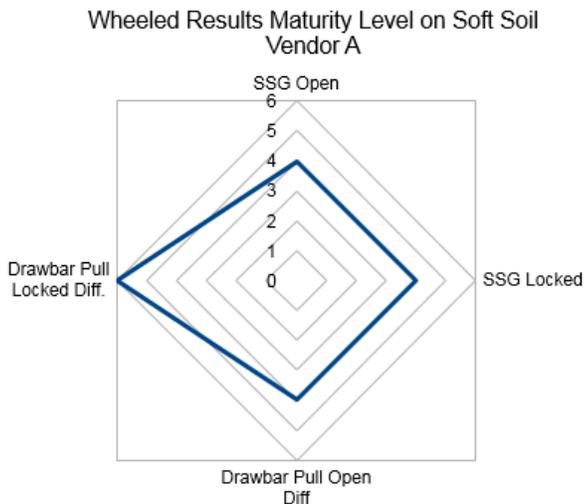
Figure 35: Wheeled Maturity Levels for Vendor A on soft surface
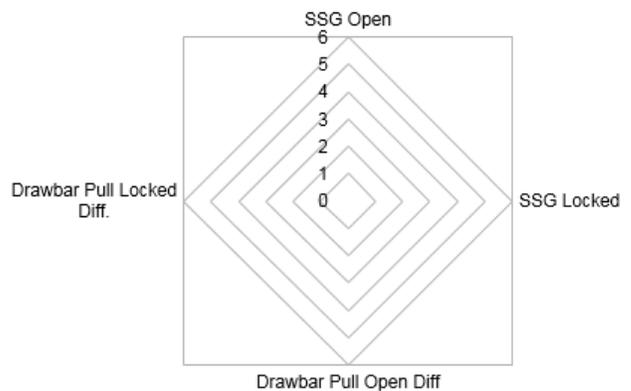
Figure 37: Wheeled Maturity Levels for Vendor B on soft soil

Vendor B
The results delivered by vendor B for the wheeled vehicle is not as comprehensive as the tracked

