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Power Tag-Axle Traction Assembly (P'TATA)

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Powered Tag-Axle Traction Assembly
(P’TATA)

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Executive Summary

Project P'TATA encompassed the design of a selectively-powered tag axle for 6X2-configured Class-8 on-highway tractors, to aid the vehicle in regaining traction during reduced-friction events. For increased fuel savings, 6X2 (1 driving axle, two unpowered axles) configured tractors are preferred over their 6X4 (two driving axles) counterparts; however, the loss of a powered axel renders 6X2 axles more susceptible to slipping events, where the amount of torque required to maintain non-slipping contact with the road exceeds the abilities of the single drive axle. For this and other reasons, the 6X4-configured tractors are chosen despite the fuel efficiency benefits of the 6X2 configuration. Therefore, improvement of the 6X2 tractors' ability to escape from slipping events should improve driver safety and enhance the tractors' competitive edge in the market.

The design process began with determination of the tag axle torque required to drive the truck out of a slipping event, and a comparison of different power transmission methods. After choosing a transmission method, the electronic control and mechanical systems were designed to so that a motor could engage the axle, transmit power, and then disengage. Using existing and custom-modelled parts, a 3-D model of the system was assembled in CAD software, and a scaled down prototype was constructed to test the control system.

An electro-mechanical add-on system was designed to meet the criteria presented by Daimler Trucks of North America. This assembly, shown in Figure 1, employs one DC motor to power the tag axle. A Bendix drive allows for engagement between the motor and the 40:1 reduction worm gear box that multiplies the motor torque. Electricity is pulled from the tractor's standard battery bank.

The electronic control system monitors the wheel speeds at the tag and driving axles, and identifies slipping conditions based on a minimum difference between those speeds. Flowchart and block diagrams of the electronic control circuit were drawn up; parts were ordered and the prototype was built based on these drawings. Once the prototype control circuit was functioning properly, a circuit board was prepared and readied to accept the components of the control circuit. The circuit board was then tested, first for proper wiring and then to ensure proper operation.

The final design provides 1120 ft-lbs of torque to the tag axle, remains lightweight at 99.5 lbs compared to the 380 lb differential used in a 6x4, and remains cost-effective with an estimated materials price of $798.42 out of the allotted $1500 (rough estimate not including manual labor). It is capable of driving the truck at 15 mph out of slip on a 4% gradient of sleek ice. The add-on also does not require significant alterations to the existing tag axle design.

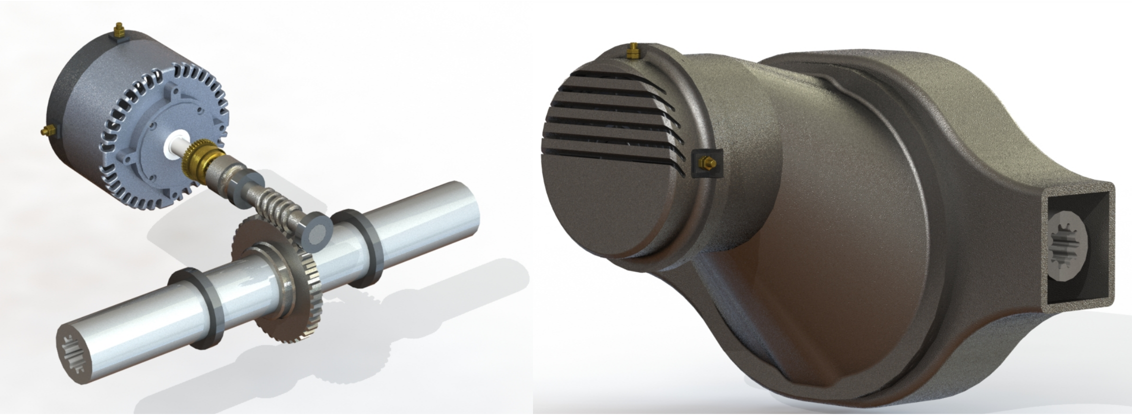

Figure 1: Final system design (mechanical components at left, full assembly at right)

The design meets the given criteria, but the industry advisor advanced some further design optimization requests that should be considered in future design iterations. The team recommends the implementation of a higher voltage 3-phase electric motor because they provide more horsepower and would require a lower gear reduction for the system. The Bendix-driven engagement mechanism may need to be redesigned to ensure reliable operation. Ultimately, the success of the system must be validated, both by computer stress simulations and by physical testing with full-scale prototypes, prior to large scale manufacturing and implementation.

Introduction

The main objective of Project P'TATA was to design and prototype a system to power the tag axle of a 6X2-configured cargo tractor, in order to regain tire traction in low-friction conditions. The project was conducted on behalf of, and with support from, Daimler Trucks North America. Daimler and its subsidiary, Detroit®, have committed their engineers to introducing fuel-efficient tractors to the transport vehicle market under the Freightliner™ brand.

In pursuit of this goal, the company has developed a 6X2 tractor configuration, meaning that only one rear axle is powered by the engine. This modification benefits fuel efficiency, but reduces the amount of torque available to help the tractor escape low-friction conditions. For this reason, the 6X2 tractor is seen as a less capable and higher-risk investment for customers. To aid the tractor in regaining traction during wheel slip events, and to help dispel any qualms about the reliability of 6X2-configured tractors, Detroit® has requested the assistance of University of Portland students in devising a creative and effective solution.

Background

Freight trucks are a primary mode of commodity transport: in the United States alone, freight trucks carried an estimated 13 billion tons of domestic and foreign goods in 2012,[1] more than that carried by all other modes of commercial transit combined. On US roadways, the 6X4 configured tractor units comprise about 97% of American Class-8 (>33000 lb.) sales[2]. In this configuration, both rear axles are powered, and propel the tractor and its cargo forward.

The 6X4 configuration is popular for its versatility: it performs well on highways, and its rear axles provide enough torque to propel the tractor over the rough and wet terrain characteristic of logging and rural applications. However, the assemblies required to transmit power from the first drive axle to the second add significant weight, and this compromises the fuel economy of 6X4-configured tractors.

6X2 configured tractors are the primary alternative to the 6X4 tractors: one axle is depowered and "tags" behind the driven axle. This can improve fuel efficiency by as much as 2%[3], while reducing overall vehicle weight by eliminating the need for heavy gears and power transmission components in the second rear axle. However, 6X2 tractors can suffer from traction loss on some roadways, especially in wet and icy conditions, leading to potentially hazardous situations and increased costs associated with towing, repair, and downtime.

Currently, the only widespread solution to traction loss with a 6X2 tractor is to use the method of "weight-shifting" – adjusting rear axle suspension to move the vehicle's center of gravity closer to the driving axle; this shift causes the driving axle to bear more of the vehicle's weight, increasing the contact force between the tire and roadway and thereby improving traction[4]. However, weight-shifting can only improve traction to a certain extent because the drive axle must never be overloaded.

Another solution, developed by MAN Truck International, utilizes a hydraulic system to power the front axle in low traction conditions[5]. While this solution is very effective on a variety of road conditions, the complexity of the hydraulic components makes a similar design infeasible given time and scope constraints; it would also drive initial costs higher, and could precipitate additional maintenance and repair costs. Likewise, the system fails to offer efficiency savings in weight and cost.

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[1] 'Freight Facts and Figures - 2013' (US Department of Transportation)

[2] 'Is a Fuel- and Weight-Saving 6X2 for You?' (TruckingInfo.com)

[2] 'Is a Fuel- and Weight-Saving 6X2 for You?' (TruckingInfo.com)

[3] Ibid.

[3] Ibid.

[4] Ibid.

[4] Ibid.

[5] 'Technology and Competence: MAN HydroDrive.' (MAN Trucks International)

[5] 'Technology and Competence: MAN HydroDrive.' (MAN Trucks International)

Discussion

Client Deliverables

During the fall semester, the team identified general goals to be achieved by the project's end: these included a detailed analysis of the truck loading condition and torque requirements for regaining of traction; 3-D computer models of the final design assembly; and working prototypes for both the mechanical and electrical solutions. These goals were approved by Mr. Aaron Schuyler-Scates, the team's industry advisor during the fall semester.

During the spring semester, and after consideration of various design challenges, the team met with Mr. Paul Bourinskie, the team's spring semester industry advisor, to identify a specific set of achievable project deliverables. Mr. Bourinskie, acting as the project client and on behalf of Daimler, set the deliverables identified in Table 1, below.

Table 1: Project deliverables

Deliverable	Description
Weight of System	Determine the approximate weight of the motor, gears, and materials added to the tag axle.
Cost of System	Determine the cost of the external equipment needed to reproduce the design.
Required Torque	Determine the minimum torque needed at the wheel and determine the torque delivered by the motor at the wheel.
Maximum Speed	Determine the speed the tag axle wheels will rotate and speed at which the truck will escape slip.
Packageability	Determine if and how all components will fit within the allotted space in the rear of the truck. Provide an aesthetically pleasing housing for the system.
Logic/Control Circuit	Arithmetic logic unit and description of how the circuit will operate during the truck's slipping condition.

Design Considerations

Before conducting research and analysis, the team identified primary design considerations and the criteria for success. These are presented in Tables 2 and 3, respectively. In Table 2, the main themes in design considerations are focused around efficient and appropriate use of materials to avoid excessive cost and waste, and design for manufacturing, assembly, and ease and safety during operation and maintenance.

Table 2: Design considerations

Consideration	Description
Economic	Add-on's total cost must keep the 6X2 tractor competitive with other manufactures and 6X4 tractors.
Environmental	Design should aim to be as fuel-efficient as possible to correspond to DTNA environmental standards.
Social	Meet manufacturing's core objectives in the areas of: safety, quality, cost, delivery, environment, and employee morale.
Political	Design has to follow regulations set by the government and state.
Ethical	Keep internal information confidential and design a system of our own originality.
Health/Safety	Design must be easy to install and maintain for the driver, technician, and manufacturer.
Manufacturability	Minimal modification to tag axle to continue its production in current DTNA plants.
Sustainability	System must be reliable and be expected to be used once per average driving year.

To summarize the contents of Table 3, the overall design of the system must be simple, efficient and reliable. The team focused on designs that required only minor modifications to the existing structure of the tag axle, and used a minimal number of components. The system had to be inexpensive and lightweight to maintain the fuel economy advantages of the 6X2 tractor, while offering reliable performance even after long periods of low usage.

