DESIGNING A PERSONNEL TRANSPORT VEHICLE FOR UNDERGROUND COAL MINES USING PARAMETRIC MODELLING

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ABSTRACT

Safety and ergonomic deficiencies in current personnel transporters used in Australian underground coal mines have led to a research project to design a new vehicle concept for low volume production.

A Vehicle Design Specification was developed from the results of initial research including: a literature review into the specific human centred issues, a study on commercially available powertrain and driveline components, a review of the mining codes and discussions with industry sponsors. Packaging studies were conducted with the use of NX Human software to perform comfort assessments and acquire reach zone data. A full-scale physical buck was used to evaluate these layouts. This served as the basis for the interior design, which focused on addressing ergonomics, safety, durability and ease of manufacture and assembly. The suspension and chassis were designed using parametric modelling techniques with CAD software such as: Unigraphics NX7, NX Nastran, and Susprog 3D.

The concept vehicle has been designed to address the deficiencies noted in existing vehicles through the following improvements: seats with geometry to provide adequate occupant spacing and headroom, facilities to assist with ingress, egress and travel over rough terrain, and a simple and logical dashboard user interface. To facilitate best ergonomic practices as well as performance requirements, the concept utilises a custom suspension system with hydrostatic wheel motors powered by a diesel engine located at the front of the vehicle. The power-source can be upgraded to an electric motor should the market shift to this technology in the future. The vehicle design utilises principles of symmetry, repetition and modularity to cater for low volume production. Further research is to be conducted detailing the vehicle concept hopefully leading to the production of a working prototype.

1. AIM

This paper presents how a multiple media and disciplinary process was used to design an improved personnel transporter for underground coal mining in an industry that typically uses outdated design methods. Techniques utilised included: Literature surveys, extensive use of Computer Aided Design (CAD) tools, sketching, scale models, full size drawings and physical models. These methods were conducted with a unified application of Industrial Design and Mechanical Engineering principles. Although this approach is common in the automotive and consumer goods industries, it is rarely used in the mining industry. This provided an opportunity to make significant improvements over existing vehicles, particularly in the areas of user ergonomics and safety.

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2. BACKGROUND

Personnel transporters that are currently used in Australian underground coal mines have been found to be poor in terms of ergonomics and safety (Burgess-Limerick, 2005, Horberry, 2004). The aim of this project was to design a new personnel transporter using human-centred design principles in order to improve the wellbeing of the users. The purpose was to produce a new vehicle concept that would establish benchmark standards of safety and comfort within the industry with the view that the work would hopefully lead to production of a working prototype within the next few years.

Personnel transporters are used to take work teams of 10-12 miners, through the mine to the coal face where their work is carried out and then bring them back at the end of their shift. Throughout the day the vehicles are used to transport light equipment within the mine and often carry only two occupants.

Figure 1: Current personnel transporters parked outside mine (author’s image)

The underground coal mine environment poses some unique challenges that need to be considered. The most critical of these include:

- Restriction on vehicle height due to the ‘seam height’ of the underground mine.
- Substantial ground clearance requirement due to the terrain of certain areas.
- Volatile environment poses limitation on surface temperatures and use of electronics.
- Enclosed environment increases exposure to diesel particulates and other emissions.

Preceding the current project a report was produced as a result of an ACARP (Australian Coal Association Research Program) funded project (Dayawansa et al., 2006). Part of this report detailed the preliminary conceptual development for a new personnel transporter. The report provided specifications for the current project including:

- The design would be a small vehicle carrying five occupants.
- Ergonomic design would improve passenger safety and comfort.
- Modern construction techniques and light weight components would be used to reduce vehicle mass, improving ride quality.
- The design would focus on reducing emissions.
- Cost would be reduced though repetition of parts.
The current project is funded by the ARC (Australian Research Council) and two industry partners; namely, Rio Tinto and PJ Berriman (a manufacturer of current personnel transporters). The concept vehicle developed is the Compact Mining Personnel Transporter™ (CMPT™), innovation patent pending.

2-1. Project Team

The project group included three chief investigators, two research assistants, one representative from each industry sponsor, two masters’ students and contained members from both Industrial Design and Engineering faculties. The core team consisted of an Industrial Design masters student, a Mechanical Engineering masters student (with a background in both engineering and design) and one Industrial Design research assistant.

