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ROAD WHEEL READINESS EXPERIMENT

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ABSTRACT

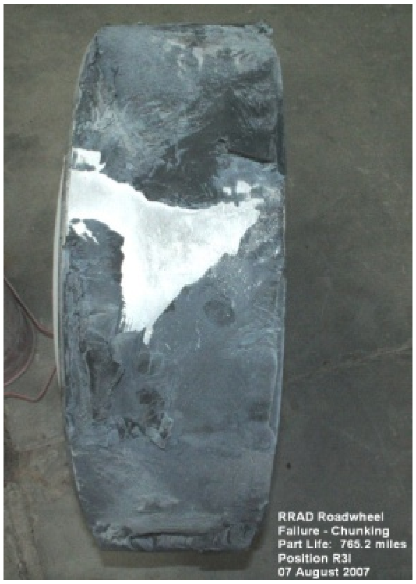
Tracks and wheels are some of the top constituents of ground vehicle mobility and sustainment cost. Even small improvements in performance parameters and support strategies can go a long way. Analyzing equipment sustainment models can help identify these opportunities in conjunction with maintaining a situational awareness of R&D activities. Specifically, understanding component failure analysis, characterizing production road wheel material properties, conducting component testing, and benchmarking diverse manufacturing capabilities provides a roadmap to establishing and identifying "Best in Class" road wheel materials. Establishing and executing an R&D compounding plan to deliver 5X-10X durability improvement is hypothesized. Leveraging the Defense Mobility Enterprise (DME) and its authority under the 10 USC 2370 Section 845 Ground Vehicle Systems Other Transaction Agreement will allow the government to rapidly determine the technical feasibility of realizing such colossal performance expectations.

INTRODUCTION: CAUSE & EFFECT OF ROAD WHEEL FAILURES

Reliable track systems provide a sustainable strategic advantage in the theater, by providing mobility in challenging terrains where wheeled vehicles are limited. The ability to outflank the enemy is a proven battle strategy that Rommel, Patton and others have successfully deployed to defeat opponents in the past [10]. To sustain a heavy main battle tank, such as the Abrams at high speed, over an extended duration requires a track system and suspension that can deliver reliable mobility.

Lessons learned in the Middle East have revealed significant durability issues with track systems, requiring replacement after only 35% of their expected durability. Figure 1 a-c depicts the magnitude of such premature disposal. TARDEC's Track & Suspension Team was tasked to understand the cause & effect of premature track failures in the Middle East and establish a road map to improve durability and reliability of the Bradley and Abrams track systems. Current and past data clearly illustrate that the elastomeric track system components are the "durability limiter".

(a) Discarded track at ~ 740 miles



(b) Discarded road wheel

(c) Track system graveyard

Figure 1: Examples of failures and disposal in Middle East

In the case of the Abrams T-158LL track system, the elastomeric components are the following: 1) Track Bushings (TBs), Ground Pads (GPs), Road Wheel Backer Pads (RWBPs), and Road Wheels (RWs). TARDEC's Track & Suspension Team established the "Elastomer Improvement Program" (EIP) in 2007 and the team designed and built a "state-of-the-art" R&D laboratory for elastomer fatigue, failure analysis, sample component extraction, and characterization. This new capability established a 3-phase process (Figure 2) to baseline the "Current State" and provide a road map "Future State" for developing and testing improved elastomer compounds and designs.

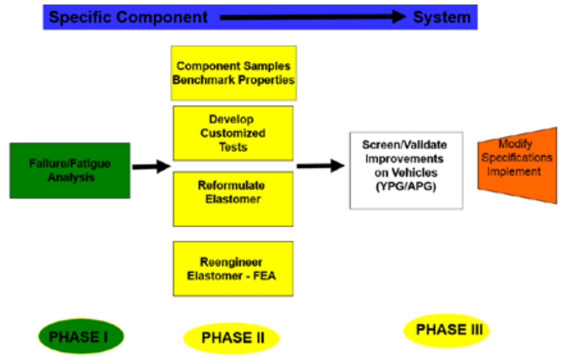


Figure 2: EIP Process - Bushing Analysis & Development

Track bushings were determined to be the first area of focus. Therefore, extensive fatigue analysis of track bushings was undertaken. It was determined that the primary failure mechanism was crack initiation, followed by crack propagation at the outbound bushing positions. These failure mechanisms cause bushings to fatigue and fracture, as evidenced by Figures 3a, 3b, and 5a. This causes metal on metal fatigue and subsequent failure of the track body, or pin breakage through excessive force and bending, as shown in Figure 3b.

a) Bushing/Track Block Failure – Bradley T-157

b) Track Block Rupture

Figure 3: Track Component Failures in Middle East

Improvements in the bushing properties and bushing geometry yielded the potential to move the crack propagation and crack growth "knee in the curve" outwards. First, this was accomplished with the bushing compounds, by optimizing key property profiles leveraging high performance fillers, stabilization packages, and optimized cure chemistry. Second, numerous bushing geometries were modeled, tested, and "Best In Class" compounds and bushing geometries were down-selected. T-158LL bushing prototypes were subsequently manufactured and tested on the MTS 832 bushing tester shown in Figure 4. Validation testing on an Abrams test vehicle confirmed a > 25% increase in bushing life.