Table 3: Criteria for success

#	Criterion	Priority	Description
1	Simplicity	Required	Minimal change to the current tag axle design. Tag axle tower and spindles must not be altered.
2	Reliability	Required	Function correctly despite duty cycle of ~5-10%.
3	Power	Required	Provide sufficient torque to rear wheels to increase traction in any road condition. Torque provided to rear wheels should not exceed torque provided to drive wheels from engine. Gradients up to 4%. System will only be engaged at speeds of 0-15 mph.
4	Cost	Required	Reduce cost of materials, installation, maintenance to increase profit. Cost should be significantly less than price difference between 6X2 and 6X4 trucks. Approximate Manufacturing Cost: $1500
5	Weight	Required	Lightweight design to retain fuel efficiency benefit of 6X2 tractor. Weight difference between 6X4 and 6X2 truck is 380 lbs.
6	Modularity	Desired	The power-control assembly will ideally be made such that it can be offered as an add-on to orders for 6X2 tractors

There are four primary transmission methods that were considered for energizing the tag axle during slipping events: hydraulic, pneumatic, mechanical and electrical. Table 4 rates each of these methods according to the design criteria. The ratings range from 1 to 5 for each power method. Then the ratings are multiplied by a value based on the importance of each criterion. The highest sum of the ratings in each transmission method will be used to determine the best option. These ratings were developed based on literature research in each area.

Table 4: Criteria ratings of power transmission methods

#	Criterion	Value	Electro-Mechanical	Hydraulic	Pneumatic	Mechanical
1	Simplicity	9	5	1	2	2
2	Reliability	10	3	1	4	5
3	Power	10	3	5	2	5
4	Cost	10	3	1	2	2
5	Weight	10	3	1	5	1
6	Modularity	7	3	3	3	1
	Total		186	110	169	155

Hydraulic and pneumatic systems would use a fluid (air or oil) to power the tag axle wheels. These types of systems can provide significant power and are very reliable when designed correctly, and could also integrate into the existing hydraulic and pneumatic systems in the truck. However, hydraulic and pneumatic systems are difficult to design, manufacture, and install; and failures can be difficult to repair, requiring additional downtime and increasing the cost of ownership. Hydraulic and pneumatic systems were therefore considered infeasible based on the team's technical knowledge and the scope and duration of the project.

A purely mechanical approach to powering the tag axle would involve a detachable drive shaft running between the drive and tag axle, or a small roller that connects the tires of the drive axle wheels to the tires of the tag axle wheels. Both designs are capable of reliable operation and can provide sufficient power. However, both options would incur significant alterations to the existing layout of the tractor, and siphoning power from the engine would decrease fuel economy. The design criteria therefore disqualify these alternatives.

An electro-mechanical system was determined to best satisfy the design criteria. This configuration would use an electric motor to provide power, moderated by gearing, to the tag axle wheels. This type of system likely will not provide as much power as other systems, though with a gear reduction, the increase in torque should be sufficient. This type of system offers distinct advantages in simplicity of design and installation. Ideally, it will also offer reduced cost and weight, and it should perform reliably in most scenarios. Further analysis on this system type will be conducted to ensure it can meet these advantages. Simplicity is also a big factor as a motor needs only be coupled with an electronic module to operate, and can run using the 48V power supply native to the truck's existing electrical power system. Almost none of the system's peripherals will require any other special service tools that a fleet would not already have on hand. However for financial interests, fasteners and perhaps other parts can be made to work with special sockets without any modification to this design, allowing for flexible maintenance profit over its service life.

Slip Scenario Analysis

To satisfy the criterion that the amount of torque provided by the system would not exceed the amount of torque available to the drive axle, the amount of torque at the drive axle had to be calculated. This computation used both engine specifications and transmission gear ratios. Given that the tag axle would be employed only when the tractor is traveling at low speeds, and would be either slipping or about to lose traction, it was assumed that the tractor would be in first gear, developing high torque but low velocity at the wheels. In this case, the engine would provide around 360 horsepower and 1750 ft-lb of torque. With a significantly large gear ratio of 14.93:1 in the transmission and a gear ratio of 2.28:1 in the differential, the torque developed at the drive axle was determined to be approximately 56,000 ft-lb. This value was taken as the upper limit on the amount of torque available to the drive axle.

Next, the forces acting on the tag and drive axle were quantified. The tractor was analyzed as a two-dimensional body sitting on an incline, based on a free body diagram provided by Daimler. While the tractor was assumed symmetric about its long axis, the scenario was statically indeterminate (unsolvable) due to the three points of contact between the tractor and the incline, as seen in Figure 2.

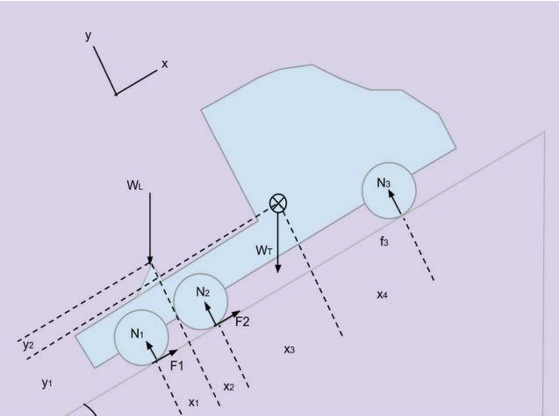


Figure 2: Free body diagram of tractor on incline

To make the free body diagram statically determinate so that the forces acting on the tag and drive axles could be quantified, the three points of contact were converted into two points by merging the drive and tag wheels. The reaction force of the merged wheel was then divided in half, the value of each half equivalent to the reaction force acting on each pair of rear wheels. Figure 3 offers a schematic demonstrating the methodology described above.

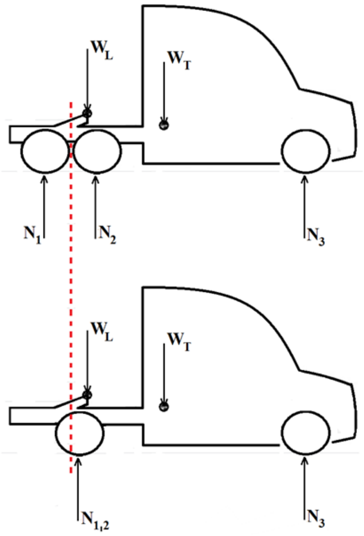


Figure 3: Merging of tag and drive axles

Next, the location for the merged wheel was determined: using the known reaction forces from the original free body diagram provided by Daimler, the equilibrium equations were solved, and the placement of the merged wheel was determined to be 2.55 inches forward of the midline between the tag and drive axles. Based on this placement, the reaction force for the merged wheel is 34626 lbs or 17313 lbs for the drive and tag wheels, based on a horizontal orientation of the tractor.

With the revised tractor model established, the reaction forces at the wheel-road contact were calculated for different inclines. Although the center of mass of the truck and load would be displaced backwards at steeper grades (resulting in a larger reaction force on the rear tire), it was assumed that, relative to the dimensions and weight of the vehicle, this change would be fairly small.

A spreadsheet was created in order to determine the reaction forces N1, N2, N3, F1, and F2. It is summarized in Table 5 and accompanied by the simplified truck's FBD in Figure 3. With the smallest coefficient of kinetic friction chosen from Appendix IV, the worst case scenario was determined. This occurs at a 4% gradient as specified in the design criteria, and with a coefficient of kinetic friction of 0.7, meaning the truck is slipping on ice. As seen in Table 5, the drive wheels provide a force F2 along the incline of 1223 lbs while slipping. However, a total force F1,2 of 1815 lbs is needed to keep the truck from slipping down the incline. This means that the tag wheels must provide an additional force F1 of 591 lbs, which corresponds to a torque requirement of 941 ft-lbs. This minimum torque is rounded up to 1000 ft-lbs in order to provide a small factor of safety for the tag axle system. Based on this torque value, the requirements of the system are identified; numerical values are presented in Table 5.

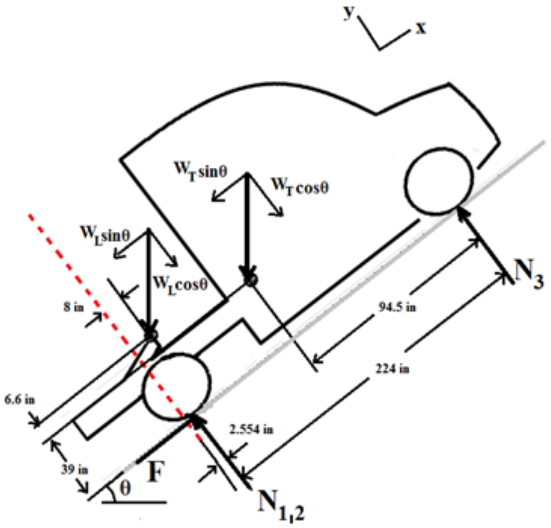
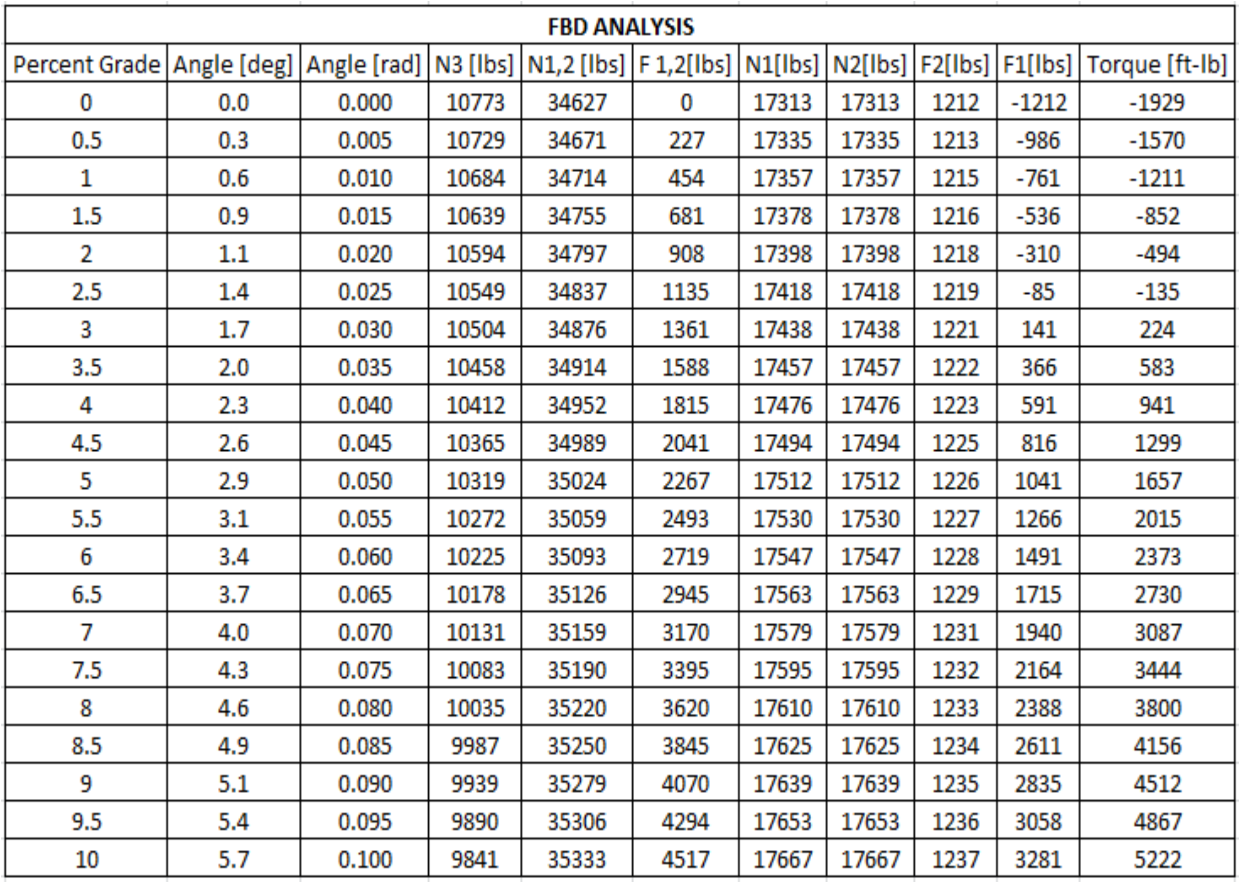