3. METHOD

Close collaboration between Industrial Design and Mechanical Engineering methods was used to ensure that the goals of the project were addressed in all areas of the vehicle development and a cohesive design was produced. Each member of the core team undertook a number of design tasks to develop their areas of the vehicle. The Mechanical Engineering masters student focussed on the design of the mechanical systems, the Industrial Design masters student developed the design of the interior and the Industrial Design research assistant worked on the exterior design. Members of the core team worked together on a daily basis and consulted with each other when making critical decisions. Meetings involving the entire project group were held monthly during the initial stages of the project and once every two months after that. These meetings were organised by the students and design progress was presented, reviewed and crucial decisions were made.

3-1. Literature Review

The Industrial Design masters student conducted a literature review on the different safety and ergonomic issues in the use of underground mining equipment and specifically, personnel transporters. The results of the investigation were:

- Rough roads and Whole Body Vibration (WBV) were identified as the main contributors to passenger discomfort and safety issues (Burgess-Limerick and Steiner, 2006, McPhee et al., 2001, Dayawansa et al., 2006, Mayton et al., 2008).

- It was discovered that three vehicle features could be improved to address the issues of Rough roads and WBV:
  - Seating - improved seat suspension can reduce effects of vibration, improved seat cushion and shape design can provide better support for the users' body and rear or forward facing seats would be safer for the users than the side facing 'troop' seating that is commonly used in current designs (McPhee et al., 2001, Kuttusamy and Buchholz, 2004, Brookes, 2004).
  - Restraints - in addition to their use in collisions (Cook et al., 2008), appropriate harnesses can prevent injuries caused by the occupants being thrown from their
seats when the vehicle hits a pothole or other roadway abnormalities (Burgess-Limerick, 2007).

- Visibility - better visibility would provide the driver with an improved chance of seeing and avoiding roadway abnormalities as well as collisions, reducing the chance of injuries. In addition, improved forward visibility for the passengers could allow them to identify and brace for rough areas of the road (McPhee et al., 2001).

- Additional issues to focus on are vehicle ingress/egress (Burgess-Limerick and Steiner, 2006) and equipment storage (van der Beek et al., 1993).

The findings from the literature review provided a set of requirements for the design of the vehicle and more specifically the design of the interior and human interface. Throughout the design process, the conclusions from the literature review were referred to by all members of the team to inform elements of the design.

3-2. Mechanical Research

A survey on commercially available mechanical components was conducted by the Mechanical Engineering masters student to inform the initial design phase of the project. The specification for the survey was a vehicle with a target mass of 2500kg, requiring approximately 50kW of power, and four-wheel drive capability.

The key factors for engine selection included: availability, power, fuel consumption, emissions rating, weight, physical size (in particular height) and flame-proofing (mine rated). The engine that best met the desired criteria was the Kubota V2607-DI-T, which was used to perform the packaging studies.

Transmissions required for mine vehicles must be heavy duty and able to withstand mistreatment from drivers. Manual transmissions were deemed to be too challenging to operate within the mine environment and standard automatic transmissions too weak, according to the industry representatives. Industrial ‘Power-shift’ transmissions that are currently used were found to be too large and heavy, making hydrostatic transmissions a more attractive alternative. This led to the idea of decoupling the pump and motor side of the hydrostatic transmission to produce a more flexible drive system, with significant packaging benefits.

Investigation of commercially available axles, including consultation with suppliers was conducted to find a suitable axle. The coal mine environment dictated the need for wet-brakes, which were incorporated only in axles that were too heavy. Using aftermarket wet-brakes on automotive axles was considered, however commercial limitations, due to proprietary restrictions, was a barrier.

As ride quality for the occupants was a major objective for the project, extensive research was conducted on suspension systems with consideration of suitable chassis types. Particularly important during the early development of the CMPT™ was the influence of the suspension on the overall occupant and vehicle package.

The review of suspension systems was based on general guidelines established from the project brief. These include requirements for the vehicle to have; all four wheels driven, a
ground clearance of roughly 250mm, wheel travel of at least 200mm, low volume manufacturability, and simple maintenance procedures.

A live axle, with leading / trailing links is the simplest form of suspension that could be used for the CMPT™, and is the type used in current personnel transporters. The unsprung mass of a driven live axle system is considerably higher than that of an independent setup for the same vehicle. This system is highly dependent on the availability of a suitable axle that is light enough but can also withstand the rigors of the mine environment.