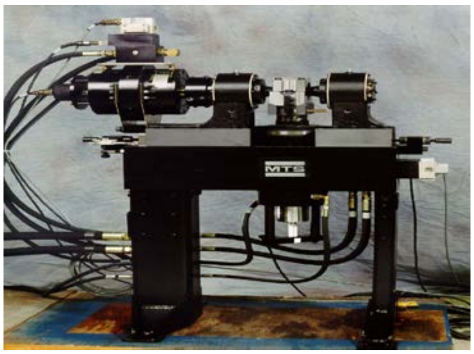
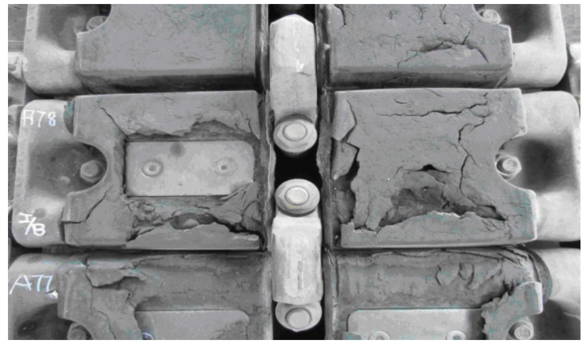


Figure 4: MTS 832 Bushing Durability Tester

The next weakest link was identified as the road wheel backer pad which has three primary failure mechanisms: 1) crack fatigue over the binocular tubes and edges, 2) hysteresis and excessive heat build-up from cyclic road wheel loading, and 3) adhesion to the track body and insert. The road wheel backer pad test specimens are shown in Figure 5b. Significant R&D activities were directed at addressing these failure mechanisms through compound improvements, resulting in successful engineering tests. The tests confirmed a 40% improvement in durability. Although the ground pads wear, they are not typically mobility limiting, as the vehicle can easily operate on the metal grousers. Despite this, development programs on the ground pads have been very successful, delivering a > 75% improvement in durability.

(a) Track Bushing (TB) Fatigue



(b) Road Wheel Backer Pad (RWBP) Fatigue

Figure 5: Track Component Failures: Track Bushings (TBs) and Road Wheel Backer Pads (RWBPs)

Individual component improvements are certainly one path for improvement - however, they may not provide an additive, overall improvement. Understanding the key durability and performance drivers for the entire track system (i.e. suspension, road wheels, RWBPs, TBs and GPs) can often yield new insight into improving durability and performance of the system. All track systems are dependent on the road wheels which link the vehicle's suspension with the track that interfaces with the road surface. The suspension system on the Abrams vehicle and its interaction with the road wheels and track has been carefully examined. Load and thermal measurements on the track system provide an energy management road map assisting in understanding the key drivers for fatigue and subsequent durability and performance. It was determined that the primary track durability predictors, for a given vehicle weight, can be determined by: 1) the average ambient temperature under which the track operates, 2) the average speed the track system experiences, and 3) the range the track travels at a given speed. This relationship and these key variables are illustrated in Figure 6.

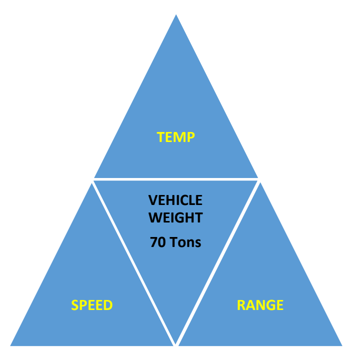


Figure 6: Primary Factors Influencing Track Durability

For example, a 70 ton track system during a test sequence at 80°F accumulates 15 miles on an oval paved test track at 40 mph, then heads off-road to traverse two other terrain profiles of 20 miles each at an average speed of 20 mph. Under this scenario, the vehicle will have a track durability rating of 10. As summarized in Table 1, increasing just the ambient average operating temperature of the track by 20°F, the track durability over the life of the test, will decrease to 7.5. At this temperature of ~ 100°F , doubling (2X) the range of each test segment on the three courses (while keeping the speeds constant at 40 mph and 20 mph respectively) will decrease the track life by an additional 20-25%, lowering the track life to a rating of 5, essentially a 50% decrease in durability. Making one more adjustment to these conditions, increasing the speed to 45 mph on the paved section, and 25 mph on the other two courses, the predicted life of the track would be only a 3 (i.e. a 75% loss in durability). Therefore, Figure 6 at a given tracked vehicle weight (50-75 tons) can assist in predicting track system durability.

Table 1: Track System Durability Scenarios (70 ton Abrams)

Scenario	Track Temp (°F)	Oval Track		Remaining two courses		Durability Rating
		Speed (mph)	Range (mi)	Speed (mph)	Range (mi)	
A	80	40	15	20	20	10
B	100	40	15	20	20	7.5
C	100	40	30	20	40	5
D	100	45	30	25	40	3

Thermal mapping of track components is a recommended practice developed by the EIP team which offers further insight into the observations tabulated in Table 1, as well as insight into the energy management attributes of track components. Extensive testing has validated that the road wheel generates the highest thermal load for the track system. Essentially, vehicle energy is transferred through the suspension, road wheels, and down onto the track. Again, this transfer is influenced by the key factors shown in the triangle diagram of Figure 6. Therefore, the RWBPs, TBs and GPs begin to fatigue quickly, if the road wheel design does not efficiently manage energy into the track system. Consequently, all the respective track components and their respective failure mechanisms are accelerated when the vehicle energy is not efficiently managed via the RWs. In the Middle East, all track systems experience ambient operating temperatures of 120-140°F resulting in unprecedented track failures estimated at ~ 35% of durability ratings. This creates significant impacts to Warfighter effectiveness, reliability, life cycle costs, logistics costs and maintenance costs. The main contributor to premature failures of the GPs, TBs and RWBPs in this environment was the inability of the road wheels to reach a stable equilibrium running temperature. Essentially, the condition acts as a thermal run-away pumping heat into the RWBPs, TBs and GPs. Given rubber is a very poor thermal conductor, the RWBPs received massive heat from the RWs and retain and distribute this heat slowly to the steel track body, accelerating fatigue exponentially. The track bushing rubber compound is the most susceptible to heat among all the rubber compounds and, therefore, degrades at a faster rate. The RWs essentially act as furnaces, pumping heat down to the track system. Unable to dissipate heat at high ambient temperatures, the track systems fails.