Vendor C
Vendor C is the vendor, that has conducted most of the wheeled events and is also achieving a high maturity level for most of the events. In general, the results corresponds well to the test data. Figure 38 shows the maturity levels achieved in the hard surface events and Figure 39 the soft soil events.
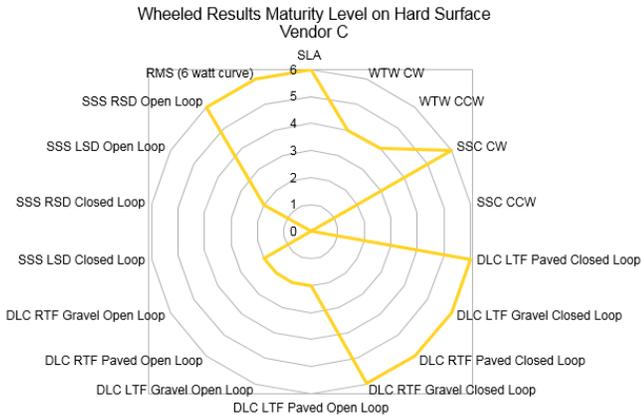
Figure 38: Wheeled Maturity Levels for Vendor C on hard surface
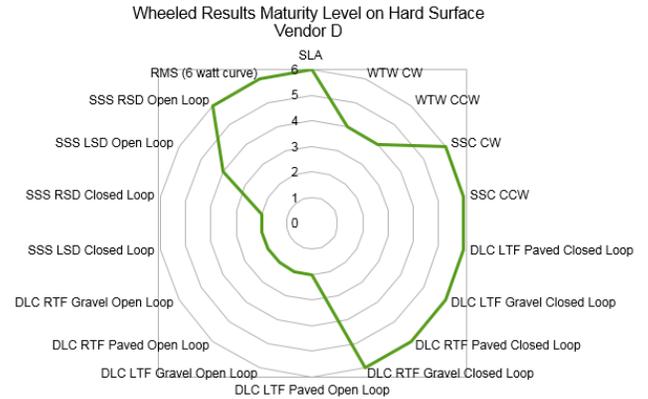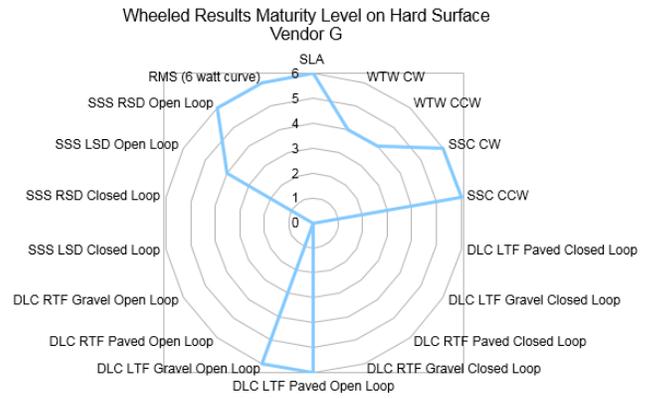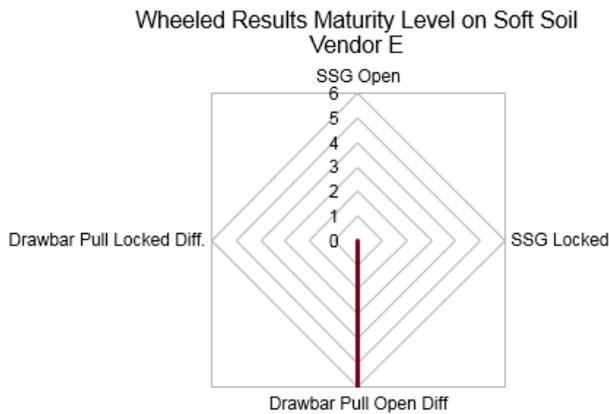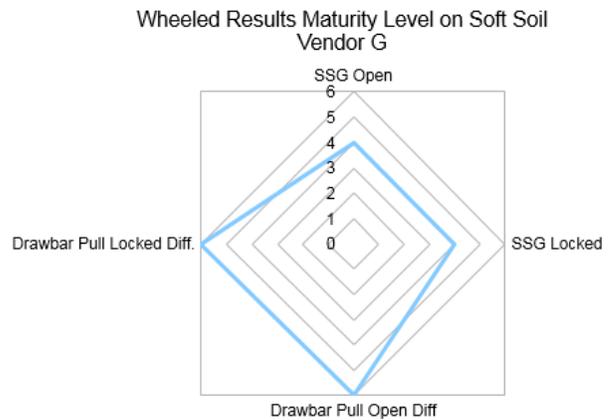

Figure 40: Wheeled Maturity Levels for Vendor D on hard surface
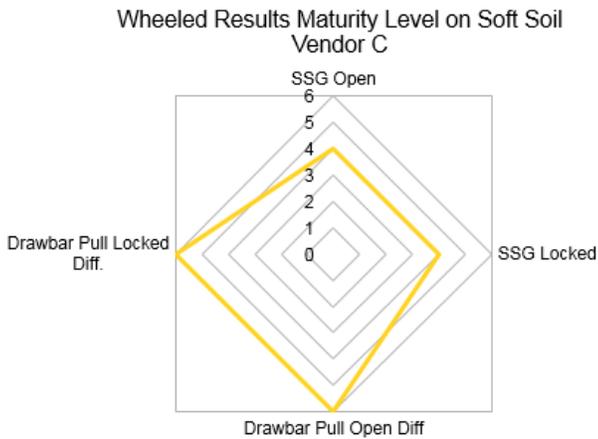
Figure 39: Wheeled Maturity Levels for Vendor C on soft soil
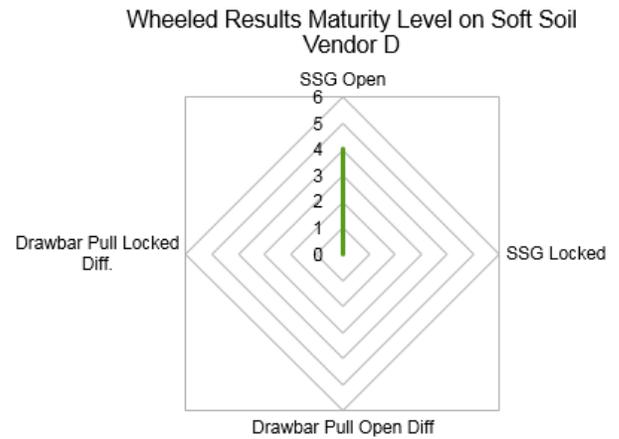
Figure 41: Wheeled Maturity Levels for Vendor D on soft soil