Independent suspension systems were reviewed because of their inherent comfort and performance advantages, these included:

- Double Wishbone - enables design of elasto-kinematic performance, providing an optimum compromise between comfort and handling. Though there is greater complexity due to the extra wishbone compared to McPherson struts, the wishbones themselves suit low volume production.

- McPherson Strut - require the shock absorber and coil springs to be located in a higher and therefore less stiff area of the chassis, decreasing performance (Reimpell et al., 2001). Additionally, the structural function of the shock absorber causes hysteresis which reduces comfort (Genta, 2009).

- Swing Arm (Rear only) - Swing arms are the simplest form of Independent Rear Suspension (IRS), but have the disadvantage of causing large camber changes during the suspension travel, making cornering unpredictable (Stone and Ball, 2004).

- Trailing Arm - offers no camber control through the suspension stroke. However since the rotation axis is in the transverse vehicle direction (Y), there is no camber change during wheel travel (Reimpell et al., 2001).

- Semi-Trailing - utilise an inclined rotation axis in the XY (transverse and longitudinal) and ZY (vertical and longitudinal) planes, which makes it possible to tune the elasto-kinematic performance.

- Guided-Trailing arm (Rear only) - offer further improvement over semi-trailing arms through utilisation of additional linkages, while maintaining the packaging advantages. However, the many adjustment points increase assembly complexity (Genta, 2009)

3-3. Vehicle Design Specification (VDS)

Initial project research, results of the previous ACARP project and parameters developed using vehicle package exploration were used to produce a Vehicle Design Specification (VDS). The VDS was also informed by knowledge gained from a visit to Ravensworth underground coal mine and PJ Berriman in Newcastle, NSW. Key findings from the visit to Newcastle were:

- Rough treatment by the users has a large influence on the design of the vehicles.
- The environment creates issues including corrosion, and clogging of mechanisms.
PJ Berriman produces 15-20 vehicles a year using low volume production techniques.

Vehicles are serviced and inspected regularly (walk around once a day, weekly service, monthly major service). They typically require frequent maintenance and an overhaul after five years of use.

During the visit, the VDS was reviewed by PJ Berriman and changes were made. Some key features of the final VDS were:

- Vehicle shall carry five occupants and be convertible to increase equipment storage
- Maximum vehicle height: 1750mm
- Minimum ground clearance: 250mm
- No aluminium due to sparking concerns
- No side facing seats
- Capable of at least 35km/h and a grade-ability of 25%
- Engine requires an exhaust conditioner (scrubber)
- Vehicle requires water, pneumatic, and hydraulic fluid tanks

3.4. Preliminary Packaging Studies

As the VDS was being produced, the core team worked together on preliminary packaging studies that explored the different possible layouts for the vehicle. Parameters used for the packaging studies included:

- Anthropometric data of a 95th percentile male (Pheasant, 2006)
- Seat and backrest angle ranges of 10° - 22° and 90° - 120° respectively (Tilley, 2002, Grandjean, 1980)
- A recommended downward visibility angle of 15° (Tilley, 2002)
- Optimal equipment loading height between 508mm and 1270mm (Lin and Harvey Cohen, 1997).
- Manufacturer specifications of mechanical components were used for their sizes.

Thirty vehicle layout ideas were produced to explore the range of options available. The finalised VDS was used to refine these down to five chosen ideas.

Figure 2: One of the thirty initial layout ideas
3-5. NX Human

To perform a more detailed analysis of the vehicle layout concerns, further packaging studies were conducted using Unigraphics NX7 and NX Human software and included more of the components required in the vehicle than the previous study. The studies were conducted by the Mechanical Engineering masters student in consultation with the Industrial Design masters student on the ergonomic and safety requirements.

Some features of the NX Human software include the ability to model a range of humans from a 5th percentile female to a 95th percentile male. The integrated posture library in NX Human assisted in establishing baseline postures for driving and seating. Changes made to posture were able to be evaluated using the built-in ‘Comfort Assessment’ tool. Reach zones were mapped and used to identify the range of seat motion required. These reach zones will be used in more detail for the positioning of controls and switches which will take place in the detailed design of the interior. The decisions made from the 3D packaging studies were:

- It would be unfeasible to have the occupants sitting in between the wheels over an axle due to ingress/egress difficulties and insufficient head room.
- A rear mounted engine should be used to increase forward visibility in the case that rigid axles are used.

