
Considerations in Tractor Chassis Design

Dennis A. Bowman

John Deere Product Engineering Center, Waterloo, Iowa

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Abstract. *Tractor Design considerations are presented regarding tractor implement system application and intent. The paper reviews various tractor configurations such as wheel versus track, or rigid unit versus articulated to illustrate differences each may bring to traction, guidance control, and operator comfort. The paper discusses how the designer may want to deal with limitations and requirements relative to target markets. It also touches on design for manufacturability, serviceability, standards, and compliance and how these elements can be complimentary in nature.*

Keywords. *Tractor design, Tractor machine forms, Track and wheel tractors, Tractor technology, Assembly, Manufacture.*

Introduction

The intent of the paper is to convey a series of topics that touch on items to be considered for successful tractor design. Many items to be touched upon may be familiar to designers in general and (or) may simply be a reminder. A common grounding in the fundamentals of the art are beneficial in the pursuit of any project. Many of the recommendations to follow could be applied to other than tractors and an appropriate inference could be made. Aside from the basic arts of physics and chemistry, there are many published articles that can provide significant insight on which to start the journey in tractor design. Many Agricultural engineers should be familiar with the text of *Tractors and Their Power Units* (Liljedahl et al., 2004).

The broad and straight forward discussion of principles found common to most current and past tractive machines are touched on in the text. For engineers tasked with identifying how to manage the machine in lieu of the operator, enhancing the operators experience, or improving the productive output of the machine would serve themselves well to become familiar with the basic principles found in the mentioned book. Other publications of use are the familiar ASABE, SAE, and other associated society published papers. Another great source for engineers involved with requirements or design would be current and historical operator's manuals provided with every machine produced. Service manuals also provide a learning adventure as do online tools common to today's technology. Reinventing what has been well understood and documented is not likely what your boss or your company intend for you to do. Initiating a literature search to educate oneself on the basic principles of tractor design and operation before executing the task would be recommended.

Foundations of Tractor Design

The state of the art of tractor design has evolved significantly over the past 100 years in many different ways. However, one can look at early tractor advertisements and generally find it extolls the significance of power, efficiency, and comfort, often in ways very similar to today's

advertisements. Though these features remain key elements of the modern tractor design, we generally see additional focus for off-board power capability, control of tractor/implement combinations, automation, and eventually autonomy. Some amount of work in tractor design today focuses on reducing the impact of the machine on the environment—emissions, for example, or efficiency which may be a bit removed from the direct impact of regulated emissions, but certainly impactful relative to carbon neutrality. An area of significant interest in tractor design to the operator and from a regulatory standpoint is comfort. Additionally of prime interest to the operator, or those around the machine, is safety. Safety and comfort in many areas go hand in hand. Vibration reduction, whether in terms of sound or inputs to the skeletal system, are increasingly regulated, but also expected by customers. In many cases operators expect safety and comfort beyond the regulated limits.

Regulatory statutes, (we'll call this compliance in the rest of the text), standards, (helpful in interchangeability—and though highly recommended but somewhat optional) and hazards can be viewed separately. All the mentioned topics have an amount of guidance associated with them. Compliance are statutes in areas (regions, countries, principalities, etc.) of sale. Included would be lighting and markings required for public transport in most countries, homologation requirements, such as ISO regulations or specific country requirements that might include items of control as well as dimensional limits or for many regulated areas electromagnetic emissions or transmitting limits. Hazard control might be considered for items such as debris accumulation, powered wire harness routing, and other considerations that could be cause for fire that would be of considerable financial loss to the customer, his insurance company, or the producing company.

Development of Requirements

Tractor design is relatively easy once requirements are established; however, the details often remain difficult. Identifying the target market is the first step in developing a successful platform design or upgrade. It provides the insight to

guide the customer requirements then the specifications to these requirements needed to create a functionally successful product. There are several faults that commonly accompany the definition of a tractor program. The first is a failure to adequately identify the market and the respective features customers perceive of value and are willing to pay for. Often, at the onset of program definition, the market intent is to satisfy a broad market to achieve larger sales volumes. Developing the set of compromises needed to satisfy a broad market can take an exceeding amount of time and sometimes with poor trade-offs for the entire market. Narrowing the target market so requirements can be better focused on a functional basis can help provide clarity and better scale the program in a more manageable fashion. The narrowing of program scope can often help to minimize program cost and provide a better adapted machine with fewer trade-offs. Understanding a market is extremely important so the design can target specific features and requirements unique to that market the customer is willing to pay for. Once the focused market is satisfied and decisions that were in conflict across multiple markets cleared, then an appropriate analysis can be utilized for a financial reality check. Once a more focused and minimally compromised design has been arrived at for the key market, it is often easier and more cost effective to adapt to other desired markets.

