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## Economic and Technical Feasibility of a Robotic Autonomous System for Train Fluid Servicing

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### Abstract

Rail traffic in passenger miles is projected to increase by 100% over the next 30 years, which presents a considerable challenge for the current infrastructure to perform the regular fluid servicing tasks. Developing robotic autonomous systems for train fluid servicing is a prospect for which no solutions currently exist. Therefore, the economic and technical feasibility of a robotic autonomous system (RAS) to perform several key fluid servicing tasks on passenger train vehicles is investigated. The fluid servicing tasks chosen include those that to a significant degree are repetitive or hazardous for humans to perform, and therefore if performed by a RAS will release service personnel to focus on more suitable tasks. The economic and technical cases presented strongly support the use of a RAS for fluid servicing of trains. Generally available RAS technology has reached a state of development capable of delivering what is required once reliable couplings and fluid hose technologies have been developed for this application. Overall, the findings are that fluid servicing capacity will at least double for around 15% of the cost of an equivalent manual servicing facility, which represents a substantially attractive business case. There will be modest technical challenges to be overcome that will add unknown cost elements such as modifications to vehicle fluid ports for RAS compatibility, and development of long power hoses.

### Keywords

Train servicing, vehicle fluids, robots, maintenance workshops, hierarchical task analysis

## 1. Introduction

The various ‘fluids’ that currently require regular servicing on passenger rail vehicles include fresh water, coolant, screen wash, fuel, effluent and wheel sand. Fluid servicing is a manually intensive and repetitive activity performed in dirty and hazardous conditions.

Rail traffic in passenger miles is projected to increase by 100% over the next 30 years<sup>1</sup>, served by an increase in total fleet from 13,377 in 2017 to an upper limit of 24,943 in 2046. This presents a considerable challenge for the current infrastructure to perform the regular fluid servicing tasks despite improvements in fleet maintenance efficiency. In order to continue to deliver the required service levels, current manual-based servicing will require major investment in new depots, which will be difficult to locate near to the point of need in congested commuter areas. This raises the prospect of developing robotic autonomous systems for train fluid servicing for which no solutions currently exist.

Industrial robots were the earliest commercial success in performing repetitive tasks such as welding and assembly. Service robots have grown over the past decade through improved autonomy, i.e. the ability to accommodate variations in environment driven by considerable reductions in the cost of hardware for sensing, computing and actuating<sup>2</sup>. Space robotics, as an exemplar of service robots, has recently developed new technologies for tackling a host of space system maintenance tasks including assembly, refueling, repair and upgrade of space craft after deployment<sup>3</sup>. Robots are no longer necessarily about replacing human labour but increasingly can collaborate with human workers in the fulfillment of tasks with greater productivity such as helping hospital patients to walk<sup>4</sup>. Advancements in robot hardware and software have reduced safety risks when working in close proximity to humans for specific cooperative tasks<sup>5</sup>.

The term Robotic Autonomous System (RAS) is used in this paper to embrace the use of robots within autonomous systems. Human-centred automation<sup>6</sup> is a key aspect of the RAS approach and it takes into account human factors to ensure that the tasks best suited to the human are allocated to the human, and the tasks best suited to automating are allocated to the RAS. Attributes of RAS that make them of consideration for application in the servicing of train fluids are in broad terms:

- Accuracy: Can complete repetitive tasks with high speed and precision.
- Safety: Can handle hazardous substances and work in hazardous areas.
- Power: Can complete tasks requiring accurate movement of high payloads.
- Cost: Robots are becoming generally cheaper to buy and maintain.

With greater degrees of automation in the transportation industry and work practices, the nature of tasks conducted by an operator while servicing a train involves significant cognitive components including monitoring, anticipating, predicting and decision-making<sup>7</sup>. Hierarchical Task Analysis (HTA)<sup>8</sup> is an ergonomic method that offers a means of describing a system in terms of goals and sub-goals, with feedback loops in a nested hierarchy. Rather than focusing only on observable aspects of performance, HTA

represents system goals and plans analysing the process at task level to assess how best to reduce human errors through design solutions. HTA enables thus to gain an understanding of how human interaction with tasks might lead to errors. The HTA methodology is based upon a theory of human performance focusing on the details of how a task is performed:

- How was the work performed?
- What was needed to perform the work?
- Why was the work performed in this way?
- How could the working methods be improved?