The ability to benchmark and fine tune the “Key Property Profile” for the RW compound is paramount in improving its performance. The EIP program, in conjunction with TARDEC’s Physical Simulation & Test Team developed an accelerated road wheel test in 2008. One of the EIP Lab’s assets is shown in Figure 7.

Figure 7: TARDEC Road Wheel Tester

Leveraging the road wheel component test, by varying the load and speed, provides a meaningful methodology to study the energy management capabilities of road wheel components. This accelerated load and speed test fails the road wheel via a “hysteresis blow-out”. This failure is caused by micro and macro imperfections in the rubber compound – in other words: poorly dispersed compound, poor compounding expertise for a highly loaded rubber application at speed, improper cure chemistry, poor choice of base elastomer, inhomogeneity of uncured runner pre-form, insufficient cure, and high run out in the rim and or rubber. The distinction between a poor energy management RW on the accelerated Road Wheel Tester versus that of a high, stable energy management RW is illustrated in Figures 8a and 8b versus Figure 8c, respectively.

(a) Production RW – 48 min at 35 mph; 5500 lbf

(b) Production RW – 46 min at 35 mph; 5500 lbf

(c) 10X - Developmental RW – 1090 min at 40 mph; 7000 lbf

Figure 8: Production RW versus Development RW

In an ideal world, component tests should correlate to field testing. The MTS 832 bushing tester has proven a correlation to bushing life for the Abrams T-158LL track system. Since the accelerated RW Tester also needed confirmation: 1) an actual road wheel test was developed and 2) an engineering test was conducted on an Abrams 74 ton test vehicle utilizing the paved track at Yuma Proving Grounds (YPG). This test directly compared production RWs versus the developmental RWs under identical conditions at 40 mph on the same test vehicle within 48 hours.

Figure 9 captures some failures on a production road wheel after only 20 miles at a speed of 40 mph, as witnessed during 80°F ambient temperature field tests at YPG. The first failure occurred at 19 miles and by 38 miles five other RWs had failed.

Figure 9: Photographs of production road wheel failure: hysteresis blow-out followed by chunking after only 20 miles (80°F ambient track temperature at 40mph on YPG paved track)

In contrast, Figure 10 showcases the results of the EIP R&D effort, which collaborated with an industrial partner to optimize the RW life on the RW Tester at TARDEC to achieve 1090 minutes at 40 mph and at 7000 lbf. Subsequently, a commercialization phase produced production quantities of the optimized RWs for the engineering trial. Under identical engineering test conditions, the 10X results from the tester were validated and no failures were found even after 200 test miles at YPG. Figure 10 was taken after this production grade version of the optimized RWs were removed from the test vehicle and looked brand new. The engineering test was stopped at 200 miles.

Figure 10: Photographs of developmental road wheel with NO FAILURES after 200 miles (80°F ambient track temperature at 40mph on YPG paved track)

SUSTAINMENT MODELING CONSTRUCT

After being introduced to the aforementioned road wheel efforts, TARDEC's Industrial Base Engineering Team (IBET) offered TARDEC's Track & Suspension Team a broader sustainment engineering view of the road wheel situation. Sustainment engineering includes "activities specifically related to product support which are primarily a result of earlier design influence outcomes" [3, p. 11, 23, 56, 57][15, p. 9.15]. Emphasizing the human element of sustainment engineering, the term logistics engineering aims to "bridge the gap" between the multiple groups and processes influencing the sustainment of existing equipment" [11, p. 11][3, p. 45]. The IBET offered that by generating more of a DoD-wide awareness, a growing road wheel community of interest would agree that critical component supportability strategies be diversely scrutinized, as opposed to limiting the performance observations and durability curiosities to only Warren, Michigan scientists and engineers [15, p. 9.15][3, p. 34]. Especially with initiatives that affect system endurance, and therefore readiness, a diverse road wheel community of interest could help correlate any "lack of material readiness due to poor system reliability, availability, and maintainability (RAM)" [3, p. 26].

Since RAM is supposed to be considered a design element and NOT a test element, system supportability characteristics, such as supplier existence and field maintenance activity, RAM should be included in these road wheel trade space discussions [3, p. 5, 11, 27][16, p. 10]. As an integral part of the systems engineering process, the IBET and the Track & Suspension Team both agree that design requirements in the form of supportability characteristics drive a system's operational effectiveness, operational suitability, and life-cycle cost projections [4, p. 4]. In all, advancing the durability of the second most influential track system cost driver (i.e. the road wheel), which also just happens to be a component critical to vehicle mobility, is "the key to a Strategic Win" in that it literally gives our forces additional "endurance to sustain operations" [14, p. iii].

The IBET knew that adding other stakeholders that deal with the implications of road wheel logistics to the road wheel community of interest would be the best place to start. Followed by formally monitoring field performance, as witnessed by the number of Maintenance Work Orders, complementing the data with testimonies from motor pool mechanics, battlefield commanders, proving ground technicians, and Armor School instructors was pursued [3, p. 27].

A single point of failure may impact many different mission profiles, as shown in Figure 11.