Vendor D

From Figure 40 it is evident, that vendor D is performing well in the hard surface events. Figure 41 also show, that vendor D only has conducted a single soft soil event, revealing, that vendor D is strongest on hard surface.

Vendor E

Vendor E has not conducted any hard surface events, Figure 42, and only one soft soil event, Figure 43, hindering an assessment of the vendor.

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Figure 42: Wheeled Maturity Levels for Vendor E on hard surface

Figure 44: Wheeled Maturity Levels for Vendor G on hard surface

Figure 43: Wheeled Maturity Levels for Vendor E on soft soil

Figure 45: Wheeled Maturity Levels for Vendor G on soft soil

Vendor G

Vendor G is performing well on both hard surface, Figure 44 and soft soil, Figure 45. The results are comparable to the test data.

NRMM
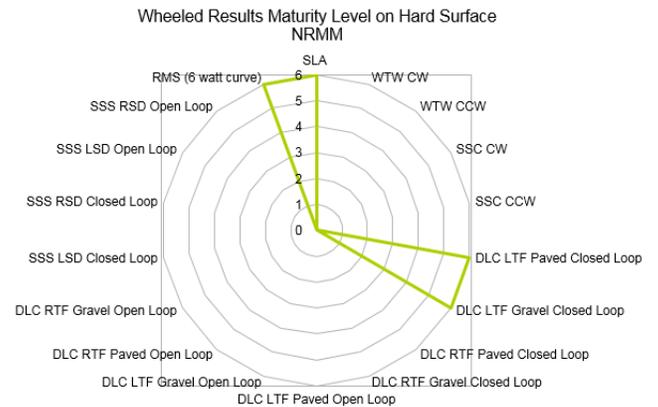
Figure 46: Wheeled Maturity Levels for NRMM on hard surface
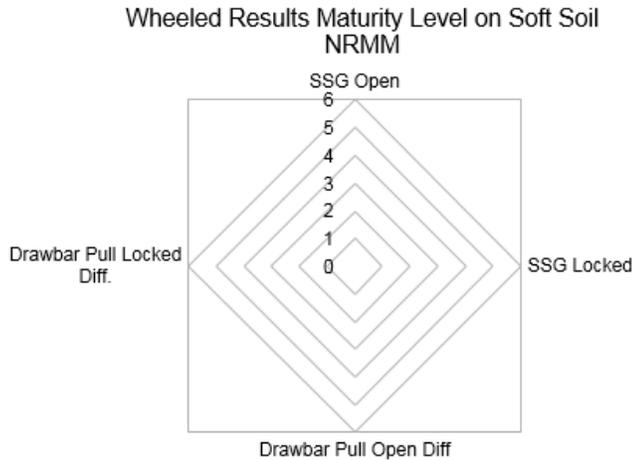
Figure 47: Wheeled Maturity Levels for NRMM on soft soil
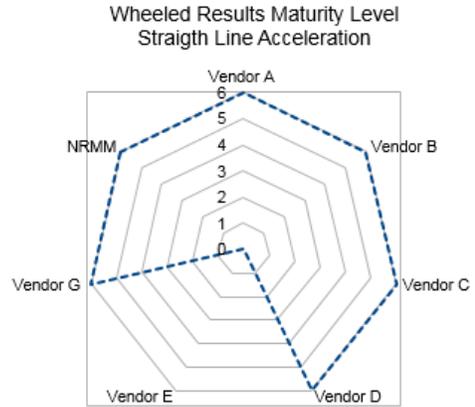
Figure 48: Wheeled Maturity Levels for Straight Line Acceleration