Annett<sup>9</sup> has argued that HTA encourages the analyst to consider not only what should happen, but also what does actually happen and how this can go wrong. The HTA approach helps the analyst to discover the indicators for success and failure of each of the sub-goals.

This paper investigates the economic and technological feasibility for a RAS to perform specific key tasks related to train fluid servicing.

## 2. Method

### 2.1 Design process

A typical design process approach, represented in Figure 1, was followed in order to arrive at RAS concepts. Firstly, the problems with current manual servicing were identified and the information gathered led to a formal specification of the problem. Solution concepts were proposed and reviewed against the specification.

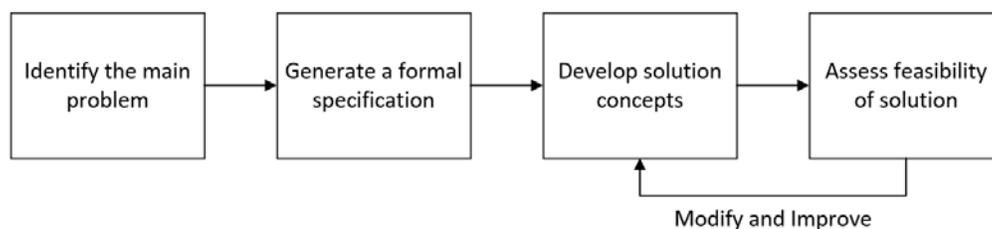


Figure 1: Overall design process approach to RAS design concepts

A human-centred approach to the design process included input from rail staff members regarding their requirements for a RAS solution, and how to best utilize the fluid service operations when conducted by a RAS. The motivation for implementing a RAS was driven by the need to reduce or remove three human-centered issues:

Dirty tasks - Reducing exposure to the fluids that are messy or unpleasant to deal with.

Dull tasks – Reducing repetitive tasks such as repeatedly inserting hoses into rail vehicles is tedious and prone to error.

Dangerous tasks - Reducing regular exposure to hazardous fluids is of benefit to human operatives and in addition working in a maintenance shed presents the risk of moving rail vehicles plus trip and other physical hazards.

## 2.2 HTA of current manual servicing of fluids

To assess the current fluid servicing processes an HTA has been conducted. The first step aimed to identify the main issues in the current practice of manual servicing the fluids of passenger train vehicles. An audit of the port locations and the depot environment was carried out, and subsequently the HTA was applied to analyze the current rolling stock fluid servicing processes. Variations in the equipment used and processes adopted are also highlighted.

### 2.2.1 Process trees

A set of basic steps is at the core of the HTA and allows for the display and interpretation of gathered information and these steps<sup>8</sup> are:

- i. Define purpose of the analysis;
- ii. Define the boundaries of the system description to be analysed;
- iii. Try to access a variety of sources of information about the system to be analysed;
- iv. Describe system goals and sub goals and link goals to sub goals and describe conditions under which sub goals are triggered;
- v. Stop re-describing the sub-goals when the analysis is judged to be fit for purpose.

The HTA was used to generate three main results:

- Hierarchal Task Tree comprising goals and sub goals (also known as tasks and sub tasks).
- Errors table with Systematic Human Error Reduction and Prevention Approach (SHERPA) error modes.
- Risk impact factors.

### 2.2.2 Error prediction and risk identification

As well as observing errors, HTA can be used as a basis for predicting errors. Systematic human error reduction and prediction approach (SHERPA)<sup>10</sup> is an analysis tool that allows to predict potential errors from the HTA sub-goal hierarchy. The idea is that each task can be linked to an error taxonomy to identify credible errors associated with a sequence of human activity. The types of error that may occur fall into one of five behavior categories: action, checking, retrieval, communication and selection. The purpose of SHERPA is not only to identify potential errors with the current design, but also to guide future design considerations and remedial strategies. SHERPA has been found useful in other HTA studies<sup>11</sup>.