Results and dimensions from the digital study were used as a guideline for the creation of a 1:1 scale physical ergonomics testing rig, called a ‘Buck’.

3-6. Buck

A 1:1 scale buck was created by the core team to help make informed decisions on the ergonomics and layout of the vehicle. The Buck allowed for the following adjustments:

- Seat, backrest and headrest angles
- Seat positioning
- Engine and scrubber position
- Floor height
- Wheelbase
- Firewall, B-Pillar and C Pillar position
As a result of the Buck study the whole project group made a number of decisions. These included:

- A front mounted engine was required to increase the versatility of the rear section. This meant that a live axle could not be used at the front due to visibility concerns.
- The general seating layout was approved, with a backrest angle of 115° and seat angle of 12.5° from horizontal with a seat spacing width of 550mm between centres.
- It was decided that the design of the vehicle should accommodate a future conversion from a diesel to an electric power source. The advantages of an electric power source would include reduced emissions, noise and hopefully reduced power train size. It was decided that the design of the vehicle should be such that when the electric power source is introduced the overall design of the vehicle would not need to be significantly modified.

3-7. Interior Development

The interior design was developed by the Industrial Design masters student with consistent reference to the results of the literature review. Initial ideation for the interior began, using sketching, as the buck was being produced.

Six potential design directions for the interior system were developed and assessed by the whole project group. From the feedback received, one of these was chosen to be developed further, incorporating desirable features from the others. The development of the chosen idea was conducted using scale mock-ups and sketch work. Two specific areas of the interior required the most attention. The dashboard was the first, as it is the main interface for the user. The second was the rear section of the interior which needed to accommodate a conversion from occupant area to equipment storage space. Multiple designs were produced for the conversion process and one was chosen by the whole project group. The choice was based on a compromise between the interior design goals, occupant packaging, engineering concerns and vehicle marketability. This was indicative of how many design decisions were made; with a consideration of the vehicle as a whole. To ensure that the design of the interior components could fit with the rest of the vehicle, a 3D model was produced in conjunction with the models from the other areas of the vehicle.
3-8. Exterior Development

The Industrial Design research assistant developed the exterior design around potential construction techniques and minimising production costs for the vehicle. Early concepts were based on chassis and packaging variations. As the chassis developed and the vehicle package evolved, a number of the concepts were eliminated and a chosen exterior direction was developed further.

Figure 5: Potential interior design directions

Figure 6: Exterior design development
3-9. Parametric Modelling

Unigraphics NX was used as the primary software package for the design of the CMPT™ chassis, driveline and overall layout. The model was set up with expressions driving all critical dimensions to allow design changes to be made easily, which not only streamlined the design development but also offered the potential to leverage the inherent flexibility of low volume production.

Parametric modelling is also useful in a multi-disciplinary team where people work separately on different areas that continually influence each other. A seed part file was used to ensure team members were working to the same vehicle coordinate system, and that all parts were assembled in car line.

Key dimensional expressions were stored and categorised in Microsoft Excel to manage and simplify input into NX. Excel was also used to interface with Susprog3D which was used to design the suspension. This was beneficial since the chassis is directly influenced by the inboard suspension pickup points. Creating robust ‘relationships’ between the driving dimensions meant the chassis model could self-modify to suit a wide range of suspension geometries.

3-10. Suspension Development

Susprog3D software was used to model the suspension geometry. Initially, the most important aspect of the geometry was the packaging of all suspension components and their effect on cabin space, rather than the precise determination of kinematic performance. An area of particular focus was maximising foot-well space for the front row occupants, to minimise overall vehicle length while achieving desired comfort. The core team used the ergonomics buck to help make this assessment, based on the exclusion zones generated from Susprog3D and NX. Additionally, Susprog3D was useful to ensure appropriate camber control over the increased range of wheel travel.