Once target markets are identified the project can be scoped. The feature set for all countries of potential sale should be identified. Once the areas of sale are chosen, the standards, compliance or regulatory factors for these countries should be identified. Also handy in such a plan would be a scheduled review for general hazards not specifically called for or outlined in published or regulated documents. Special attention should be paid to essential elements identified to build a commercially acceptable product.

Once requirements are identified for countries or regions of sale, a formal compliance plan should be developed that contains 1.) Company requirements, 2.) Relevant industry Standards, 3.) Compliance necessary for sale in the intended region of sale. A tremendous amount of guidance will be achieved very early on by executing this important task. It often identifies challenges management may decide not to include in the program due to performance compromises in principle markets, manufacturing complexity, or excess cost for a low volume target market.

There are a number of items that drive tractor design. From a very basic approach, compliance, safety, and emissions drive a tremendous amount of what has to be done but is relatively common to all manufacturers. Often power, performance, and convenience become the real state of advancement. Getting the intended task of the tractor done faster and more easily can drive tractor sales. We know there is a continual growth in tractor HP year over year. It varies by region and by tractor class, but if normalized to a percent growth is fairly uniform.

Discussion of Tractor Machine Forms

Tractors have taken on many forms over their evolution. Some are larger than others but generally the forms are intentionally well suited to their various markets. From the inception of steam driven traction units running on coal or wood through the evolution of kerosene and gasoline units to today's Diesel-powered machines on to the future of electrical, hydrogen, methane or other fuel powered units we have generally used the state-of-the-art technology to do basically the same tasks of pulling, pushing, carrying, and controlling implements principally for agricultural use as well as various other tasks.





Tractors have taken on many forms over the years. There have been many specialized adaptations and approaches. It seems the most popular approach has been a basic form with relatively simple interfaces that are versatile enough to be used with a large variety of implements. Though some tractor forms have disappeared and reappeared in markets as farming practices or economics have dictated, it's hard to imagine what could reappear or be uniquely developed in the future.

The other interesting aspect of tractor design is how it utilizes various technologies to achieve the same end. Examples might be the hydraulic front drive, shown at right, as opposed to a mechanical front drive. Some in the market use the combination of the two to achieve certain objectives. Another example in the past were hydraulic PTOs as opposed to mechanically driven ones. We see the variants of air versus hydraulics for the braking of tractors or implement systems. We see electrical versus hydraulics for control of implement functions. The point is there are many ways to accomplish any given task and the designer should not assume any particular way is best. In some regards, the approach may be best with today's technology or the availability of that technology, but engineers may find better ways to employ technologies in the future.



Understanding Differences in Various Track and Wheel Tractors

Today there are tractive variants in some common machine forms. Typical in the market are wheeled and tracked machines. Of the wheeled versions there can be powered rear axle drives, all wheel drives, front axle steer, or combinations of front and rear wheel steer. Wheeled tractors can also be articulated as can be tracked tractors. Tracks can also be offered as two-track skid steer machines or steerable front axle machines. Understanding certain details of the various configurations can be important to attain the maximum capability of the machine for the intended chore. The various performance criteria generally required of the machine is to push, pull, carry, lift, power, or control itself and associated implements.

Performance of the traction of the machine will be optimized if a thorough understanding of the type of machine being used is considered. Understanding the machines steering characteristics is also important for control of the machine and any implement combination for both comfort and guidance control. The need for this consideration is especially important based on machine type. Understanding certain aspects of the machine characteristics will lead to better control, reliability, and efficiency.

The traction aspect of the machine has many tentacles, whether it is equipped with tires, belted tracks, or both. Regardless of tires or tracks, a dominant factor in tractive pull capability in most all conditions is weight. Coulomb friction is a large determinant in traction. Of additional concern is the shear strength of the soil, and the ability of the tractive element and its cleats or lugs to bite through organic material or wet soil on the surface of the underlying soil in order to get to a regime capable of an appropriate level of shear strength or friction for the tractor to propel itself. For those interested, the soil tire interface is examined in detail in several texts, papers, and the studies well documented.