Risks are associated with some of the errors identified in the HTA. For these risks, impact scores were calculated using two values as described by Talbot<sup>12</sup>. The first value is the likelihood of occurrence score, or probability score; this is a number between 1 and 5 that represents how often the error occurs. The second value is the severity of the error

consequence; this quantifies the damage to people that can occur. An example being the ignition of spilled fuel; where the probability of occurrence is 1, as it is very rare but if it occurs could have considerable consequences for human health and so a severity score of 5 is given, thus resulting in a risk score of 5.

Another benefit of the analysis is that it identifies decision making points that a RAS will have to make. Once the decision points are outlined, it will show which aspects of the servicing processes should be automated and which will require human input. Once a core set of results are obtained from the HTA then variations between depots can be discussed by comparing visual evidence.

### 2.3 Specification

The information gained from the HTA was used in conjunction with information obtained from maintenance workshop managers, risk assessments and rail industry standards to inform a Quality Function Deployment (QFD) phase 1 matrix that developed into the system specification.

A British Rail (BR) Class 168 passenger rail vehicle was used as the target vehicle for the RAS concepts; which represents a sizeable portion of the Chiltern Railways fleet (main project partner) and very similar to other classes of vehicle (such as 170, 171 & 172) widely used in the UK modern DMU fleet. The port locations for this range of vehicles are shown in Figure 2, which effectively specifies the working envelope of the RAS.

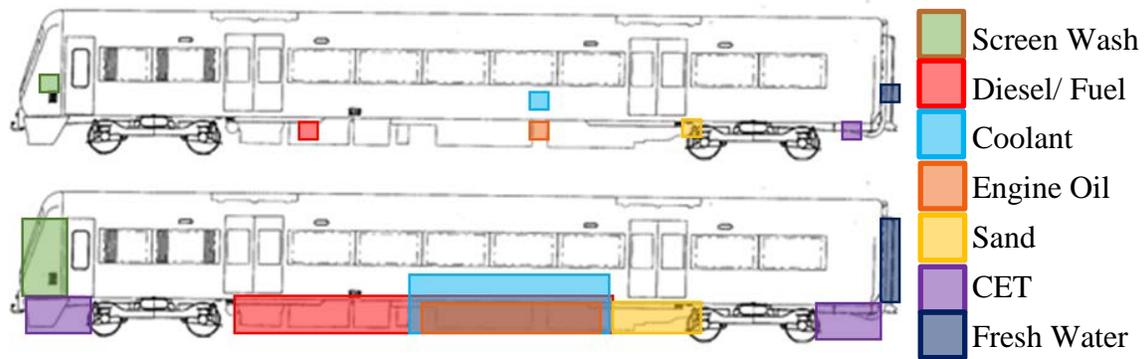


Figure 2: Fluid port locations on a BR Class 168 rail vehicle (top) and across similar vehicles (bottom)

### 2.4 Concept design

The HTA and design specification were referenced in designing RAS concepts, which aimed to complete the fluid servicing tasks with the assistance of a single human operator. Currently available commercial RAS technologies are targeted in order to demonstrate plausible designs. More than one concept was proposed to allow a comparative study of the concepts for assessment of economic and technical feasibility.

## 2.5 Economic and technical feasibility

Two chosen RAS concepts were assessed in greater detail for their economic and technical feasibility against the current manual approach as a benchmark. Industry stakeholders provided estimations of upfront and ongoing costs.

## 3. Results

### 3.1 HTA observations

The HTA combined with the SHERPA analysis on error predictions reveal that redesigning the system for a RAS will reduce the risk of human error. For example, one simple solution like utilising RFID tags will remove certain identification errors. Due to the nature of the processes human errors vary in their type and complexity, however they are all based on the fact that humans can be inconsistent. Below is a set of generalised errors identified which can lead to improper fluid servicing, infrastructure damage or vehicle recalls; all of which will be reduced or removed if a RAS were to be introduced:

- Admin errors (Example: incorrect fluid usage documented).
- Not correctly assessing fluid levels (Example: Forgetting to top up fluids to appropriate levels).
- Not correctly completing the fluid service (Example: leaving caps off the port).
- Fluid wastage (Example: fluid topped up until past maximum).
- Fluid contamination (possibly due to caps being left off).