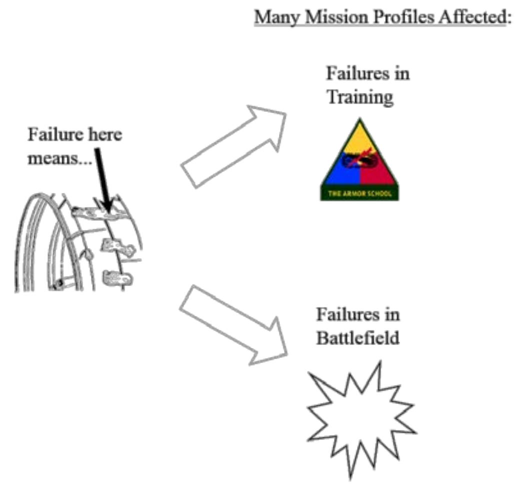


Figure 11: Single Point of Failure

For example, road wheel failures which translate to track failures at the Armor School affect the preparedness of our future forces, as Warfighters strive to log in as many hours with operationally available equipment as possible, prior to deployment. Durability limitations, witnessed during training, result in Warfighters spending precious time developing tactical workarounds to optimize the performance of the systems they have to live with. Road wheel and track system failures in the battlefield, on the other hand, can have an even more grave impact in that they can directly influence Warfighter survivability. When an Abrams track system is inoperable, for example, an M-88 crew is deployed to the rescue, putting even more Warfighters and assets in harm's way. Thus, RAM improvements to road wheels yield benefits that extend far beyond mere component cost savings. The aforementioned relationships prompted the creation of a simple sustainment model to depict the business opportunity aspects of the road wheel in relation to the technology transition hurdles that R&D initiatives face. Understanding the bigger picture through the aid of logistics and sustainment M&S addresses the criticism that "little attention [is given] to operating and support costs and readiness at the beginning of development when there is the greatest chance of affecting those costs positively" [13, p. 2] [3, p. 25, 26]. The sustainment model began with assembling together a plethora of road wheel business case elements with hopes to first gain a better understanding of the economic opportunities and threats to road wheel sustainment. Many of these business case elements are commonly referred to as "sustainment data" which offers visibility into things like: equipment demands, prices, maintenance philosophies, and supply chains.

The sustainment model's data mining strategy was to compare Department of Defense (DoD) road wheel sustainment data:

1) against other equipment within a platform and

2) across other tracked vehicle platforms with surrogate road wheel designs, in order to observe how past life cycle resource allocation trends compare with those of current R&D efforts.

The DoD databases queried included the Integrated Logistics Analysis Program (ILAP), Logistics Modernization Program (LMP), Federal Logistics Information System (FLIS), Logistics Information Warehouse (LIW), and Haystack Gold™. Specifically, the sustainment model aimed to depict the DoD tracked vehicle road wheel market and introduce how the industrial base (IB) could be involved with future support strategy concepts. This is in line with the supportability analyses activities that are part of any robust systems engineering strategy in that product support analysis must also be "an integral part of the systems engineering process" [12, p. ii].

First, the Sustainment Engineering Risk Assessment (SERA) relational database was queried, which is a conglomeration of previously mined sustainment data that can be easily sorted and filtered [7, p. 8]. In this case, a script of each National Stock Number (NSN) that makes up the various systems of a particular DoD tracked vehicle platform (that will remain anonymous) was used to return a list of historical contracting quantities originating from Haystack Gold™. The respective prices paid for each NSN were also included in the returned list. NSNs with multiple contracts over the years, as well as equipment with similar nomenclature were then grouped into equipment domain clusters. For example, all electrical wiring was clustered as a group, as was all engine components. The list of equipment groups was rank-ordered by total contract value (NSN quantity multiplied by its piece price) which spanned over the last few decades. Figure 12 shows a Pareto chart of the top 15 NSN groupings, depicting where most of the money has been allocated on a particular tracked vehicle platform, up through 2012. According to the figure, the top six groups equate to a total contract value of over $1B USD, each, throughout the years. Note that the road wheels for this particular platform, highlighted in yellow, have consumed about $181M USD over this particular contract history. As a high wear item, road wheels exhibit some of the most potential for cost saving through durability improvements. Without any prior awareness of R&D initiatives, the beginnings of this sustainment model already suggest R&D focus areas reflecting a high return on investment.

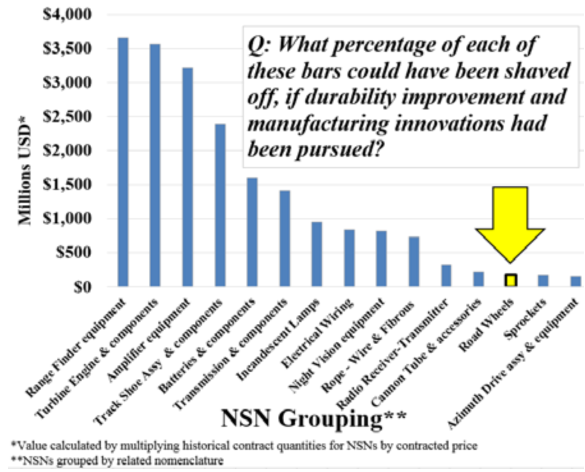


Figure 12: Example of approximate contract values of equipment in a tracked vehicle platform*

Expanding on this further, a broader view of the global buying power is revealed when including other tracked vehicle road wheels into the sustainment model. Looking through a Warfighter's lens at DoD road wheels, in general, brings new light into how field requisitions drive the road wheel business as a whole. Figure 13 depicts the economic trade space of DoD road wheels, by mapping out the price of various road wheel designs (y-axis) against the volume of road wheels consumed through field requisitions since 2011 (x-axis), and the resulting business value (bubble diameter). ILAP was queried to capture the field requisitions, where FEDLOG was referenced for the current road wheel price, per the Army Master Data File (AMDF). A single vehicle-set of road wheels for each of the tracked vehicles currently in the fleet (i.e. per LIW) was also added to each platform of road wheel volumes, in order to account for somewhat of a baseline volume of road wheels that were needed within the period. As an example, if 10,000 M1s and 50 Wolverines were currently in the field, then 321,600 road wheels (i.e. 32 times the total number of vehicles using the M1 design) were added to the ILAP volumes from field requisitions since 2001. The different colors represent some of the most popular DoD road wheel designs currently in the field. Some road wheel designs, like the one shown in red, are leveraged by multiple DoD platforms, exemplifying an efficient re-use strategy and resulting in higher volumes than what would normally be required if every vehicle had its own unique road wheel design. This view of the DoD road wheel business reveals some promising opportunity in that road wheel pricing ranges from around $100 to almost $1000 and overall business value equates to almost $500M (since 2001). This visual analytic also shows some challenging manufacturing variability, as the order quantities can be as little as 16,000 road wheels and as great as 431,000 road wheels, depending on the platform.