The following text will discuss traction in general terms when field conditions would be reasonable to perform typical farming tasks in at least or better than what agronomists would consider marginal. When flotation is the dominant requirement weight will still come into play depending on the number of powered axles and specific conditions. For a given field, road, and tractor set up, and when power is sufficient, pull capability of the tractor is largely a factor of weight and weight distribution. To put bookends the spectrum, unless there is some special condition or engaging mechanism, and the tire or track is sufficiently sized and matched to the machine, the pull force of the tractor will only ever slightly exceed the downward force on the tractive axles. When pull to weight nears a one-to-one ratio, it is usually on clean, dry concrete and generally does not exceed a 1.03 pull/weight (P/W) ratio factor. Obviously, the opposite end of the spectrum is zero. For general field conditions as you might expect, we can see a wide range of values with practical significance. For most field work we might expect typical ratios from 0.4-0.7 P/W. In hard pack dry clay, such as a field road or a clay mine, as an example, the expectation might be 0.8 P/W ratio or better but could vary. A good average take-away ratio for normal



design considerations based on typical tillage conditions would be 0.6 P/W ratio, but it is certainly based on many factors.

These factors include many considerations. Here are a number of examples. Tire or track, and the physical aspects of either considering sizing for a particular vehicle, the field condition including soil type, moisture level, and crop cover on top of the soil. For discussion purposes we will assume tires are aired to the proper level based on the load inflation table for the tire type, (tires generally like to have a constant static loaded radius, so as load increases so should the air pressure to maintain a constant deflection. There are special situations where we may want this to vary, but for a wide range of conditions the load inflation tables will provide the proper compromises for tire traction, wear and durability. Temporary exceptions might be flotation in wet or sandy conditions, or higher inflation for transport efficiency and durability, not necessarily wear) and for tracks to have a proper weight distribution. Keep in mind the design rigidity of track undercarriages may require more care in ballasting relative to tires. The ballasting of two-track machines and how the hitch, drawbar, and the implement the tractor is pulling may be configured is especially sensitive relative to an articulated or front axle steer machine in terms of compaction and steering sensitivity and ability. A tire will deflect as momentary load increases to spread the load out while a track in general will concentrate the load. Another way to think about the concept would consider that a tire aired to 20 psi will exhibit about 20 psi plus whatever the sidewall stiffness contributes. A track will exhibit the ground pressure specific to the weight exerted on it at a point. It is necessary to keep the load concentration in mind if compaction is a concern in the development of a tracked machine.

Other factors for consideration with regard to tires are tire type, including bias ply, radial ply, radial ply with high deflection capabilities, or other wheel types with flexible inner sections that do not use air. Each have characteristics that may be utilized to optimize them in a given situation. Bias tires tend to have much different properties from radial tires than radial ply to radial ply with high deflection characteristics. Machine design along with the tire can be optimized for a given set up. Key elements to best matching the traction device desired will be the conditions the tire or track is intended to be used in. Tires to address wet and muddy conditions may have deeper lugs with steeper angles than tires intended to be used in arid areas. Some engineers and most laypeople have a misconception that the deeper lug tires have better traction in all conditions, and often this is so in wet fields or fields with heavy covering of organic matter, but in an arid climate with hard or clean soil, the additional deflection from high lugs may decrease efficiency to a degree and reduce tire life. As an aside, the off-road industry and the on-highway industry have established the increased efficiency and durability of radial over bias tires in general and provide a high percent of the application in radial tires today, not that bias tires don't have benefits and exist in certain applications today.