The fluid servicing processes were found to be similar between depots although with some differences in types of fluid ports. New designs of fluid ports and nozzles will be required for a RAS to service all of the fluids due to the fact that current ports are designed for human usage:

- Engine oil port location varies greatly between passenger train designs and could be quite challenging to reach in most cases. Therefore engine oil is likely only to be monitored by a RAS not actually serviced.
- Adapting the fuel, coolant, fresh water, sand, Controlled-Emissions Toilets (CET) and screen wash ports will allow a RAS to service the fluids.
- Development of standardised port connections across all vehicles will increase the potential uptake of RAS.

### 3.2 Specification

Senior staff from five maintenance workshops (MW) supplied their user requirements from which a set of design requirements were generated and both sets were input to a QFD matrix in order to evaluate priorities and relationships (Figure 3).

User Requirements	Design Requirements														
	Importance Rating	Reduce man hours required to service fluids	Port to be adapted for spill- less RAS interfacing	Use data to develop planned vehicle maintenance	Increased trains per day serviced	Precise fluid dispensing and fluid tracking	Integrate with current maintenance management software	Real time accurate fluid sensors	Alarming system to notify low fluid levels	Remove dispensing hoses at floor level	Staff will work inside the vehicle or around the RAS, away from rail areas	Remove need for staff to handle fuel, engine oil, coolant and screen wash	Remove need for staff to handle CET extraction	Not to be located in current depots	Equipment for current fluid servicing tasks can be replaced and removed
Increase capacity using current labour capabilities	15.0	9		1	9		1								
Reduced spills and fluid loss	6.0	1	9	1		3					3	3	3	1	
Reduced vehicle maintenance costs	5.5	1		9		1	3		3						
More vehicles per hour serviced	8.9			1	9	1	3			3					
Reduced vehicle recalls	4.6		1	3		9	3	3	3						
Improved fluid servicing efficiency	4.6	1		3	1	1	9		1		1	1			
Better fluid monitoring	9.9					9		9	3						
Improved diagnostics information	9.9					3	1	9	9						
Reduced slip/ trip hazards	5.8		9							9	3	3	3	9	
Remove humans from hazardous areas	9.8		3							3	9	3	3	9	
Reduced human exposure to hazardous chemicals	4.1		3			1				1	3	9	3	1	
Reduced human biohazard exposure	2.9		3			1				1	3	1	9	1	
Improve depot accessibility	5.2									9	3			9	
Improved space around vehicles	7.8									1	3			9	
QFD Scores	100.0	6.4	6.8	4.5	9.3	8.7	5.2	8.2	6.5	6.1	8.2	4.7	4.6	12.0	8.8

Figure 3: Quality Function Deployment RAS specification

### 3.3 Design concepts

Two concepts were developed prioritising the top design requirements identified in the QFD matrix (Figure 3). The RAS concepts were designed to be installed trackside close to current MW but not within them.

#### 3.3.1 Concept 1 – Cartesian RAS

The Cartesian RAS concept is based on an XYZ axis Cartesian gantry robot (Figure 4), for example, a ‘Ro-ber’ palletising gantry system<sup>14</sup> has an operating envelope of 30m x 4m x 2.7m which is generally larger than most rail vehicles. Two motorised hose reels<sup>15</sup> will allow the hoses to be unravelled by the RAS, which moves them to their required location. Thus this Cartesian RAS has simple movement and the configuration aims to reduce the number of powered hose reels thereby minimising cost and complexity.