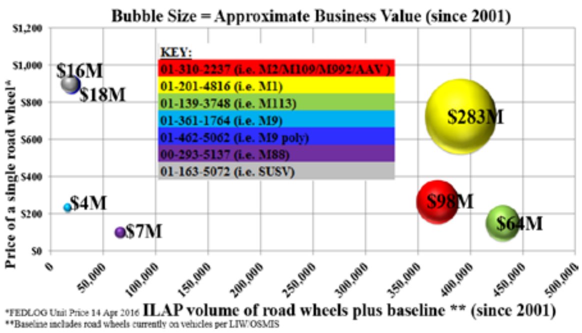


Figure 13: Approximate road wheel market attributes since 2001

Looking at the DoD road wheel business over the entire life cycle would entail gathering field requisitions all the way back to the 1960s for some of the platforms. Even platforms that currently leverage the same road wheel design, like the M2, have varying individual histories that complicate the estimation of field requisitions prior to 2001, as conveyed in Figure 14. Therefore, the business value estimated in Figure 13 is considered to be conservative from a life cycle manufacturer's point of view. Furthermore, field requisitions do not include prototype road wheels and those produced for developmental testing.

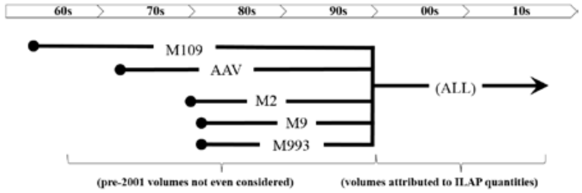


Figure 14: Depiction of multiple users of a particular road wheel over a collective life cycle

Perhaps the more familiar lens through which to view the road wheel business volumes is LMP or i2LOG, while consulting with the appropriate Item Manager. However, raw demand data can be misleading, if wholesale demands are not clearly distinguished from retail demands. Figure 15 illustrates this common misconception. The logistics and delivery chain for a piece of equipment between the manufacturer and the Warfighter can have multiple segments – some harboring buffers of inventory that regulate upstream order frequency.

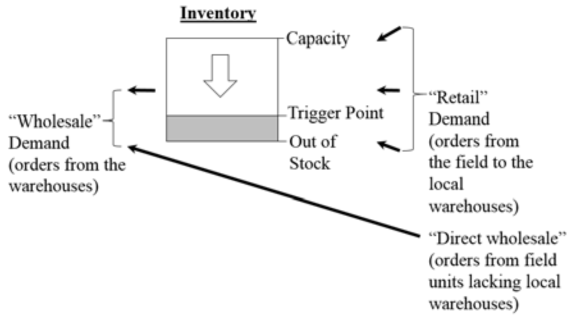


Figure 15: Model complexity: beware of nested demands

The center of Figure 15 illustrates an inventory buffer with three states: capacity, order trigger point, and out of stock. Although orders from the field may be occurring all the time, as shown by the arrows on the right side of the figure, the inventory between the capacity and order trigger points meets this "retail" demand without having to generate a "wholesale" demand back to the manufacturer. This dynamic is common with stock replenishment systems. The demand model becomes even more complex when some Warfighter units are forced to order equipment directly from the manufacturer, as depicted by the long arrow, bypassing the inventory buffer on the bottom of the figure. In these cases, retail demand is synonymous with wholesale demand. In all, haphazardly adding up various demands queried from i2LOG can get an analyst into trouble, especially when considering all of the double counting possibilities that can take place when retail demands are nested within their subsequent replenishments or wholesale demands. This is why a better strategy for capturing true business volumes is just to consider actual production output from the manufacturer. Unfortunately, analysts may not have complete supply chain visibility nor accurate production outputs.

Capturing the range in annual DoD road wheel demand from both an ILAP and i2LOG (under guidance from the appropriate Item Manager) perspective adds a credible facet to the road wheel sustainment model. Figure 16 shows the demand ranges in any given year for some tracked vehicle road wheel designs. Looking at the M2 road wheel design, as witnessed by either ILAP (since 2001) or i2LOG (since 2010) for example, reveals that the annual demand volume (whether retail or wholesale) ranged from 422 road wheels in one year to almost 50,000 in a surge year. As can be seen in the figure, the demand for the M1 road wheel has a year-to-year variation potential that rivals that of the M2, peaking at around 40,000 road wheels in the surge year. Capturing the "bookends of demand" in this manner diffuses the wholesale versus retail demand debate into more of a production volume variation representation against which a manufacturer would need to prepare. Whether meeting a production schedule to restock a warehouse or to fill direct orders from a motor pool mechanic, being able to meet any given demand in any given year is paramount to a robust manufacturing system.