Figure 4: Free body diagram of simplified truck model

Table 5: Free body diagram analysis results



FBD ANALYSIS										
Percent Grade	Angle [deg]	Angle [rad]	N3 [lbs]	N1,2 [lbs]	F 1,2[lbs]	N1[lbs]	N2[lbs]	F2[lbs]	F1[lbs]	Torque [ft-lb]
0	0.0	0.000	10773	34627	0	17313	17313	1212	-1212	-1929
0.5	0.3	0.005	10729	34671	227	17335	17335	1213	-986	-1570
1	0.6	0.010	10684	34714	454	17357	17357	1215	-761	-1211
1.5	0.9	0.015	10639	34755	681	17378	17378	1216	-536	-852
2	1.1	0.020	10594	34797	908	17398	17398	1218	-310	-494
2.5	1.4	0.025	10549	34837	1135	17418	17418	1219	-85	-135
3	1.7	0.030	10504	34876	1361	17438	17438	1221	141	224
3.5	2.0	0.035	10458	34914	1588	17457	17457	1222	366	583
4	2.3	0.040	10412	34952	1815	17476	17476	1223	591	941
4.5	2.6	0.045	10365	34989	2041	17494	17494	1225	816	1299
5	2.9	0.050	10319	35024	2267	17512	17512	1226	1041	1657
5.5	3.1	0.055	10272	35059	2493	17530	17530	1227	1266	2015
6	3.4	0.060	10225	35093	2719	17547	17547	1228	1491	2373
6.5	3.7	0.065	10178	35126	2945	17563	17563	1229	1715	2730
7	4.0	0.070	10131	35159	3170	17579	17579	1231	1940	3087
7.5	4.3	0.075	10083	35190	3395	17595	17595	1232	2164	3444
8	4.6	0.080	10035	35220	3620	17610	17610	1233	2388	3800
8.5	4.9	0.085	9987	35250	3845	17625	17625	1234	2611	4156
9	5.1	0.090	9939	35279	4070	17639	17639	1235	2835	4512
9.5	5.4	0.095	9890	35306	4294	17653	17653	1236	3058	4867
10	5.7	0.100	9841	35333	4517	17667	17667	1237	3281	5222

Proposed Design

At the end of the fall semester, the team had identified a high-level design proposal for the tag axle assist device. The proposed alternative would have utilized two electric motors to provide the necessary added torque in a loss of traction event; dual motors were chosen to reduce the weight associated with use of a more traditional differential-driven design. The power source to these motors was specified to be a collection of ultracapacitors; these offered lower weight and larger, quick voltage generation relative to similarly-equipped batteries. All power needs and assembly activity would be moderated through the electrical system control circuit. Figure 5 on the following page presents a simple diagram of the proposed design.

With the proposed design, gearing would still be required to multiply the motor torque up to that required to overcome slipping; but the weight of those gears was anticipated to be lighter than the weight of an entire differential assembly. Within the tag axle housing, the wheel axles would interface with an inner pair of axles that were driven by the motors. Mated bevel gears would form the motor-inner axle interface, while dog clutch-derived geometries would allow for the engage/disengage design functionality.

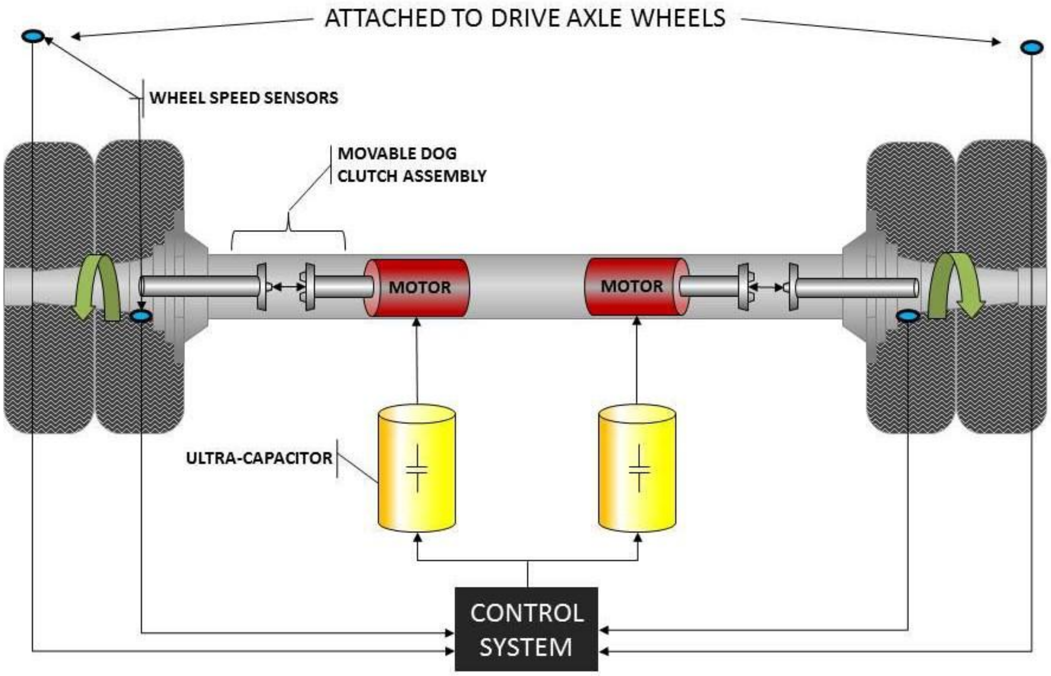


Figure 5: Proposed power/mechanical design alternative

At the time, two primary assemblies were considered for actuation of the engage/disengage mechanism. The first would employ traditional transmission selector forks connected to linear actuators (See Fig. 6), which would slide the dog clutch into mate with the axles when energized by the control system. The other method would involve the use of a spring-loaded Bendix drive, whose rotation (by the motor) would force the spring to stretch, pushing the gears into mate (See Fig. 7).

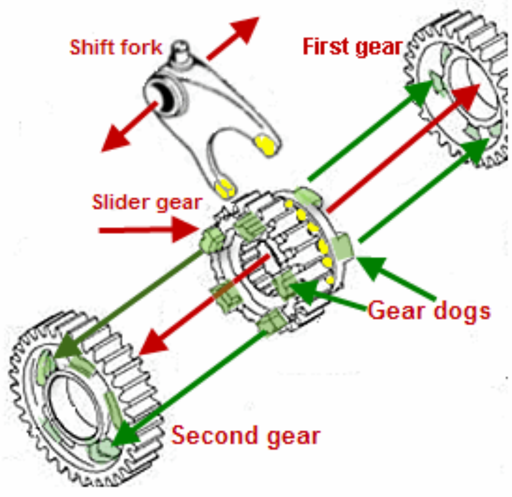


Figure 6: Dog clutch schematic[6]

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[6] 'Troubleshooting gear shifter on a 1983 honda 200 atc three wheeler.' (Fixya.com) http://www.fixya.com/motorcycles/t14597436-troubleshooting_gear_shifter_1983_honda

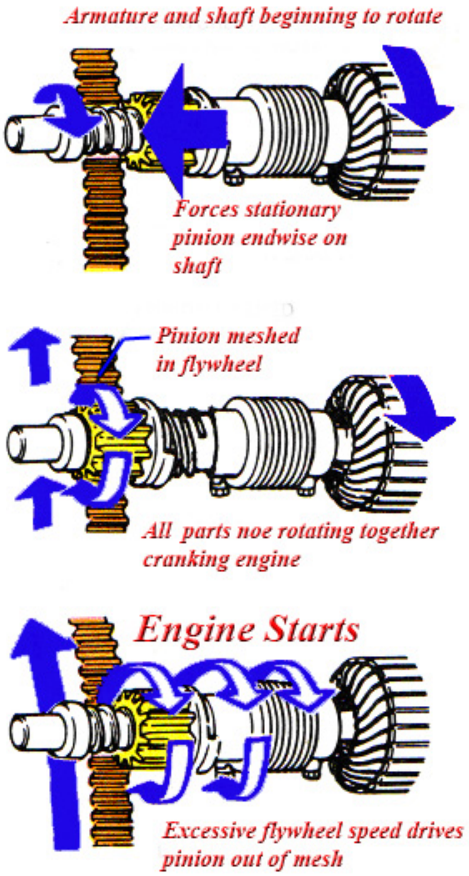

Figure 7: Schematic detailing Bendix Movement in an Engine Starter Mechanism[7]

The proposed design appeared to fulfill the simplicity, reliability, power output, and weight and cost reduction criteria established in the design considerations table. It was expected to necessitate few alterations to Daimler's current tag axle design, and perform reliably despite infrequent use. With appropriate selection of motors and gearing, the design would be able to generate sufficient torque, and with fewer and smaller parts than more traditional assemblies, would reduce the cost and weight of the system. With the agreement in comparison to the criteria and the performed analyses, this design alternative was chosen for further development in the spring semester.