With guidance of machines common place, and accuracy becoming more important if not extremely important in many applications, it is key to understand some of the differences we see in machine types. Understanding how directional control for the machine and implement combination

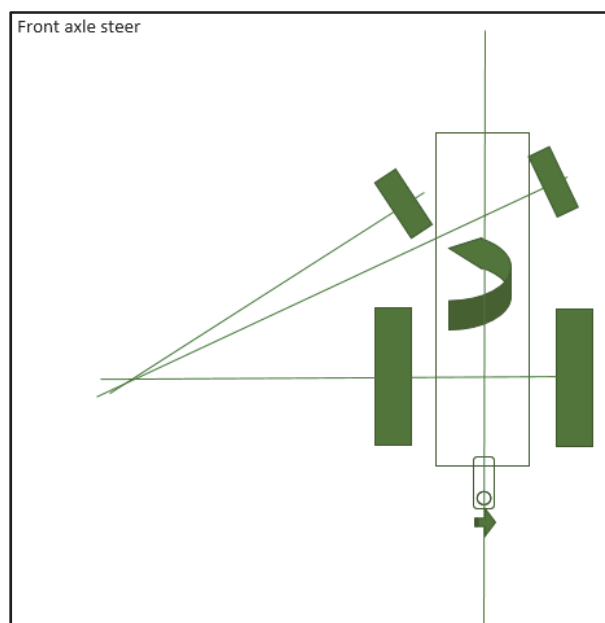


Figure 1

responds to commands is important for the different machine types, especially when the tractor/implement system combination is considered.

Let's take a Typical Row Crop style tractor. It can be a 2WD or all-wheel drive. See (Figure 1). First, consider the basic Ackermann steering used for most front axle steer products. One would note the tractor correction occurs about a point to the left or right of the rear axle depending intended direction of turn. The vector error to the implement drawbar relative to the turn direction is very small when the tractor drawbar is designed to existing ASABE or ISO hitching standards. It also shows a small relative error to the implement tongue direction when the tractor is correcting for path guidance, the magnitude depending on angle of turn, at least when compared to two-track or articulated machines forms. We'll review that in a bit.

Now consider a two-track type tractor when steering or correcting for path (Figure 2). On this type of machine, the point of rotation for steering occurs about the load center of the track pair. Here, the vector change to the drawbar implement interface is more pronounced than on a steered front axle machine. Elements in play for the system are the impact on guidance of the implement (greater dislocation of the direction of the implement to desired correction path) and of the tractors ability to correct due to deviation of the implement and the resistance a highly directional implement may provide when attempting to correct. Steering command (or ability to steer) is an important consideration on two-track machines. Two track tractors have a more aggressive steering input to the drawbar which means it also requires more force for given correction. Also consider that many larger implements have a degree of directionality or a resistance to direction change. Then also consider the leverage of the machine is limited by relevant physical forces the same as any other machine. If all the tractive force is being used to pull the implement, then none will be left for the traction required