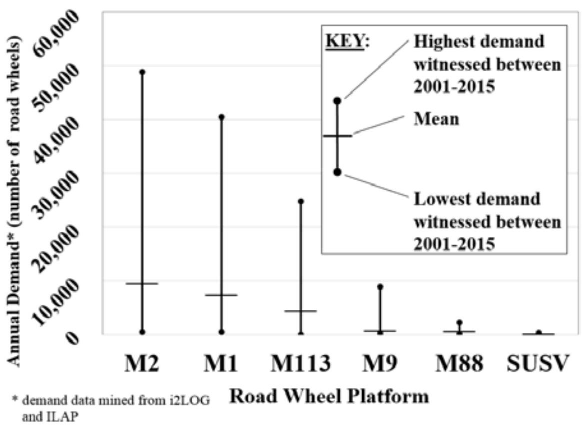


Figure 16: Annual demand fluctuation across platforms

Meeting surge demands, such as those experienced during wartime, while maintaining a minimum profit margin, or minimum sustainment rate (MSR) during slow periods, is a fragile balancing act the DoD IB often struggles with. This suggests that modern, agile sustainment support strategies may be worth looking into. For example, hybrid sourcing solutions that leverage more of the organic IB, could possibly help absorb some of the unfavorable demand variation. Since the organic IB is not solely driven by profits, a hybridization of the organic IB with that of private industry could offer unique advantages, along with flexible manufacturing systems that are designed to technologically accommodate demand variation.

Taking this thought further, the IB facet of the sustainment model should be able to answer the following questions:

Q: Who supplies the road wheels now?
Q: Who used to supply the road wheels in the past?
Q: Who could quote road wheels in the future?

Visualizing and quantifying the collective IB in this manner, where the past is merged with the future on one score, could look something like Figure 17. Displaying on one user interface the number of Commercial and Government Entities (CAGEs) that used to supply, currently supply, and are interested or capable of making a quality road wheel inspirationally calibrates the sustainment analyst in a complete picture of the collective IB. Most importantly, it transforms the analyst into a mindset that considers potential change, or, *the art-of-the-possible*.

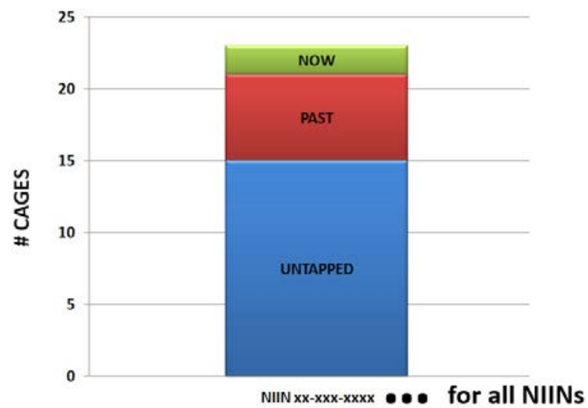


Figure 17: Visually capturing the collective IB

Complementing Figure 17 with a corresponding map depicting the geographical location of each CAGE, or the "where", can help establish the strategic lens with which we ought to view the IB [9, p. 2]. Note that the "who" and "what" facets of IB visibility naturally pave the road to R&D dialogue that includes the "how" things are made, such as:

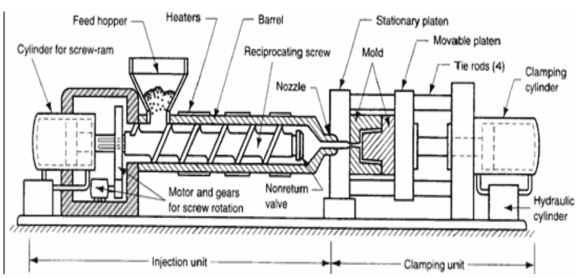
Q: How are road wheels made now?
Q: How were road wheels made in the past?
Q: How could road wheels be made?
Q: How should road wheels be made?

MANUFACTURING: ROAD WHEELS DESIGNED FOR HIGH DYNAMIC LOADS AND SPEED

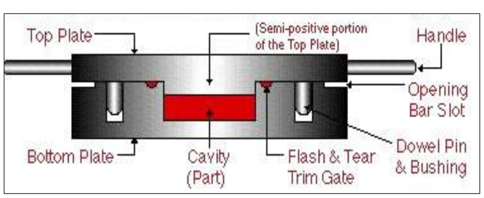
Traditionally, four manufacturing stages are considered to manufacture RWs as follows: 1) prepping the uncured rubber, 2) bonding the primer and top coat to steel (or aluminum) wheel, 3) building the uncured rubber/rim road wheel tire assembly, and 4) molding and curing the component. Figure 18 shows one method for prepping the uncured rubber compound prior to forming around the steel (or aluminum) rim.

Figure 18: Uncured pre-molding preps

There are other manufacturing options, such as direct rubber ribbon into and extruder/injection press, as shown in Figure 19a. This injection press transfers the highly viscous rubber material at high pressure through a cold runner sprue system at a temperature below the cure temperature. This material would then be directly injected into a mold at the preferred cure temperature and would fill the cavity with the steel (or aluminum) wheel in place.

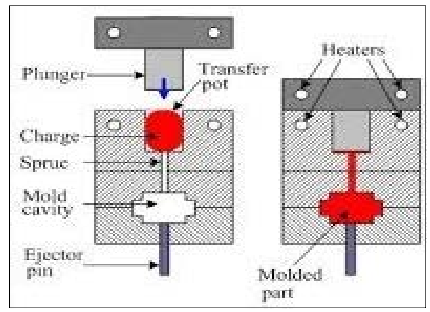


(a) Injection Molding



(b) Compression Molding

(c) Calendering uncured rubber stock for tire building and curing



(d) Transfer Molding

Figure 19: Examples of different molding technologies

An alternate production method would be to produce a cold feed extruded rubber ribbon, slightly larger than the finished road wheel shape, splicing this uncured band around the rim. Then, the spliced section would be joined around the rim and placed in a compression mold to be cured, as shown in Figure 19b.