APPENDIX D: Wheeled Vehicle: Maturity Achieved for All Vendors Presented by Each Individual Event

Straight Line Acceleration, SLA

Only vendor E has not achieved a result in the straight line acceleration test. The remaining vendors have all achieved blind correlation to the test data, indicating that all vendors are capable of simulating acceptable results.

Wall to Wall, WTW

From Figure 49 it is evident, that the vendors, that have performed the event, all have achieved a maturity level of 6.
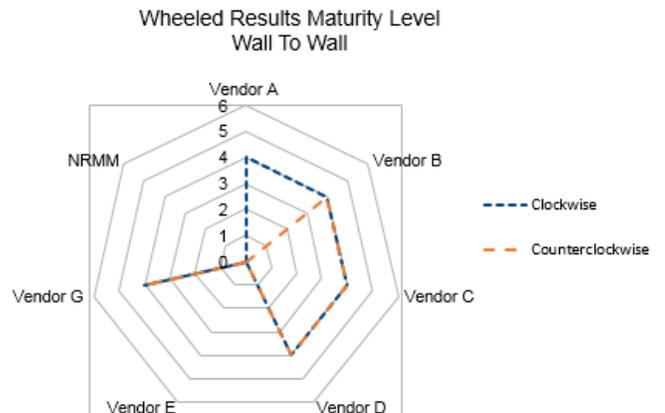
Figure 49: Wheeled Maturity Levels for Wall to Wall

Steady State Cornering, SSC

All vendors that has performed the steady state cornering test achieved reasonable correlation with test data, hence, receiving Maturity Level 6.

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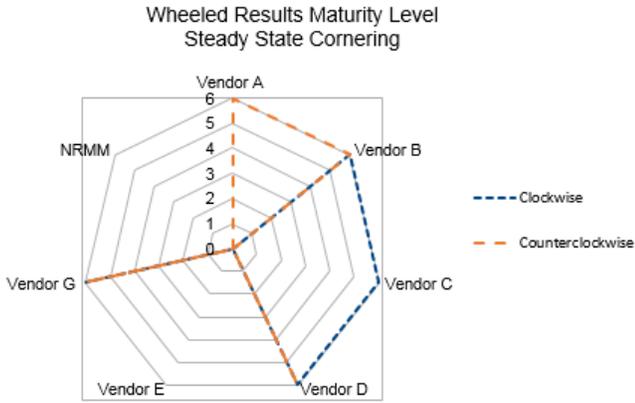
Figure 50: Wheeled Maturity Levels for Steady State Cornering
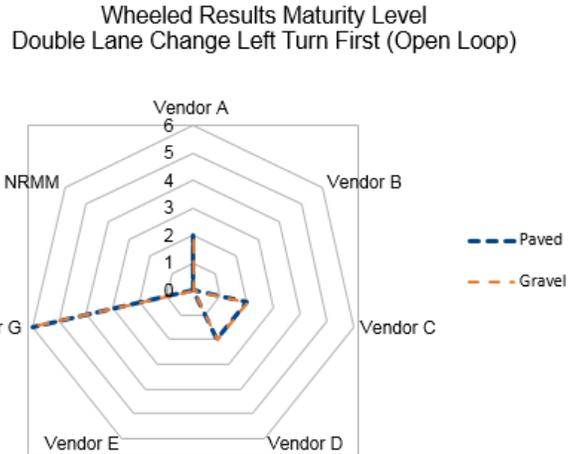

Figure 51: Wheeled Maturity Levels for Double Lane Change Left Turn First (Open Loop)