The electrical control system for the fall semester design proposal controlled both of the electric motors simultaneously, but allowed the motors to operate independently of each other. This allowed for differential wheel speed while cornering as well as reduced drag during turns. Figure 8 offers a block diagram for the motor control system of the fall semester design proposal. Appendix V depicts a preliminary diagram of the control system.

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[7] 'Starter Engagement System.' (Autocorner.ca)
http://www.autocorner.ca/pages/starterdrive.html

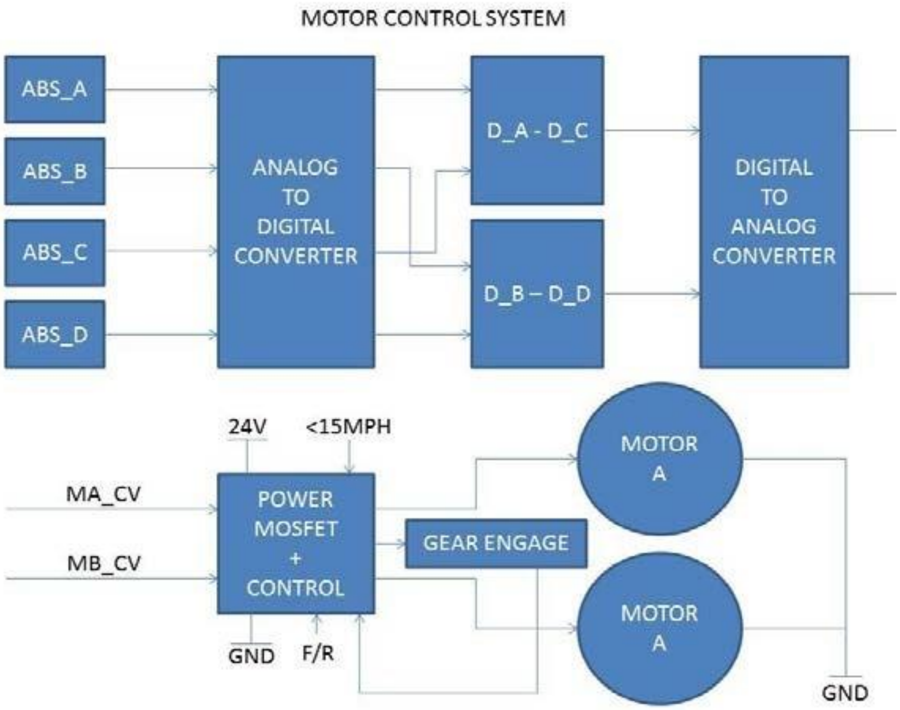

Figure 8: Motor control system block diagram

To begin, the electronic control system would need to detect the direction of drive movement, either forward or reverse. This would be done using the reverse gear sensor in the transmission case: when the reverse gear is not engaged, the associated sensor would notify the control system that the two motors need to turn in the ‘forward’ direction. When the reverse gear is engaged, the sensor would alert the system to turn the motors in the ‘reverse’ direction.

The system would then read the rotational speed of each wheel through the vehicle’s existing ABS system tone rings. These readings would be sent to the control system, where an analog-to-digital converter would convert the analog input into a digital signal.

The digital representation of each wheel’s speed would then be compared using a subtractor. Specifically, the drive and tag axle wheel speeds of each side of the truck would be independently compared to each other. The output of each comparison then becomes the difference of wheel speeds for each pair. These differences would then be passed into the digital to analog converter which would regulate a high power MOSFET transistor, which would supply an amount of power directly proportional to the difference in wheel speeds.

A timer would also be needed to be set so that the system engages only when there are true slip conditions and not when there is rapid loss and gain of traction. One solution would engage the control system if there was a differential wheel speed that exceeded the threshold for a certain amount of time such as 2-3 seconds. This is to prevent high cycling of the system which would subject the motors and power circuits to high power spikes as well as wear out gears.

Refining and Modification of the Proposed Design

During the spring semester, the P'TATA team invested their time and knowledge in the detail-level phase of the design cycle, examining and designing the components and subassemblies required for the complete assembly. As a result, numerous modifications and refinements were made to the original proposed design, primarily motivated by insight from the team's industry advisor.

The first major revision was the reorientation and quantity reduction of the motors. In the proposed design, two motors were to be utilized, and would have been mounted concentric with the axle shafts. However, the team determined that, to generate the torque required to regain traction, larger motors were required than would fit within the tag axle housing; as a result of their size, these motors were also too heavy and expensive for the proposed design to satisfy the applicable criteria. The team therefore modified their design so that a single motor could be utilized, mounted perpendicular to the axle shaft, with torque transmission accomplished via a worm-ring gear box.

The team also revised the location and type of engage/disengage mechanism. To reduce the number of required components, and save additional weight, the team decided to employ a Bendix drive engagement design, rather than the dog clutch-shift fork design. To further simplify the design, and also to allow for easy maintenance in the full scale product, the engage/disengage mechanisms were relocated from their position in-line with the axle shaft, to between the motor and the gearbox. This design decision also reduced the number of required engage mechanisms from two to one, since the gearbox would feed motion to both of the tag axle wheels.

As the team was researching and selecting a proper gear set, it became clear that the tag axle housing currently employed by Daimler lacked sufficient internal volume for the gearing to be placed inline with the axle shaft. Alternate methods for transmitting torque to the axle shaft would have required extensive modification to the existing tag axle structure. After consulting with and receiving approval from their industry advisor, the team elected to use Daimler's more traditional, driving axle housing (see Fig. 9), which included a widened midsection to accommodate a differential. Review of technical drawings for the driving axle housing revealed sufficient space for the proposed gear system, and additionally provided convenient mounting points for the motor and other components, so it was chosen to replace the tag axle housing.

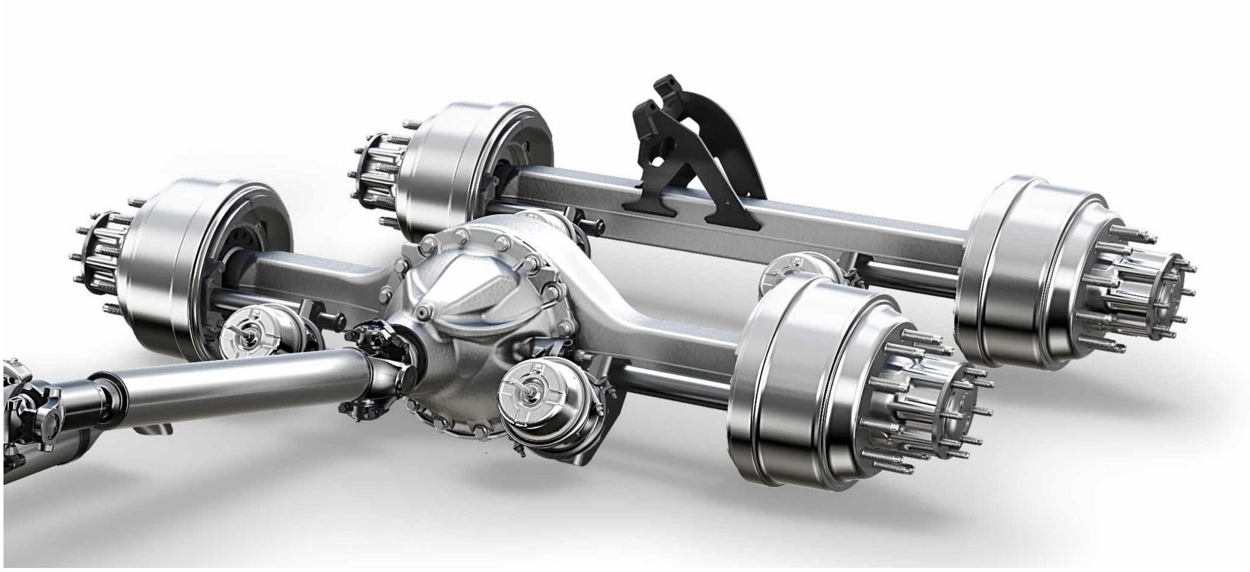

Figure 9: Size difference between drive (foreground) and tag axle housings[8]

Final Design

The final design proposed in this report consists of a single electric motor that powers a worm gear assembly to drive the wheels of the tag axle. A Bendix drive is used to engage the gearbox with the motor. The system is powered by the existing battery bank installed in the 6X2 tractor. Sensors determine when the drive wheels are slipping in a loss-of-traction event, alerting the control system to power the electric motor. The rotation of the motor shaft extends the Bendix drive until it engages with the worm gear assembly, at which point the entire assembly is active, providing the extra torque required for traction regain. When the sensors determine that traction at the main drive wheels is reestablished, the control system will shut off the motor, causing the Bendix drive to retract from the worm gear and normal operation of the truck to resume. Please refer to Figure 10 for an annotated, exploded view of the entire assembly.

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[8] 'New model 6 drive axles now available from Detroit' (westernstar.com)
http://westernstar.com/MediaCenter/PressReleases/default.aspx?n=new-model-6-drive-axles-now-2015-02-12

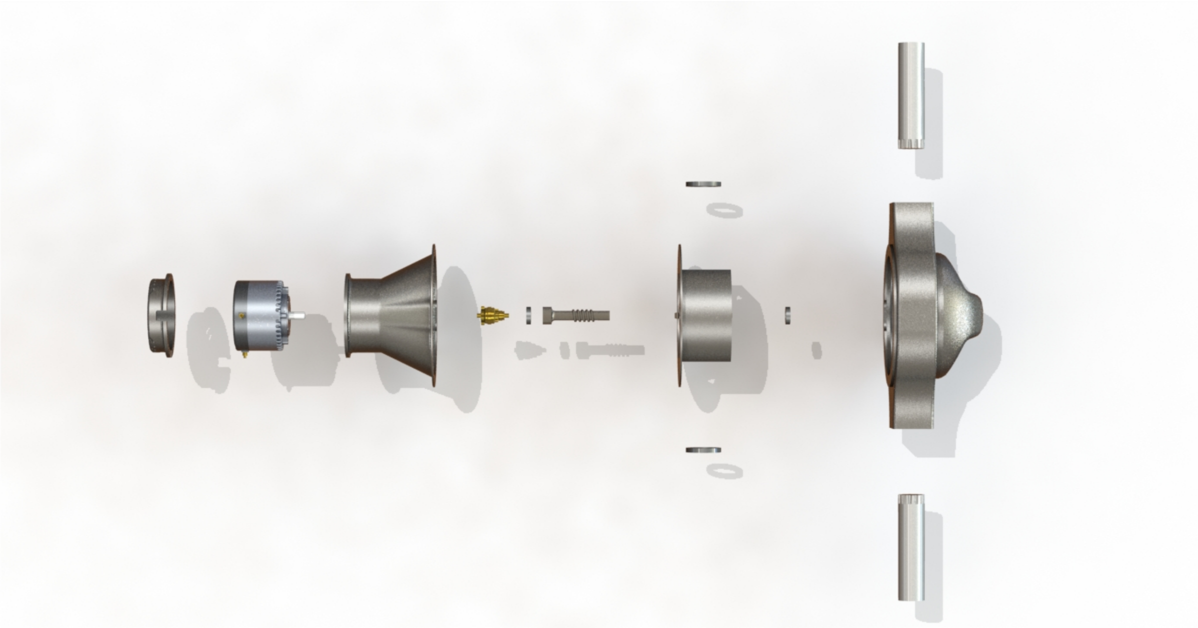


Figure 10: Exploded view of entire assembly (ring gear concealed by gearbox insert)

The electric motor chosen for this system was the Motenergy ME0708 Brush-Type DC motor. This motor was chosen primarily because it offered attractive power ratings: continuous power at 6.5 hp, or up to 20 hp for 1 minute, with a stall torque of about 28 ft-lbs, and a maximum rotor speed of 5000 RPM. Given that the motor must provide the maximum amount of torque for a duration of 10-15 seconds, the motor will be operating at full power and at the highest torque possible. Because it will only operate for short durations, the motor is not expected to overheat.