Another technique would be: 1) calendering thinly extruded, uncured widths, slightly larger than the road wheel rim, as shown in Figure 19c, 2) place the uncured rubber stock under tension until the required thickness was achieved, then 3) insert the uncured rubber rim fixture into a compression mold, like in Figure 19b, and cure. A manufacturing option could also be to utilize a transfer molding, as illustrated in Figure 19d.

The preferred road wheel manufacturing process must be wisely chosen by those skilled in the art of producing thick rubber parts designed for high dynamic loads at high speeds. The R&D activities, thus far, with TARDEC's EIP team have already demonstrated an outstanding Abrams road wheel by combining "Best in Class" rubber compounds, and a superior manufacturing process, to deliver a 10X durability as validated in component and vehicle tests.

HYPOTHESIS

Leveraging the collective experience of the entire ground vehicle systems IB, may reveal how road wheels "should" be produced and supplied moving forward. Without being limited by traditional Federal Acquisition Regulations (FAR) constraints on the speed of R&D, the authority of the 10 USC 2370 Section 845 Other Transaction Agreement (OTA) offers more attractive R&D cycle times with fresh competition through the Defense Mobility Enterprise (DME). The DME fosters the ability for government managers and researchers to reach out to the entire ground vehicle systems IB, via a single consortium, and gather R&D proposals that best satisfy technical feasibility curiosities. Under the DME, much of the traditionally agonizing contracting work, including proposal evaluation and staging, can happen upstream from when funding is even released by Congress. Perhaps most importantly, the most highly rated research proposals from the IB are permitted to reside in a "Basket" until government funds are released. The DME Basket is analogous to online shopping in that desired solutions can be compared and pre-designated, before money is exchanged – thus, speeding up the process if/when funding does become available.

Exercising the Defense Mobility Enterprise (DME) for road wheel readiness initiatives could quickly generate alternative materials and processing solutions, while decoupling from traditional operational test modes that prevent evaluating track system durability with correlated component and vehicle tests. This is possible because the DME taps into the collective power of the ground vehicle systems industry, to include academia, government-owned-contractor-operated (GOCO) facilities, and organic manufacturing national assets, such as arsenals, depots, laboratories, and test campuses.

Looking at our sustainment model through the lens of the entire government-industry technology enterprise cannot be over emphasized. Solutions and technology breakthroughs often have ties to visionaries considering multiple levels of abstraction, where different domains are forced to interact with one another. Oftentimes, these domains of people are not even aware of each other's existence under "business as usual". As depicted in Figure 20, instead of only considering the production IB to sustain a steady flow of spare parts, why not involve the R&D IB in the challenges that the supportability loop faces, so advanced upgrades can be developed for tryout? Similarly, exposing the sustainment logisticians to various R&D initiatives that one day may replace the systems the logisticians are currently managing will help establish a sense of opportunity cost. This, in turn, should lead analysts to a deeper understanding of what capabilities "could cost", as opposed to just "should cost" [6].

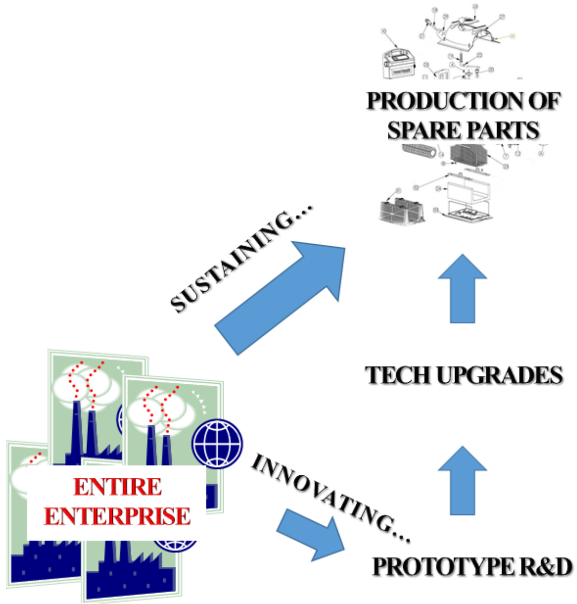


Figure 20: Enterprise level of abstraction

The future road wheel developmental process is expected to include a similar 3-4 stage manufacturing approach as previously mentioned, precluded by compound characterization and wheel design phases, as shown in Figure 21.

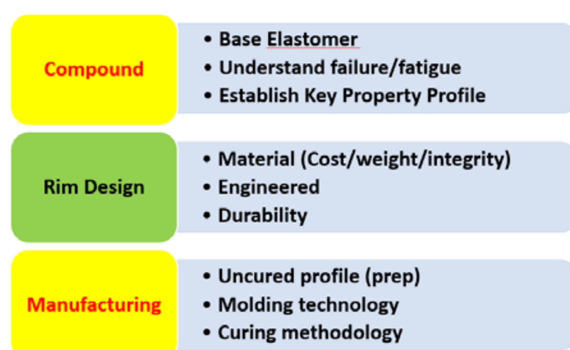


Figure 21: Vision of future developmental process

To show an example of the road wheel trade space, Table 2 lays out the Net Present Value (NPV) for a hypothetical road wheel forecast. In this scenario, the incumbent road wheel is from one of the more popular DoD platforms and, therefore, experiences relatively high demand volumes, not unlike that seen in Figure 16. Some of the demands are assumed to be due to suboptimal durability performance, and each road wheel, regardless of whether it is new or refurbished through a return program, has a price point of $291.91. Including an induced surge volume of 40,000 road wheels during the first out-year, the NPV of this hypothetical road wheel design after five years of declining demands is still over $23M USD.