Double Lane Change, DLC

Figure 51 and Figure 53 depicting the maturity levels obtained for the double lance changes using the given steering input show that the vendors in general have performed poorly, when using the steering input due to DLC boundary crossing. However, Figure 52 and Figure 54 show that the vendors are more capable of creating results that resembles that of the test data, when the vendors use a steering controller. The general shape and absolute values of yaw rate, roll rate and lateral acceleration plots from test data have been compared to the vendor results.
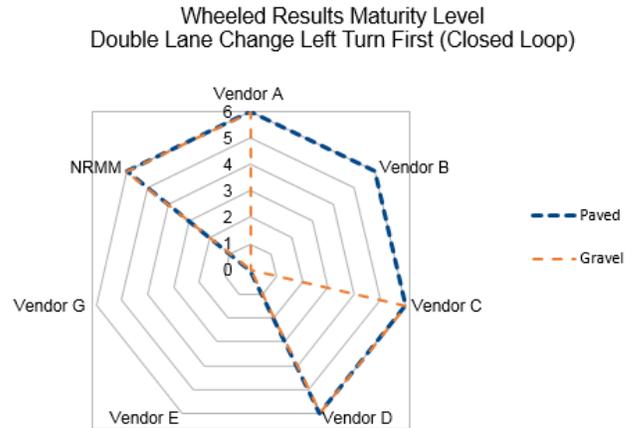
Figure 52: Wheeled Maturity Levels for Double Lane Change Left Turn First (Closed Loop)
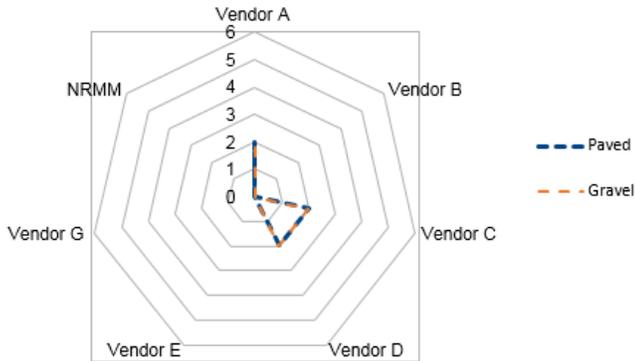
Figure 53: Wheeled Maturity Levels for Double Lane Change Right Turn First (Open Loop)
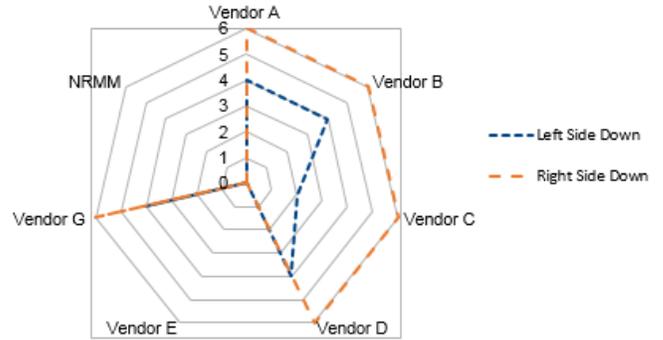

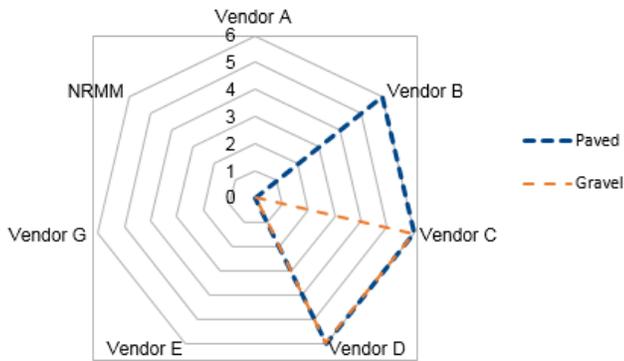Figure 55: Wheeled Maturity Levels for Side Slope Stability (Open Loop)