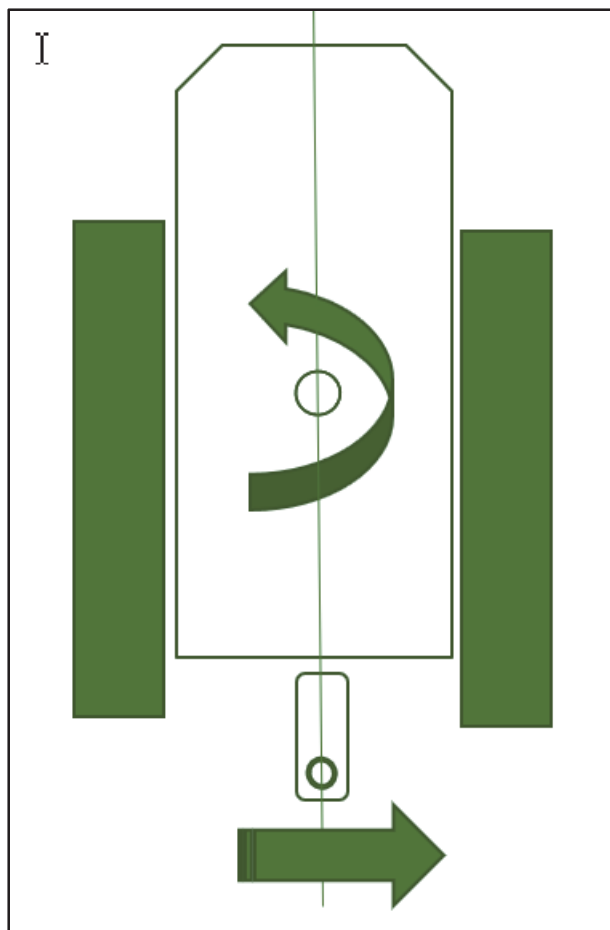


Figure 2

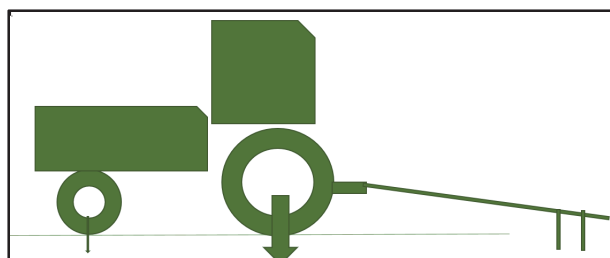


Figure 3

to skid-steer the machine in the commanded direction. Amplification of the traction required to skid steer the machine can be achieved by a wider track setting as is evidenced by most two-track machines having tread settings as wide as can be accommodated by cropping practice or transport considerations. These machines started at 60 in. minimum tread setting for 30-inch rows. Few 2-track machines remain at this setting with the onset of 120 in. tread settings and the inherent ability for better steering control capability. Recall the turn center of the tractor is about the load center of the tracks, so a 120 in. tread setting would have roughly twice the moment arm capability for steering command given the tractive capability remains the same relative to pull. Also consider wider machines can contribute more traction to pulling or pushing if the goal is to retain the same command of steering. Also note that since the most popular two-track

belted ag tractors steer with counter rotating tracks. Therefore, in order for a tractor with twice the tread spacing, it will require additional rotational differential speed to achieve the same turn angle correction for any given forward or reverse speed. One might also note the counter rotational steering aspect the machine will rotate about its tractive load center at zero machine velocity but will increase its turn circle radius as it's forward or reverse travel speed increases. This is important when considering turn speed feedback to the operator or for guidance purposes. As a side note, the counter rotational speed of most two-track machines is around 10 kph.

At this point it should be brought to the design engineers' attention of the weight transfer from the implement to the tractor. Two aspects are important to assure the tractor/implement combination offer the best tractive optimization. First, the weight of the tractor is important as a starting point for any tractor/implement/speed/soil match. We'll use the two-track machine as an example. Typically, a two-track belted ag tractor starts with about 60% of its weight on the front portion of the machine. (Placement of mid-rollers relative to drive and idler wheels can be a discussion point but we will keep the conversation simple for the specific weight distribution of the machine which will vary by specific tractor or manufacturers construction.) The important point to note is that the draft of the implement generally pivots the machine rearward when pulling such that the weight at an optimum point eventually evens out on the belted undercarriage to uniformly distribute all the weight. The weight includes the tractor weight plus what is transferred from the implement due to implement weight, down draft, or pull. This is true for all tractors but is most pronounced on two-track machines. Understanding the implement type and characteristics will be most important for the operator of the machine and will hopefully be detailed in the Operators Manual as to how best to optimize the tractor with specific implements. The key role of the designer will be to provide the versatility on the machine to ballast, hitch, and provide the proper tire or tracks to allow the customer to get the most out of his machine.

Now consider articulated machines (Figure 4). These machines have yet another form of steering to review. Picture first as an articulated machine steers the front half of the machine directionally in the direction commanded, the rear half steers in the opposite direction. The drawbar initially heads in the direction commanded then heads opposite of the direction commanded. The implement then follows the rear half of the machine. The magnitude of the changes may seem slight for small degrees of correction, but nonetheless, impart error to parts of the machine and the implement. Depending on the operation, the magnitude may have little impact or may become significant if precise implement guidance is being performed. Within reason, most of the error can be accounted for in guidance with software manipulation but must be acknowledged. As always, the corrections can also have impact on the stresses of the structural components given the directionality of many implements and based on tractive conditions the ability to correct. Other aspects of articulated machines expose

themselves as we move the articulation points closer or farther from the center of the wheelbase. This is often done out of convenience. Often the configuration of the machine is modified for packaging items such as the operator station, drive train components, fuel and so on. Impacts to steer angle and turn radius, following of rear tires or tracks to the front tires and tracks, clearance of tires or tracks to the machine components are all considerations when choosing the articulation point. When addressing compliance to standards or regulations, the choice of the articulation point and wheelbase will also come into play. Width restrictions, either regulated or practical may confine turn angle and pivot placement based on what features are intended to be optimized or compromised.