Table 2: Incumbent road wheel sustainment support strategy: baseline NPV over 5 years

Incumbent Solution: Repair old and make some new with current process
Repaired road wheel costs $291.91, but has durability concerns

Year	Cost	10% Discount Factor	Net Present Value (NPV)
1	$11,676,400	0.909	$10,613,848
2	$7,297,750	0.826	$6,027,942
3	$4,962,470	0.751	$3,726,815
4	$2,919,100	0.683	$1,993,745
5	$1,459,550	0.621	$906,381
Total (Discounted)			$23,268,730

The demand profile for a scenario like this may look like Figure 22.

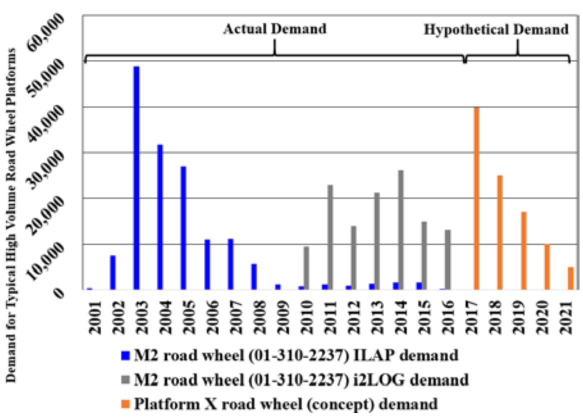


Figure 22: Typical high volume road wheel demand

If a 5X road wheel durability improvement ever comes to fruition, a significant window of investment freedom opens up, allowing hundreds of additional dollars to be allocated towards the piece price of a single road wheel, while still realizing a lifecycle cost savings. Table 3 tabulates this fact.

Table 3: Alternative road wheel sustainment support strategy with 5X durability improvement over 5 years

Alternative Solution: make new every time with new process leveraging entire enterprise
New road wheel estimated at $825, with 5X durability improvement

Year	Cost	10% Discount Factor	Net Present Value (NPV)
1	$6,600,000	0.909	$5,999,400.00
2	$4,125,000	0.826	$3,407,250.00
3	$2,805,000	0.751	$2,106,555.00
4	$1,650,000	0.683	$1,126,950.00
5	$825,000	0.621	$512,325.00
Total (Discounted)			$13,152,480

Figure 23 compares how the increase in road wheel piece price (shown in green) from the incumbent design to an alternative design could be worth the investment if the decrease in lifecycle cost (shown in red) is deemed the more important metric.

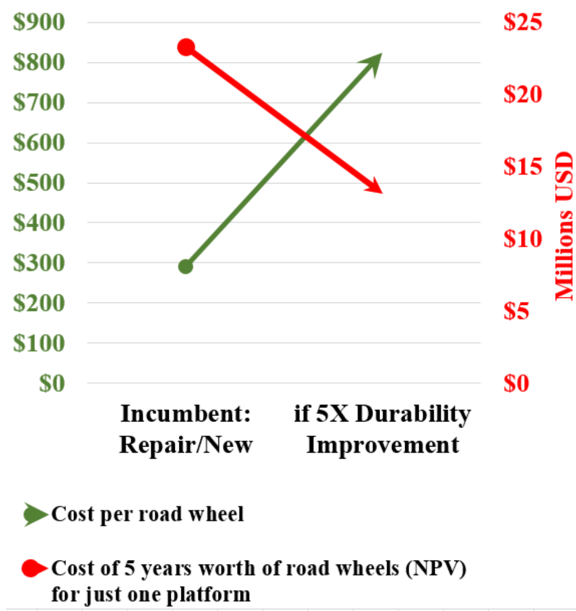


Figure 23: Road wheel piece cost versus 5-year lifecycle cost

EXPERIMENT

A road wheel R&D project was created by TARDEC's Track & Suspension Team and sent out to the DME in February 2016 soliciting white papers from the National Advanced Mobility Consortium (NAMC), a non-profit organization of almost 250 industry, academia, and non-profits vested in current and future advancements of ground vehicle technologies. The solicitation asked the NAMC members to generate white papers on a possible demonstration of advanced road wheel manufacturing leveraging current legacy road wheel rims to meet emerging requirements for improved readiness of tracked ground combat vehicles (over 40 tons).

The desired project milestones are:

1. Benchmarking/Characterization of production road wheel material properties. Establish key property profile for improvements.

2. Establish/Execute R&D compounding plan to deliver 5X-10X durability improvement.

3. Establish "Best in Class" manufacturing process to deliver 5X-10X durability improvements and manufacture prototypes for lab testing.

4. Down select preferred rubber compounds, optimize manufacturing process, validate durability improvements with component test in lab.

5. Conduct vehicle testing under accelerated track test protocols (government furnished) and compare performance versus current production.

6. Scale up manufacturing process to manufacture road wheel components for vehicle testing at Yuma Proving Grounds (YPG).

In March 2016, the NAMC responded with three white paper submissions, each from a different company within the NAMC. Each white paper was evaluated by the government and the companies that submitted the white papers were given feedback in May 2016 as to how well their white paper addressed the challenges of the solicitation.

NEXT STEPS

In June 2016, the three companies that submitted white papers have the opportunity to submit full proposals on how they would execute the aforementioned project milestones. The proposals that do get submitted will be evaluated by the government, and depending on the evaluations and the funding availability, will be selected for either: 1) immediate negotiation and award, 2) placement in the Basket, or 3) neither (if the proposal is not suitable for award due to low evaluation ratings and/or lack of importance to the project objective(s)/requirements). If any proposal is selected for placement in the Basket, any DoD organization or combination of organizations can pull a proposal from the Basket (within 3 years) and negotiate an award on any or all of the incremental milestones. It is anticipated that all services would be interested in collaboratively funding this research, as the advancement of tracked vehicle road wheels is important to all.

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