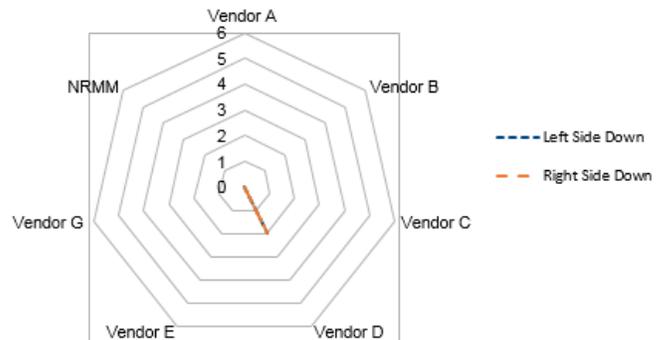Figure 54: Wheeled Maturity Levels for Double Lane Change Right Turn First (Closed Loop)

Figure 56: Wheeled Maturity Levels for Side Slope Stability (Closed Loop)

Side Slope Stability, SSS

The vendors have been more successful in using the given steering input in the side slope stability event, see Figure 55. Only vendor D have conducted the closed loop event using a steering controller Figure 55.

Sand Slope Gradeability, SSG

From Figure 57 it can be observed, that most vendors have been able to perform the sand slope gradeability event, but that the results were not comparable to the test data.
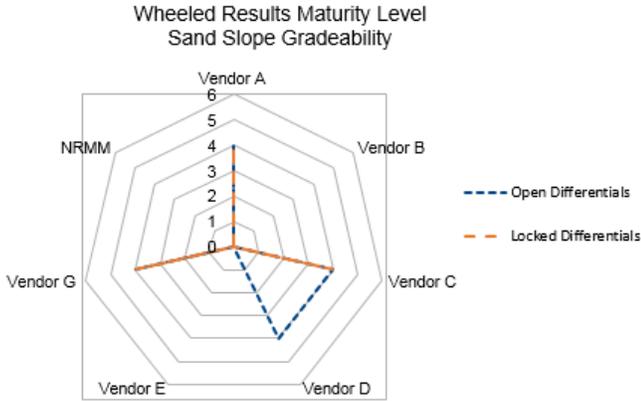
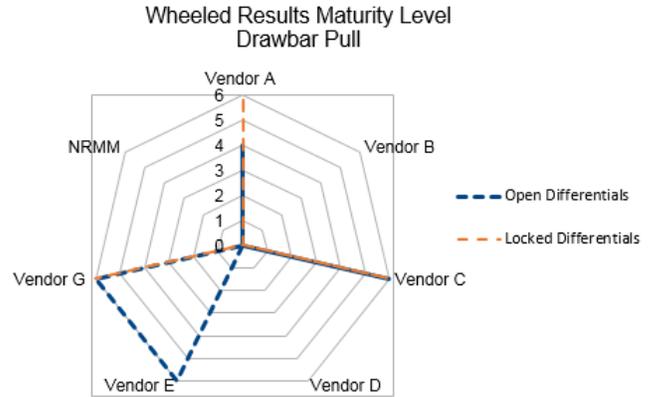Figure 57: Wheeled Maturity Levels for Sand Slope Gradeability

Figure 59: Wheeled Maturity Levels for Drawbar Pull

Ride Quality

All vendors that have performed the ride quality tests achieved reasonable correlation with test data, hence, receiving Maturity Level 6
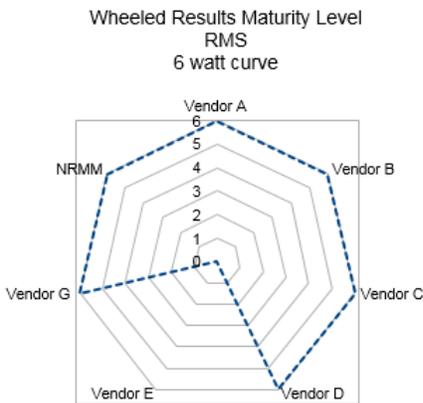

Figure 58: Wheeled Maturity Levels for RMS

Drawbar Pull

Only two vendors have conducted the drawbar pull event and has achieved great similarity with the tractive effort achieved by test.

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