Managing technology

Applying new technology because we can apply it may not always be the best way to execute a project. Understanding what the technology does is most important to understanding how we should apply it. Often technology becomes addictive. Accomplishing functions in a unique way has an allure that engineers and managers sometimes can't say no to. Often the idea starts as an incredible or novel way of solving a historically complex issue or executing a novel new feature. Most of our machines provide their value through harnessing power from IC engines and delivering an exceedingly seamless flow of off-board and tractive power in the best manner as possible—efficiently, quietly, and reliably. Any design should always start with the basics. Creating a mechanical, hydraulic, electrical, or electronic system should employ the basics of good design. Employing novel techniques or technically complex systems to solve system issues with poorly designed mechanical, electronic, electrical, or hydraulic systems is never a good idea—although if you're at the 11th hour of production you may not have an out. It would have been a better idea to get the basics right. Technology should be used to design solid foundations and enhance systems in ways that bring productivity to the machine.

Working with familiar designs and understanding the processes and shortcomings will significantly reduce risk in the product. The performance should be closer to what is expected even though it may not be the desired outcome. This is completely appropriate when the risk of failure is high with little time for recovery or when faced with limited resources and short schedules. Working with new approaches to achieve more desirable outcomes is most likely the preference of most engineers and certainly is admirable. The key to providing any new vision is a solid grounding in reality, including the physics, chemistry, and practicality of the concept—considering the cost is reasonable and the source can be identified.

Contingency roadmaps should be a part of any project, project feature, or project schedule. Contingency can also be carried forward into what may happen or be needed in future versions. Often features, material, or space can be added or reserved for very little cost or compromise to new designs that allow for future upgrades as needed or identi-

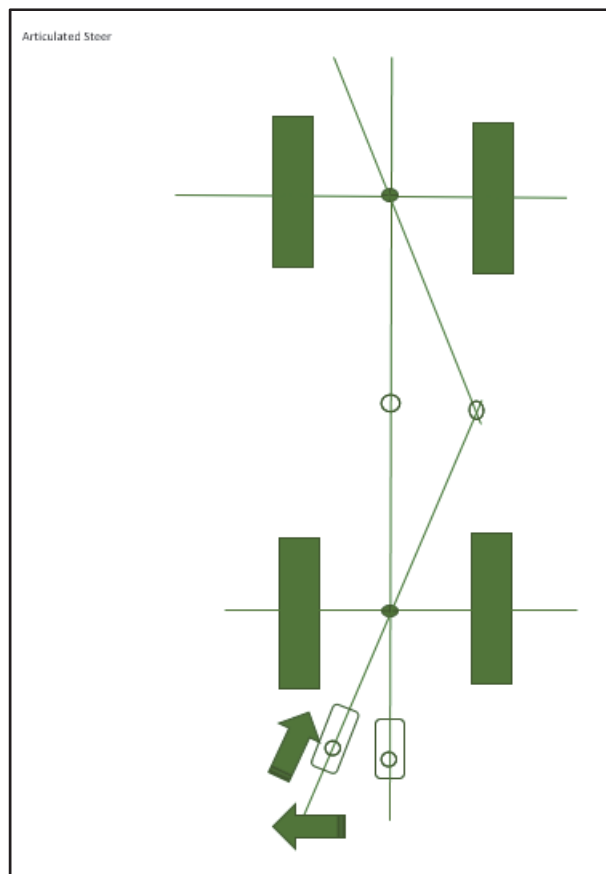


Figure 4

fied. It does take insight to achieve in an appropriate manner, and really should have a potential probability of significance.

Analysis

It is generally practical to model most all aspects of the vehicle with the tool sets available in the industry. Structural analysis, modal analysis, and CFD are very typical. It has been said many times, “All models are wrong, some are useful.” Depending on the familiarity of the tool and the experience of the analyst, some models are very close to correct before a correlation to physical parts or systems have been made. In most cases, the model can be improved once a physical system is available. Test data can be used to update and more accurately reflect the actual part or system. An accurate analysis requires expected machine loads and representative boundary conditions to deliver an accurate assessment of the machine, machine system, or components. Some models can be used to analyze a wide range of operating conditions, while others may not have the fidelity to achieve a broad range of operating conditions or situations. An honest review of the capability of any model is required and a determination made as to whether additional testing may be necessary to assure a good product in the marketplace.