The motor requires 48 VDC input, which the existing battery system in the truck can provide. As a brush-type single-phase DC motor, the ME0708 should provide more torque relative to brushless-type models; additionally, DC motors allow for a more simple control circuit. Lastly, the motor is very light at 28 lbs and fairly inexpensive at $450-$500, making it ideal for the relevant specifications for the system.

The selected electric motor offered several advantages to the system in terms of weight, simplicity, and cost, at the expense of insufficient power and torque. To rectify the difference between the 28 ft-lbs torque output by the motor and the 941 ft-lbs torque required at the wheel, a 40:1 reduction gearset was implemented. A ring-and-worm assembly was chosen, as it allowed for introduction of a relatively large gear ratio in a minimum amount of space. Combined, the electric motor and worm gear should provide up to 1120 ft-lbs of torque to the wheel, adding a factor of safety to the requirement of 941 ft-lbs determined in the mechanical analysis.

While the torque multiplication reduces the speed of the wheel, this issue was less important as the tractor did not need to move at high speeds escaping a slipping event. Another difficulty in choosing a worm gear assembly was the worm's inherent characteristic of self-locking: due to interactions between the teeth of the ring gear and the thread of the worm, the ring gear generally cannot drive the worm. This phenomenon becomes problematic when the drive wheels of the truck regain traction and cause the tag axle to drive the ring gear. To solve this issue, the worm had to be designed in such a way that it could be driven. This process will be discussed later in the discussion.

When the tractor regains traction, the tag axle mechanism will experience intense forces as the rotation of the tag wheels (now rotating at the same, higher speed of the drive wheels) feeds back into the mechanism. Because the tag wheels are directly connected to the tag axle which is directly connected to the worm gear assembly, these components will always rotate together. While this interaction may be acceptable for the worm-ring assembly, which was designed to be non-self-locking, it is not acceptable for the electric motor to be driven by the tag axle as the main drive wheels regain traction.

For this reason, a method of engagement and disengagement is necessary between the motor and worm gear. To accomplish this, the worm gear was modified to mate with a Bendix drive mechanism. The Bendix drive is attached to the motor shaft, and remains retracted under normal operations of the truck, meaning the electric motor is not attached to the worm gear. When the truck loses traction and the system is needed, the electric motor powers on, providing torque to the Bendix drive. This torque winds a spring internal to the Bendix, causing it to advance and engage with a splined collar at the end of the worm (See Figure 11).

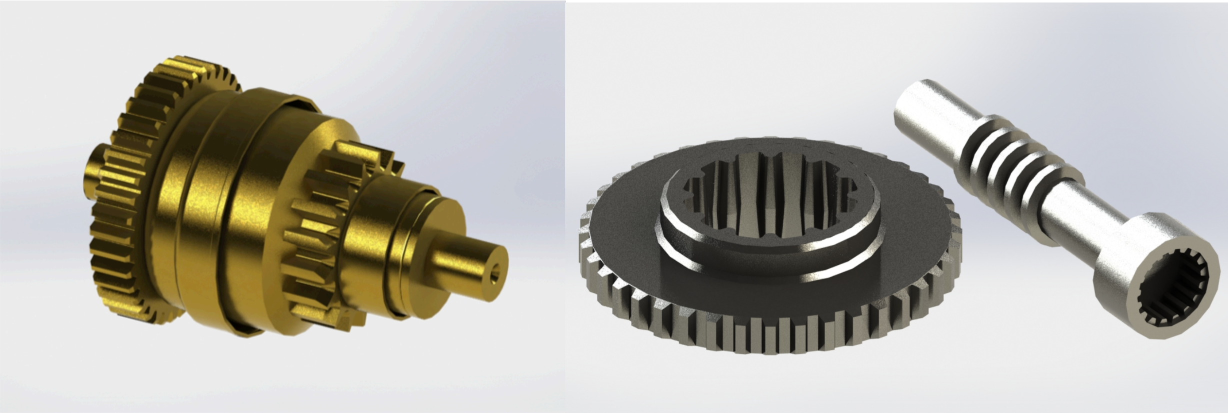


Figure 11: The Bendix drive (left) mates with the splined collar of the worm gear (far right)

When fully engaged, the electric motor is able to transmit power through the worm gear and to the wheels of the tag axle. When the truck does regain traction and the main drive wheels begin powering the tag axle, the electric motor quickly shuts off, so torque and the outward force is no longer provided to the Bendix drive. The Bendix drive then retracts, disengaging from the worm and ensuring that the motor does not receive rotational feedback from the wheels.

With the primary mechanical components identified, the group focused their attention on creating a protective housing for the entire assembly. The domed housing of the standard Daimler drive axle provided an appropriately-sized, protected envelope for the components, and required no modification for compatibility with the team's mechanism. The open end of the axle includes a mounting surface with bolt holes, to which a housing could be attached, and so the group designed their housings around these geometries to ensure proper fit.

To support and align the mechanical components with the tag axle shaft, a gearbox insert was designed (See Figure 12). This insert included the supports and bearings necessary to support the worm-ring gearset, and was made to self-align when inserted into the axle housing. A motor covermount sandwiched the insert with the axle housing, and provided support for the electric motor. A vented cap was designed to bolt to the exposed end of the motor and covermount, fully enclosing the internal components from the environment. These designs were chosen to improve manufacturability and ease of assembly.

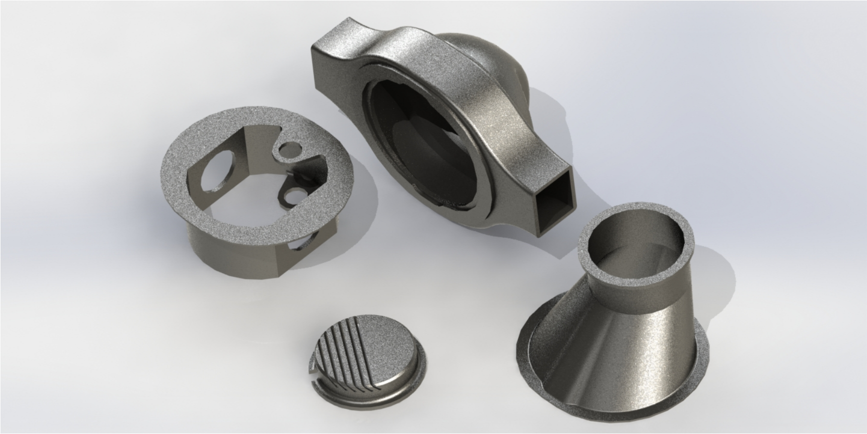


Figure 12: Counterclockwise from upper left: gearbox insert, covermount cap, motor covermount, and axle housing

In all, this final system design offers many distinct advantages in terms of the design criteria. In terms of design simplicity, the proposed system utilize pre-existing and proven axle housings to simplify manufacturing and assembly, and draws power from the existing battery bank rather than utilizing a separate, add-on supply. With a relative limited number of moving components, the mechanism should offer reliable usage over its service life, and also allow for easier and faster repair and replacement of components.

The proposed system also satisfies the criterion for power, providing 1120 ft-lbs of torque to add on a factor of safety to the requirement of 941 ft-lbs deemed necessary in the mechanical analysis. The highest possible cost of manufacturing the system was set at $1500 by Daimler. This will be detailed in the budget section of the report, but the system is able to satisfy this criterion because of the low cost of the electric motor. Likewise, the system is able to satisfy the low weight requirement because of the lightweight motor. Lastly, the proposed system design satisfies the modularity criterion. This, again, is because the system connects only to the drive axle at existing connection points. This makes the system ideal as an add-on option that customers can order when purchasing a 6X2 tractor. Overall, the final system design, seen in Figure 13, is a very efficient and versatile solution to the engineering problem proposed in this report.