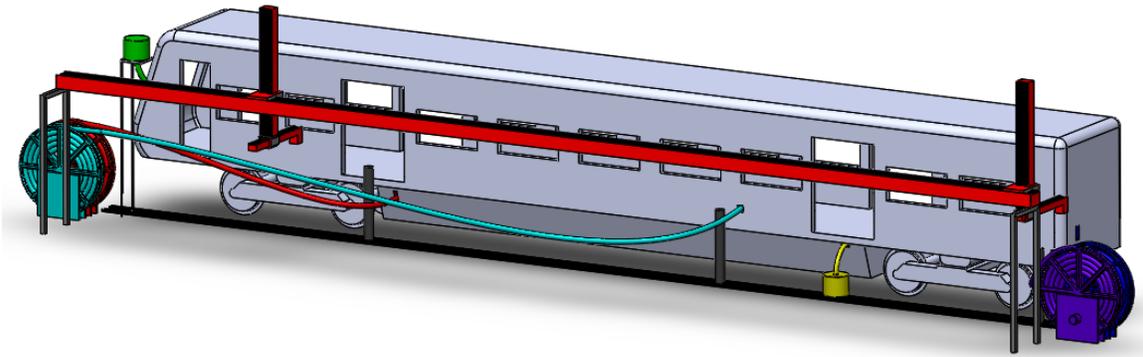


Figure 4: Concept 1 - Cartesian RAS.

The Cartesian RAS picks up the hoses from the hose reels in turn and methodically moves down the vehicle inserting the hoses at the required fluid ports and working both sides of the train simultaneously (not shown). As the locations of the ports will be known, the hoses will be inserted in a sequence that avoids interference, starting at the front of the vehicle and working backwards until all the hoses are attached. Once the fluid tasks are complete hoses are detached in reverse order.

### 3.3.2 Concept 2 – Articulator RAS

The Articulator RAS (Figure 5) uses multi-axis robotic arms commonly employed in industry for a wide range of tasks, for example the Kuka KR 120 Quantec 2500 robot<sup>16</sup> meets the specification for this application. This solution uses multiple hoses of the same fluid, and thus multiple powered hose reels, to cover the range of port locations and to avoid tangling and snagging. It does not need to service the ports sequentially. Screen wash reel is only shown on the front of the vehicle and the CET and fresh water reels only at the rear of the vehicles; these are the typical locations of these fluids common across most vehicle types.

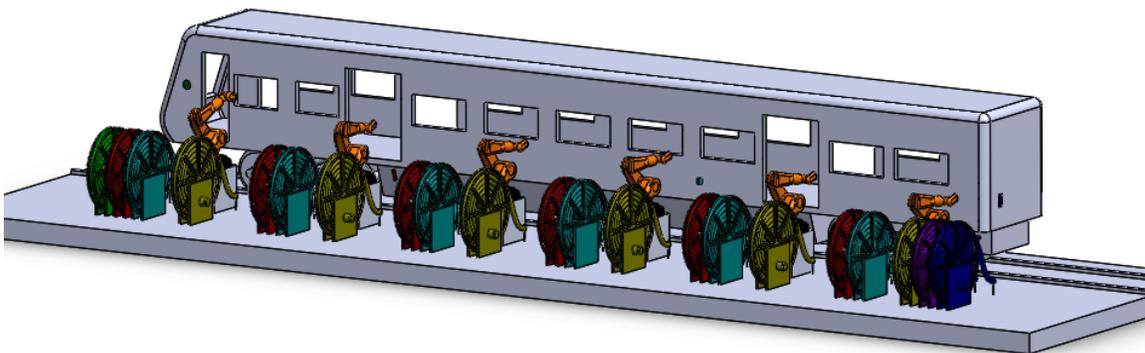


Figure 5: Concept 2 - Articulator RAS.

### 3.4 Timing diagrams

Timing diagrams were developed to show the cycle time for completing current and RAS fluid servicing tasks, using estimations based on the speed of the current technologies to be employed. The distance between the ports is calculated using port location measurements for a BR Class 168 vehicle (Table 1 and Figure 6).