![Figure 7: Susprog3D suspension development](image)

3-11. Hydrostatic System

Calculation of the capacity requirements of the hydrostatic system was conducted using Microsoft Excel. It was then refined with MATLAB to simulate expected vehicle performance through iterative solving. The simulation specifically focused on the vehicle’s ability to climb the typical grades expected in the mines.
4. FINAL SYSTEM CONCEPT

4-1. Exterior Design
The design of the exterior was developed around the following aims:

- Repeatability of parts and symmetry to reduce manufacturing and component costs
- Cheap manufacturing processes
- Easy assembly
- OEM stock reduction
- Easily replaceable and durable parts due to harsh environment and vehicle treatment
- Lightweight components
- Styling applicable to environment
- Effective use of space
- Utilitarian design

To fulfil these aims the exterior design of the vehicle employs a number of methods that reduce the cost, weight and assembly time required for the vehicle. Use of symmetry allows common parts and assemblies - these are:

- One rotationally moulding tool is used to mould all four door inserts
- The front and rear bumper bar is the same part
- Diagonally common rotationally moulded quarter panels
- One rotationally moulded storage box component is used on both sides at the rear
External plastic panels that would suffer repeated impacts are designed to be flexible to increase durability. If damaged, moulded parts are intended to be easily replaceable. In addition to the storage in the rear section, there is potential storage provided in the door inserts (accessible from outside the vehicle), the storage boxes at the rear (accessible from both sides) and under the rear equipment tray floor. The roof does not extend over the rear storage section which makes it possible for the equipment tray to be used as a work platform. The rear door is rear-hinged to improve ingress and egress for the occupants.

Figure 9: Exterior design

4-2. Interior Design
The key themes and aims of the interior design were:

- Comfort and safety of user
- Repeatability of parts for cost savings
- Durable light weight components that are easy to manufacture and assemble
- Simplified and user friendly controls and instrumentation
- Provide easy access for maintenance
- Accommodate simple change from right to left hand drive during manufacture
- Convert during use to increase storage space
- Accommodate change to alternate vehicle function at point of manufacture. PJ Berriman wished to be able to create vehicles with different functions (such as personnel transporter, ambulance, utility vehicle etc) using same vehicle architecture. The specific design of these alternate versions was not within the scope of the project.

In addition, advice was received from the industry partners that influenced the design. In regards to the nature of the users they stated that it could not be assumed that they would use the vehicle features in a safe manner and it should be assumed that they would always do what was easiest or quickest to achieve what they wanted. The industry partners also suggested that the design should use the minimum number of mechanisms possible and the mechanisms that are used should be simple and robust. Lastly they advised that no extra electronic features should be used due to the flame proofing requirements.
The interior is treated as separate front and rear sections so that the rear section can be replaced at point of manufacture. The front section contains the driver and a passenger and the rear section contains the rear three passengers with equipment storage located behind them. Storage space can be increased by folding down the rear cargo barrier (when there are no rear passengers) and a permanent cargo barrier separates the front and rear sections. The interface has simple and clear instrumentation consisting of a digital speedometer, oil pressure gauge, air pressure gauge and six pneumatic indicators. The instrumentation is centrally located for easy right/left hand drive conversion.

A large percentage of the interior is rotationally moulded to reduce the weight of the vehicle with only the simple flat sections being constructed from laser cut sheet steel/tread plate. To reduce assembly times the number of parts has been minimised.

Accommodating drivers of different sizes is achieved through adjustable steering wheel position and vertical/horizontal seat adjustment. Grab rails, including one located on the centre console for the front passenger, are available to assist the occupants with ingress/egress and provide support while traversing rough terrain.

To reduce vehicle size the front seats have a single rear leg enabling rear passengers to place their feet further forward, allowing a more forward position for the rear seat. The 150L water tank required for the exhaust conditioner is located within the centre console instead of in the engine bay, reducing front overhang which improves visibility.

All occupants’ seats contain isolation mounts to reduce the effects of vibration. A cut away in the seat and backrest accommodates the miners’ equipment belt and attachments. In addition, the headrests are split to allow for the miners’ helmets and head lamp. All seats are fitted with three point harnesses with heavy duty buckles.
4-3. Power-train Design

A hydrostatic drive system in the CMPT™ was selected for its packaging and flexibility advantages which were: a flat floor due to elimination of the drive shaft, the reduction of engine bay space requirements, and the mechanical decoupling of the power source and the power delivery systems. The decoupling made the engine position far less critical, and enabled the concept of a removable ‘Power-pack’.