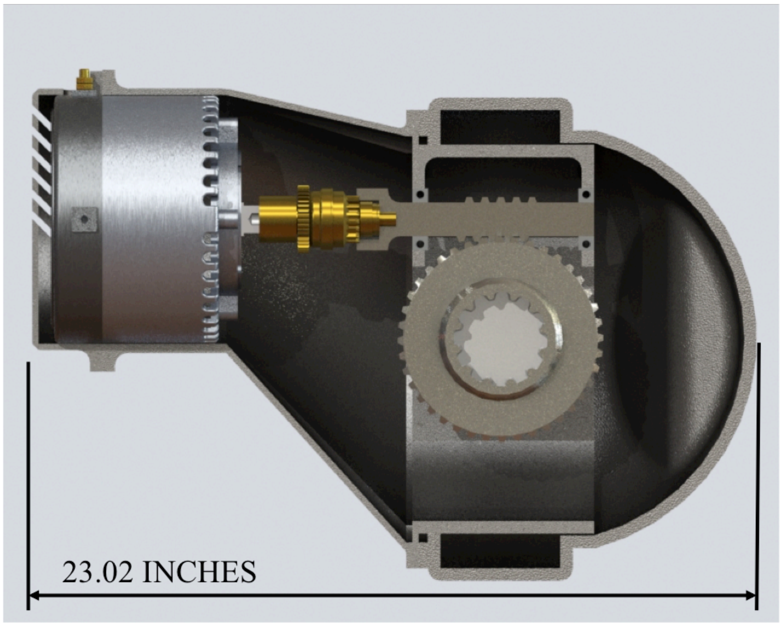
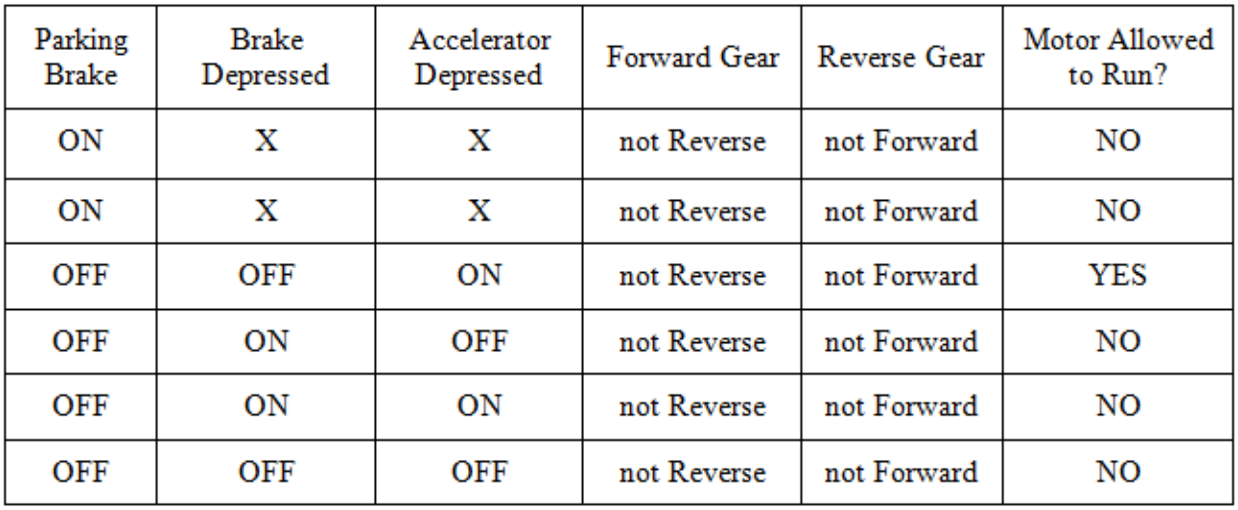


Figure 13: Cutaway view of assembled and packaged tag axle traction system

The electronic control system final design consists of an analog to digital converter that converts the analog sinusoidal wheel speed sensor signal, an arithmetic logic unit which subtracts the tag axle wheel speed from the powered axle wheel speed, and an H-bridge motor control circuit that sends power to and controls direction of auxiliary motor drive. The arithmetic logic unit continuously compares the two wheel speeds with four bits of resolution affording 16 levels of comparison. The triggering mechanism consists of sending a signal to the H-bridge motor control circuit whenever a certain threshold is seen. The threshold consists of 3 bits which can be customized with the 4 bits of resolution from the logic unit. Once the threshold is exceeded a signal is sent to the motor control circuit which actuates the motor in the appropriate direction.

The directional control circuit uses logic and sensors from the transmission to detect forward or reverse direction of the truck. Using this information, the motor direction is regulated. The control circuit is also fed information regarding brake usage, gas pedal depression, high speed sensor, and cab switch activation in order to activate or deactivate the entire system. The system is deactivated once truck speed exceeds 15 mph. Lacking any real interface with a real vehicle, all signals are simulated using switches that are either on or off, signaling the condition of each system check. Table 6 below shows some conditions that affect the operation of the circuit. It also shows that, for safety purposes, the auxiliary motor can only turn on when the brakes are off and the accelerator is being depressed.

Table 6: Usage Case Scenarios and Motor Availability



Parking Brake	Brake Depressed	Accelerator Depressed	Forward Gear	Reverse Gear	Motor Allowed to Run?
ON	X	X	not Reverse	not Forward	NO
ON	X	X	not Reverse	not Forward	NO
OFF	OFF	ON	not Reverse	not Forward	YES
OFF	ON	OFF	not Reverse	not Forward	NO
OFF	ON	ON	not Reverse	not Forward	NO
OFF	OFF	OFF	not Reverse	not Forward	NO

The arithmetic logic circuit was drafted using B2Spice and the resulting schematic provided a wiring diagram for use when making the connections on the circuit board. The analog to digital converter and the motor control circuit were simple enough to be simply drafted with pen and pencil and wired to spec without any debugging or simulation necessary. Basic formulas for inverting operational amplifier gain as well as Schmitt trigger threshold voltages were used to amplify a small abs signal and generate square wave pulses.

The analog to digital converter subcircuit is shown on the top and the motor control circuit on the bottom in Figure 14.

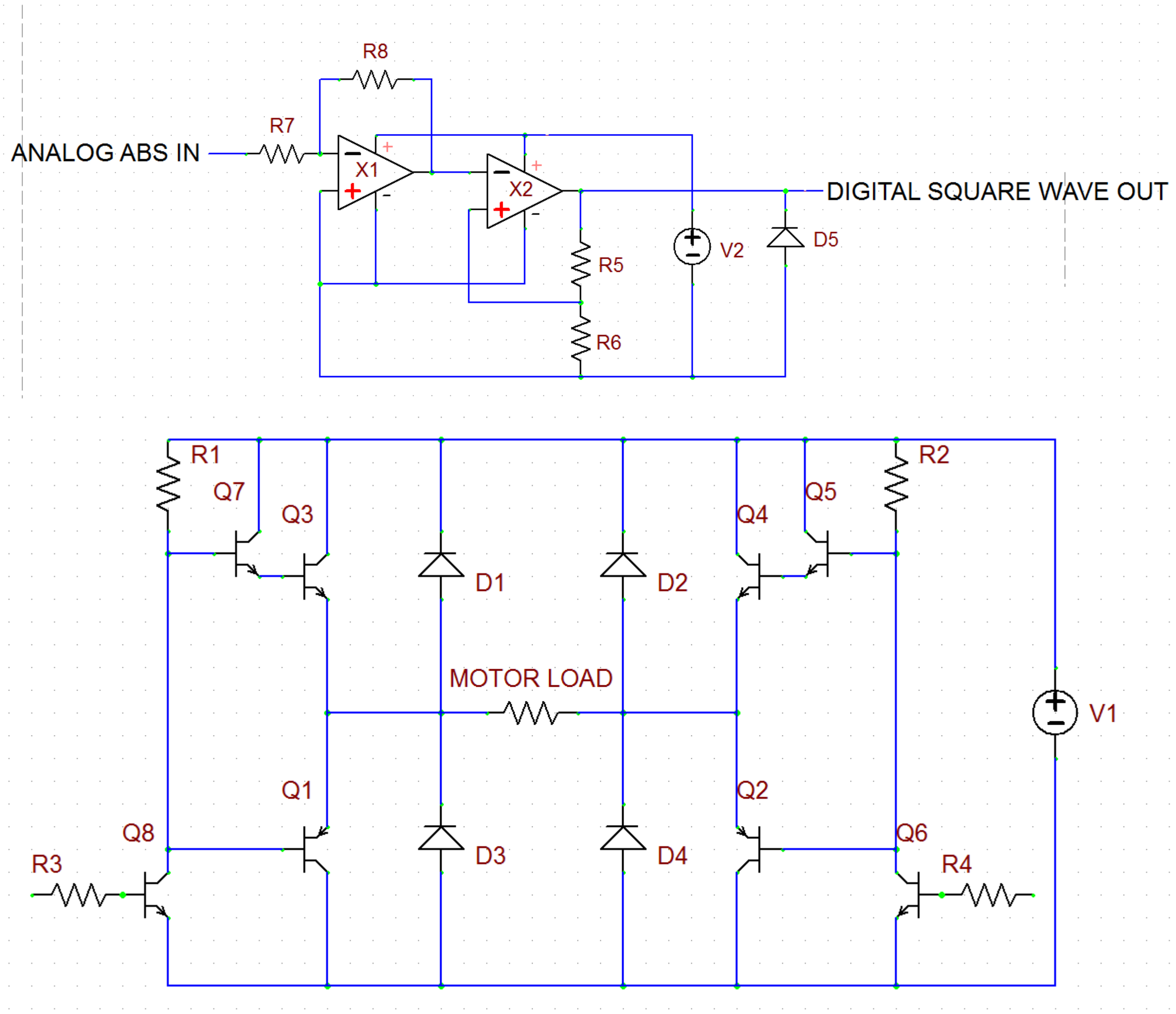


Figure 14: Analog to digital converter and motor direction control circuit

The arithmetic logic unit is shown below in Figure 15.

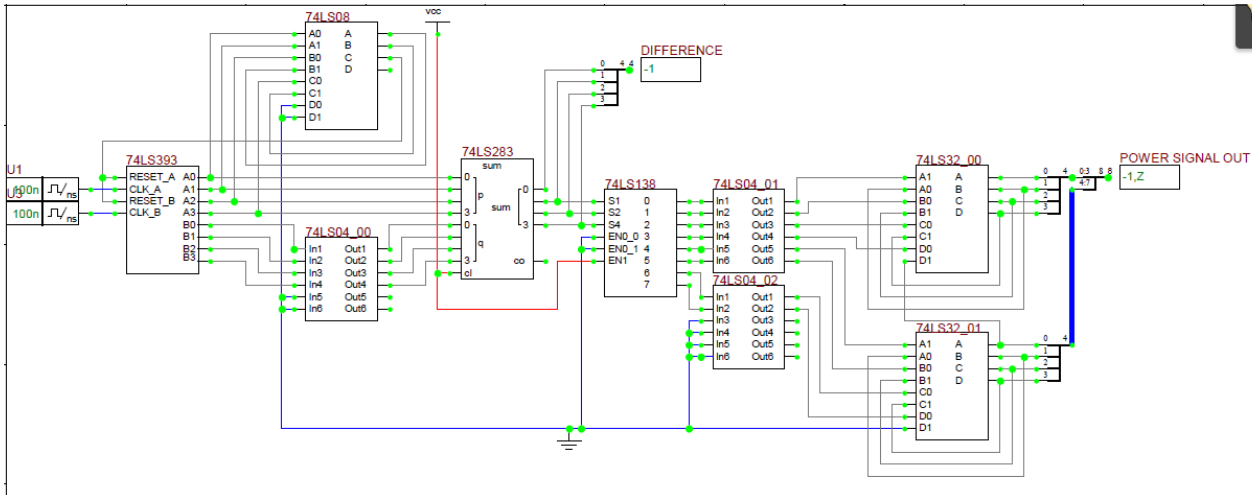


Figure 15: Arithmetic logic unit

Table 7, located in the Budget section, includes the bill of materials for the components required to build this circuit. These were all off the shelf parts which totaled less than $10 as most were provided through the senior engineering lab for free, with only special order components such as the power transistor and dual operational op amp integrated circuit purchased independently.