Relative to structural analysis, the writer finds strain plots to be more interesting than stress plots as guidance for addressing structural issues. Often a smoothing of geometric section will reduce high stress areas and often deliver a more

manufacturable part. The writer has often found the use of CFD can bring projects to best in class performance when the first pass at the design with solid calculations fail to optimize a system. Often it is hard to tell the difference in parts between a marginal system and a highly optimized one when using CFD without looking at the prints. Bottom line, analytical tools are extremely powerful and useful.

When the models, assumptions, unexpected loads, or something completely different cause parts to fail, look at the parts. Advice from colleagues in the analysis groups indicates that there is nothing more enlightening than looking at the hardware or control systems that went awry. Every broken part is telling a story. Though it might be elusive, the part is telling its story. Experience would indicate if a failure were dismissed as an anomaly, or an assumed reason is used to explain the issue away, it's highly likely it will return. Experience also tells the writer that any failure that occurs in a test program will arise again unless the root cause is identified and corrected. If the root cause cannot be found in a timely fashion, then the symptoms may be addressed, which in general, is often more costly than identifying and fixing the root cause.

Design for Assembly/Design for Manufacture

Depending on volume and complexity of parts for a typical machine, fewer parts can sometimes be considered fewer problems. Eliminating parts or combining functions offer several benefits. The most obvious benefit would be the removal of interfaces, their cost, the integrity of the joint, reduction in manufactured or purchased parts and assembly simplification. Often communication among engineers is necessary for optimal application of part reduction. Communication seems more than challenging in most disciplines so an emphasis on discussion among participants is usually paramount. Goals are also a hinderance if applied inappropriately. The organization should be challenged to consider reduction of parts and an increase in the utility of any given part. There are a number of different software packages available to assist with the concept but there are a multitude of factors to deciding if the design should be a consolidation of features or kept separate.

Serviceability

It is often beneficial to have Engineers build and service their own designs, at least once, and under the pressure a dealer faces. Often current designs are practical starting points. Engineers have a general attitude their parts are designed to never fail and thus find little reason for designing for serviceability if inconvenient. The reality is all parts fail at some point for some reason, and not always outside the boundaries of intended use. Even in general use we deal with a curve that anticipates some amount of infant failure and eventual wear-out failure. In between, of course, are mistakes in manufacture, assembly, or anticipated loading. Many times, the failure is of secondary nature from some other type of failure. In all cases if seems appropriate to

achieve a high degree of serviceability in terms of low downtime, low cost of fix, easy diagnostics, and be relatively non-invasive to other parts or components. The fewer systems disrupted during any service relieves the potential of introducing a failure mode during disassembly, movement, or re-assembly of the components. Mistake proofing for service is can also be as import of a feature as it is for manufacture, arguably more so due to infrequent need to service, (hopefully) level of familiarity, conditions in which the part is being serviced including dirt, temperature and ergonomic access such as lifting and positioning devices, access, and weight.

Design for serviceability is hard to add after the fact. Goals and direction should be identified up front in requirements. Communication among design and manufacturing teams is of highest importance in order for everyone to understand the sequence of events that may be needed to R&R a part so as to accommodate with proper decisions.

Manufacturability

Another very important aspect of tractor design is the manufacturability of parts, assemblies, or machines. Designers need to find processes that are consistent and can be repeated efficiently and cost effectively. An engineer's job is to apply technology in a cost-effective manner. Understanding the processes and assuring the designs are within the capability of the people, suppliers, and machines making the parts is important. Ergonomics for making and assembling parts as well as investment are also important aspects of the design of the machine. Often manufacturing and assembly teams have guidelines and limitations that should be shared and addressed up front in requirements before design commences.

Conclusion

It is important that markets be defined, and requirements outlined as the first and most important part of any tractor project. Regulations, standards, and hazards should be a key element of the requirements. Decision analysis is an important part of choosing the best systems and technology to address the product requirements. Understanding the application and fundamentals of tractors and the systems of which they are a part is necessary to develop capable systems to support the requirements. Manufacturing, assembly, and service are all key factors of successful tractor product design and must be a part of the requirements at the beginning of the program. Analytical tools are readily available and very capable. The tools should be foundational in analyzing designs prior to any hardware build and correlated once hardware is available. Proper preparation in the areas identified should lead to a highly successful product with few surprises.

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