A Poclain hydrostatic drive system is utilised which incorporates four 2-displacement ‘MS02’ wheel hub motors driven by a ‘P90-075’ variable displacement pump. The pump has a maximum displacement of 75cc/rev and is coupled directly to a Kubota V2607-DI-T Diesel engine, with maximum power of 49kW and can operate at a maximum speed of 2700rpm. This system has an operating efficiency of 80-85%.

The hub motor has integrated wet-brakes with an emergency, spring applied, hydraulic release system. A variation of the Poclain motor exists with an integrated steer axis that could be used to simplify the suspension design.

With a target weight of 2500kg the system allows the vehicle to achieve a maximum speed of 42km/h on flat ground, be able to climb a typical drift grade of 12.5% at 24km/h and climb a 25% grade at 13km/h.

4-4. Suspension Design

The suspension research found that a Short Long Arm (SLA) double wishbone system would best address the overall vehicle performance and packaging requirements. Reasons were:

- Engine bay packaging advantages
- Ability to design elasto-kinematic performance
- Low unsprung mass and no mutual wheel influence increase ride quality
- Wishbone fabrication suited intended manufacturing techniques
- Potential to use the same 'module' front and rear, which enables four wheel steering
- Accommodation of Hydrostatic hub motors.
Off-road ability of the CMPT™ is achieved through 250mm of ground clearance and 260mm of wheel travel, 100mm more than existing personnel transporters. The extra travel enables a much softer spring rate significantly improving ride quality for the occupants (Dayawansa et al., 2006).

The steering is fully hydraulic to meet packaging requirements. A possible wheel angle of 35 degrees enables a turning radius of 6700mm which is a 1000mm less than larger transporters. Modularity of the suspension system enables implementation of four wheel steering.

4-5. Chassis Design

The chassis design needed to be lightweight, and suit the chosen suspension, power-train, and occupant arrangement. The occupant arrangement required a flat floor with no transmission/driveshaft tunnel, while to maximise suspension performance, sufficient torsional rigidity was required. Important considerations included:

- Low volume production – upfront tooling costs must be low and leverage inherent flexibility.
- Structural integrity – the vehicle should be able to endure minor collisions from rough use and mine design guidelines specify the ability to withstand a 1 tonne vertical and 0.5 tonne lateral load.
- Robust design that is simple to manufacture – the design must include structural redundancy, must tolerate manufacturing variations and be easily repairable.
- Stringent packaging requirements – the design must accommodate 95th percentile male dimensions, with a vehicle height restriction of 1750mm and 250mm of ground clearance, while providing sufficient head room.

As such, a semi-space frame construction, utilising fabricated steel RHS (Rectangular Hollow Section) sections was deemed most appropriate. This has the additional benefits of: being a familiar construction technique for the industry; simplifying the design process due to its flexibility; and being simple to perform computer structural simulations. Strength of the chassis is enhanced through the use of laser cut and folded self-jigging gussets and cross members.
Symmetry in the longitudinal (X) and transverse (Y) directions with the use of CNC bent tubes reduce the number of separate members required, streamlining manufacture. To simplify jigging, the chassis utilises continuous floor rails that pick-up both front and rear inboard suspension wishbone points. This rail is also a useful reference for fitting other members. All chassis members require capped ends, and are coated with corrosion resistant paint after welding.

Effective utilisation of space between the wheel arches enables front row occupants to be positioned further forward, creating a more compact package.

5. CONCLUSION

Through the use of contemporary design methods unfamiliar to the mining industry, a compact vehicle concept that establishes a new benchmark standard in occupant comfort and safety was developed. A collaborative approach incorporating Industrial Design and Mechanical Engineering principles enabled cohesive design goals. Extensive use of software tools streamlined the vehicle development process by allowing digital simulations of design decisions. This led to targeted physical testing to make final ergonomic assessments. Parametric modelling afforded a flexible design environment where changes from different members of the core team could be incorporated with ease. It also efficiently leveraged the inherent flexibility of low volume production.

The new vehicle architecture that was developed has an improved occupant layout, access, usability, safety and comfort over current vehicles. It also incorporates an independent suspension system that increases ride quality. The vehicles hydrostatic drive system was a key factor in allowing the layout and weight advantages over current personnel transporters. Further research is to be undertaken to detail the design in order to produce a working prototype.
REFERENCES