Design Validation - CAD Modeling and Physical Prototyping

Due to the size and complexity of the mechanical apparatus, computer-aided design software was used extensively for geometric design and validation. SolidWorks® 3D CAD software was used to design particular components, visually compare the size and compatibility of particular components, and to compute part volumes for the weight calculations.

Some elements of the tag axle assembly had accessible engineering drawings from which dimensions and geometry could be gleaned (primarily the motor and axle housing); once modeled, these components were used to design and size other components to ensure compatibility - for example, the motor covermount was modeled using dimensions from both the axle housing and the motor, to ensure proper fit with both. In some cases, the models were simplified for time efficiency - features such as bolt holes were omitted, but sufficient clearance for these items was incorporated into the model to ensure that these features could be added in later and more refined iterations.

For the prototype circuit, function generators were used to simulate wheel speed sensor signals from the drive axle and the tag axle, feeding signals to the control circuit. To test for proper operation, the signal generators were set at varying frequencies which simulated varying wheel speeds. When the two signal generators were at the same frequency, the control circuit indicated an operational light signaling that it was powered and currently detected a difference of zero. When the function generator simulating the tag axle was set at a zero frequency representing slip conditions, the control circuit immediately registered a maximum difference of 8 and actuated the electric motor of the ⅓ - scale prototype depicted in Figure 16.

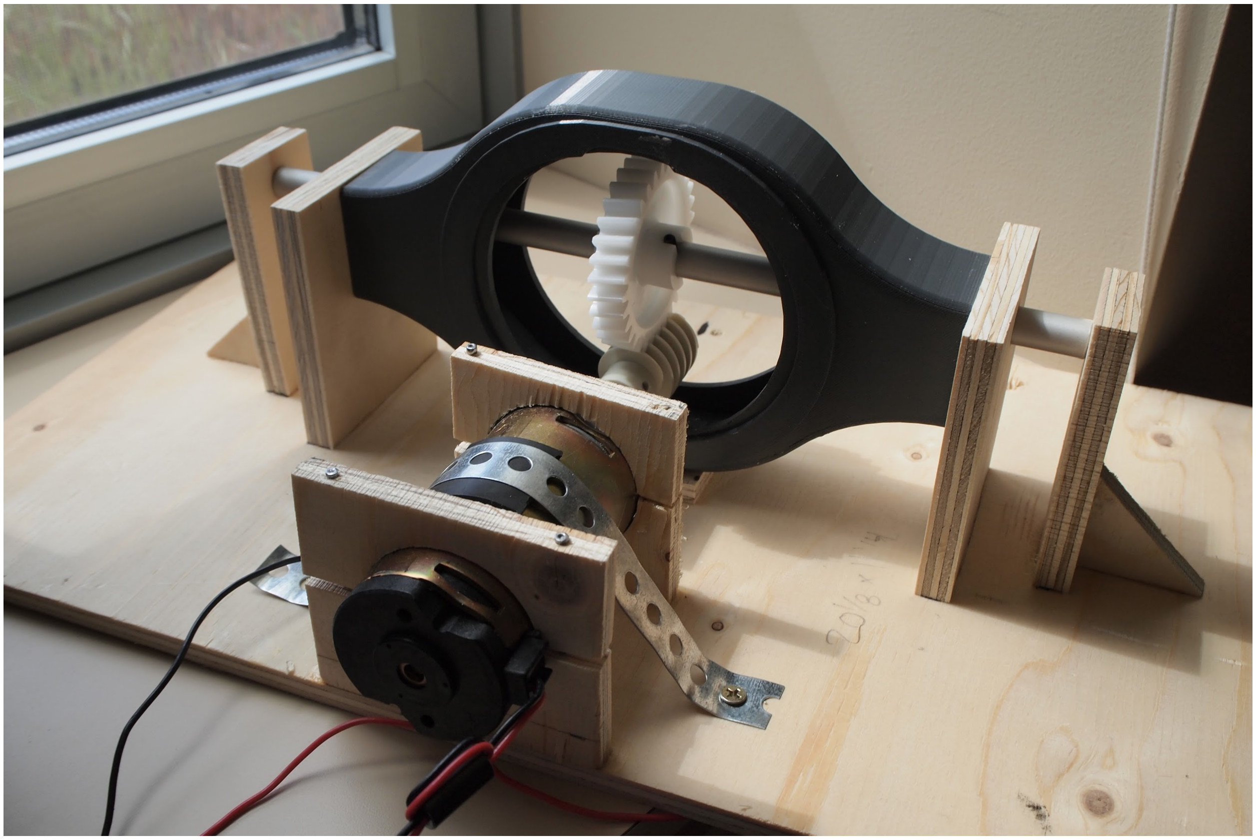


Figure 16: ⅓ scale mechanical prototype (red and black wires link motor to the control circuit)

When the function generator simulating the tag axle was set at varying frequencies lower than the drive axle, the control circuit responded appropriately by tracking the difference between the two wheel speeds as a difference up to a maximum of 8. The direction of the motor was tested using a switch that simulated the reverse gear sensor of the truck. When the switch was in the depressed position signifying a reverse direction, the motor was operated in a reverse direction. A switch bank was used to simulate an on and off switch for the whole system and for other redundancies such as brake on or gas applied. Given the state of the switches as above in Table 6, the circuit performed as expected.

Professional Responsibility

The project required the sharing of internal information from Daimler Trucks of North America to the P'TATA group. With the sensitive information, the group was responsible in keeping the information confidential and using the information towards the main advancement of the project. There were weekly communication and meetings between the student group and the industrial adviser. Ideas, plans, and progress were reported and discussed. There were instances when deadlines were not met between the parties, but emails were sent as reminders. Unfortunately, these events caused delays but the group kept on working to stay on schedule.

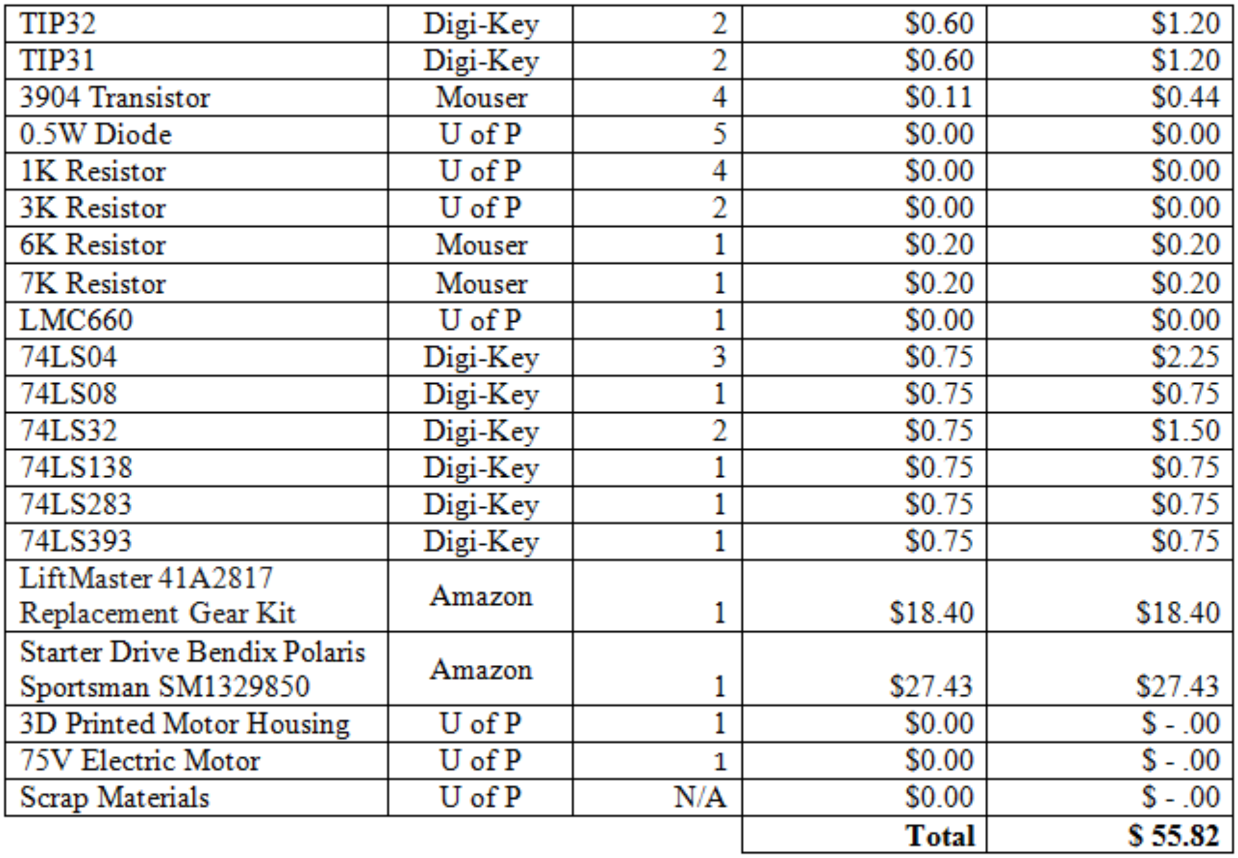
When doing research, the group encountered designs from other manufacturers, but the group decided to pursue its own designs due to the nature of the project. Questions and concepts were not only discussed with the industry advisor, but also with the academic advisor and various other professors. When trying to make a decision, the group made sure it was the most suitable from inquiries and research performed.

The initial goals of the project were ambitious and proved to be too demanding of the group. Over the two semesters, the two parties realized what a college capstone group is capable of doing with the resources provided and adjusted the benchmarks accordingly. It would have not been professional nor a good idea to rush the work and reach erred results. In conclusion, clear communication between the parties is an essential part of professional responsibility.

Budget

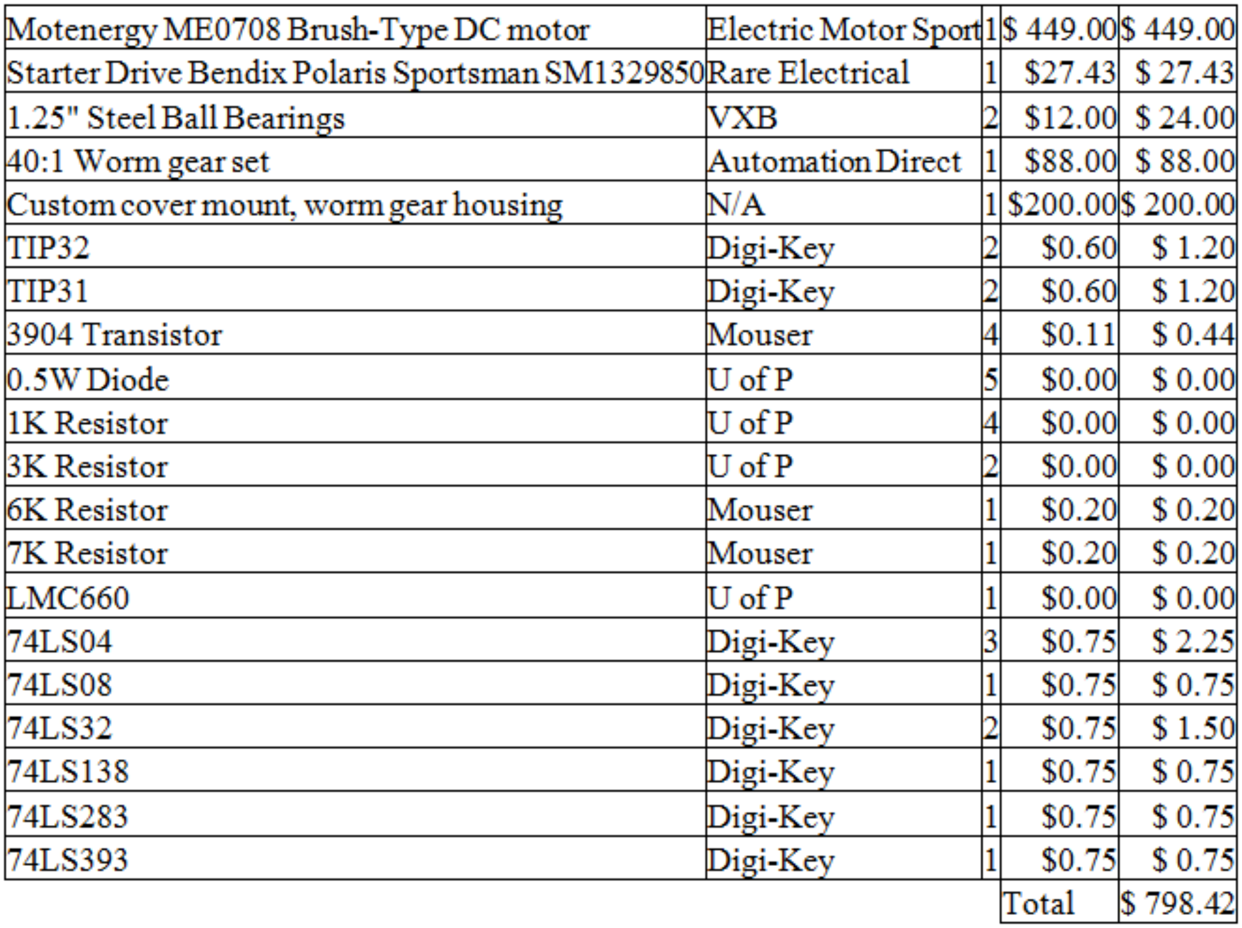
Two budgets had to be created for this project, the first for the proof-of-concept prototype that was made and the second for the full-scale system that was developed as a CAD model. Table 7 shows a bill of materials for the electrical and mechanical components necessary to make the □ scale prototype. Table 8 offers a bill of materials for the final design described in this report. This includes the full-scale electric motor, worm gear assembly and Bendix drive. The custom covermount and worm gear support are not included in the budget because the cost to make these components is unknown. Likewise, cost of fasteners, the axle shaft, and the drive axle housing are not included in the budget because only Daimler knows the cost to produce these components. The team had a budget of $30,000 through Daimler, and all purchases were made through Daimler. As a design constraint for cost, the team had to ensure the proposed system would have a manufacturing cost less than $1500. The team succeeded, producing a system that is less than $800. It must be noted, however, that this budget does not include cost of labor.

Table 7: Bill of materials for small-scale prototype



TIP32	Digi-Key	2	$0.60	$1.20
TIP31	Digi-Key	2	$0.60	$1.20
3904 Transistor	Mouser	4	$0.11	$0.44
0.5W Diode	U of P	5	$0.00	$0.00
1K Resistor	U of P	4	$0.00	$0.00
3K Resistor	U of P	2	$0.00	$0.00
6K Resistor	Mouser	1	$0.20	$0.20
7K Resistor	Mouser	1	$0.20	$0.20
LMC660	U of P	1	$0.00	$0.00
74LS04	Digi-Key	3	$0.75	$2.25
74LS08	Digi-Key	1	$0.75	$0.75
74LS32	Digi-Key	2	$0.75	$1.50
74LS138	Digi-Key	1	$0.75	$0.75
74LS283	Digi-Key	1	$0.75	$0.75
74LS393	Digi-Key	1	$0.75	$0.75
LiftMaster 41A2817 Replacement Gear Kit	Amazon	1	$18.40	$18.40
Starter Drive Bendix Polaris Sportsman SM1329850	Amazon	1	$27.43	$27.43
3D Printed Motor Housing	U of P	1	$0.00	$ - .00
75V Electric Motor	U of P	1	$0.00	$ - .00
Scrap Materials	U of P	N/A	$0.00	$ - .00
			Total	**$ 55.82**

Table 8: Bill of materials for final system design



Motenergy ME0708 Brush-Type DC motor	Electric Motor Sport	1	$ 449.00	$ 449.00
Starter Drive Bendix Polaris Sportsman SM1329850	Rare Electrical	1	$27.43	$ 27.43
1.25" Steel Ball Bearings	VXB	2	$12.00	$ 24.00
40:1 Worm gear set	Automation Direct	1	$88.00	$ 88.00
Custom cover mount, worm gear housing	N/A	1	$200.00	$ 200.00
TIP32	Digi-Key	2	$0.60	$ 1.20
TIP31	Digi-Key	2	$0.60	$ 1.20
3904 Transistor	Mouser	4	$0.11	$ 0.44
0.5W Diode	U of P	5	$0.00	$ 0.00
1K Resistor	U of P	4	$0.00	$ 0.00
3K Resistor	U of P	2	$0.00	$ 0.00
6K Resistor	Mouser	1	$0.20	$ 0.20
7K Resistor	Mouser	1	$0.20	$ 0.20
LMC660	U of P	1	$0.00	$ 0.00
74LS04	Digi-Key	3	$0.75	$ 2.25
74LS08	Digi-Key	1	$0.75	$ 0.75
74LS32	Digi-Key	2	$0.75	$ 1.50
74LS138	Digi-Key	1	$0.75	$ 0.75
74LS283	Digi-Key	1	$0.75	$ 0.75
74LS393	Digi-Key	1	$0.75	$ 0.75
			Total	$ 798.42

Conclusion

An electro-mechanical add-on system was designed to meet the criteria presented by Daimler Trucks of North America. This system provides 1120 ft-lbs of torque to the tag axle, remains lightweight at 99.5 lbs (not including the weight difference between drive axle housing and tag axle housing) compared to the 380 lb differential and is cost-effective at $798.42 out of the allotted $1500 (rough estimate not including manual labor). It is capable of getting the truck out of slip on a 4% gradient of sleek ice at 15 mph. The add-on also does not require significant alterations to the existing tag axle design. It employs one Motoenergy ME0708 BT DC motor to power the tag axle. In between the two there is a Bendix that can engage and disengage to a 40:1 worm gear box that multiplies the torque delivered. The power source comes from the truck's battery. The electronic control system design can identify slip conditions and actuate the motor to allow the truck to recover. A flowchart and block diagram of the electronic control circuit, parts were ordered and a prototype was built in the Spring semester. Once the prototype control circuit was functioning properly, a circuit board was prepared and readied to accept the components of the control circuit. The circuit board was then tested for proper wiring and then tested again to ensure proper operation.

Recommendations

During the final weeks of the project, the team identified a number of design alterations that would be necessary for the manufacturability and functional viability of the traction assistant. Additionally, the industry advisor advanced some further design optimization requests during meetings held in that time period. Because these modifications were identified so close to the end of the project, the team was unable to integrate them into the existing final design; however, they must be addressed in further iterations of the traction assist design to ensure the proper functioning and durability of the device.

The electronic control circuit could be improved with a hold timer ensuring that the system does not cycle rapidly during a short time period, thus reducing stress and wear on the mechanical components and the electrical motor. The use of a high voltage 3-phase motor will also improve power and efficiency. A stand alone motor control circuit included with a 3-phase motor can be directly couple with the existing circuit. For circuit simplicity, one could transfer the logic over to a microcontroller for added flexibility and functionality. The best implementation of the circuit would be the design of a custom application specific integrated circuit which would provide very reliable and robust operation.

If a high voltage 3-phase electric motor was chosen, the great increase in horsepower would mean less of a gear reduction would be necessary. This would be beneficial because the use of a worm gear would not be necessary. Using a different means of gear reduction would remove the concerns regarding self-locking of the worm gear. Self-locking of the worm gear would likely destroy the teeth of the assembly. For a future improvement, the worm gear would be replaced with a spiroid gear, which offers high gear ratios without the concern of self-locking.

More work must be done for the engagement/disengagement interface for the system. The Bendix drive must first be tested in a full-scale analysis to ensure that it can sustain the significant forces involved when the system transitions from powering and depowering the tag axle. The Bendix drive offers great advantages in terms of weight and spatial requirements, but these advantages are meaningless if the Bendix drive is too weak to act as a method of engagement and disengagement. If the Bendix drive is too weak for this application, a dog clutch system or shift fork system would have to be designed. These systems would be stronger, but they would also make the system significantly more complicated and heavy. The engagement/disengagement interface should also be moved from between the electric motor and worm gear to a position along the axle shaft. This would ensure that the worm gear is not continuously spinning during normal operation of the truck. Rather, the gear assembly would only move when the motor is providing power to it. This would ensure little wear occurs on the gears, improving the life of the system. These changes would greatly enhance the functionality of the system.

Final enhancements to the system would require testing and prototype iterations. These enhancements would include optimizing components in terms of material type as well as refining the supports for the system. The covermount and the dome of the axle housing could be made of some type of plastic, which would significantly reduce weight. Alternative methods of supporting the system could also be designed if problems exist with the current support structure proposed in this report. However, the current support structure offers great advantages because it requires minimal modifications to the currently used domed axle housing. Future redesigns of the support structure must offer this same advantage.

Overall, the proposed system that was developed through this project offers an ideal solution to the original problem proposed by Daimler. Future work on the system should start with full-scale testing and analysis, before more complicated redesigns are pursued.

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