Table 1: Location of fluid ports with reference to Figure 6

Fluid	Sides	X (m)	Y (m)	Z (m)
Screen Wash	B	22.5	1.7	1.3
Fuel	AB	15.5	0.8	1.0
Coolant	B	9.4	1.6	1.3
Sand	AB	5.4	0.8	1.1
CET	AB	1.3	0.6	1.0
Fresh Water	AB	0.0	1.8	0.8

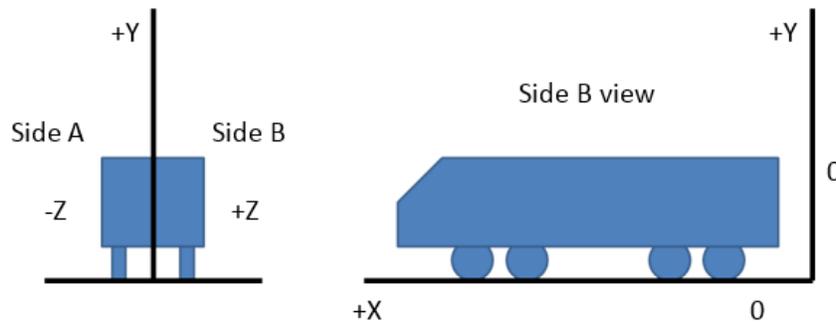


Figure 1: Vehicle coordinate reference frame

#### 3.4.1 Manual service timing

Manual service task timings in Figure 7 were approximated from videos and observations of fluid servicing taken at MW visits. Fluids with the longest service times principally determine the operator servicing route due to the fact the operator services each fluid in sequence. Therefore fuel is the first fluid to be serviced, typically followed by CET and then fresh water. While these fluids are being processed, the operator moves up and down the vehicle servicing the other fluids, and the order can vary depending on the vehicle type. It takes approximately 14 minutes for one operator to service all fluids for one vehicle.

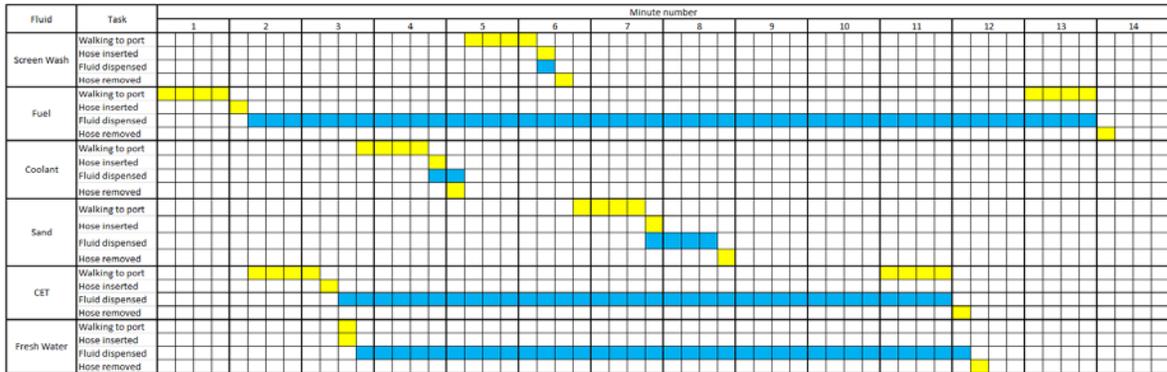


Figure 7: Timing diagram for manual fluid servicing

A single manual operative can only service one vehicle at a time, which means that for two operators it takes approximately 37.5 minutes to service 5 vehicles or approximately 8 vehicles per hour. It is important to note that the gaps between operator actions in the timing diagram are where other non-fluid based tasks are completed while waiting for fluids tasks to finish.

### 3.4.2 Cartesian RAS service timing

Assuming 2m/s as an average speed of a typical gantry robot<sup>17</sup> the time taken for the Cartesian RAS to move between ports was calculated. The RAS will start at the front of the vehicle and make its way sequentially backwards until all the hoses are attached. Once the fluid reservoirs are suitably filled the RAS will look to detach the hosing in reverse order (from fresh water to screen wash in this example). The Ro-ber gantry robot can use 2 manipulators per gantry meaning the front fluids can be serviced at the same time as the rear fluids are serviced. Therefore, Side A and Side B will be serviced simultaneously, although ports still have to be addressed in sequence, to halve the cycle time.

Figure 8 shows that it will take approximately 9 mins to service 5 vehicles with a 5-car Cartesian RAS. By adding time (5 minutes) to move trains into and out of the RAS it can service up to 20 vehicles an hour.

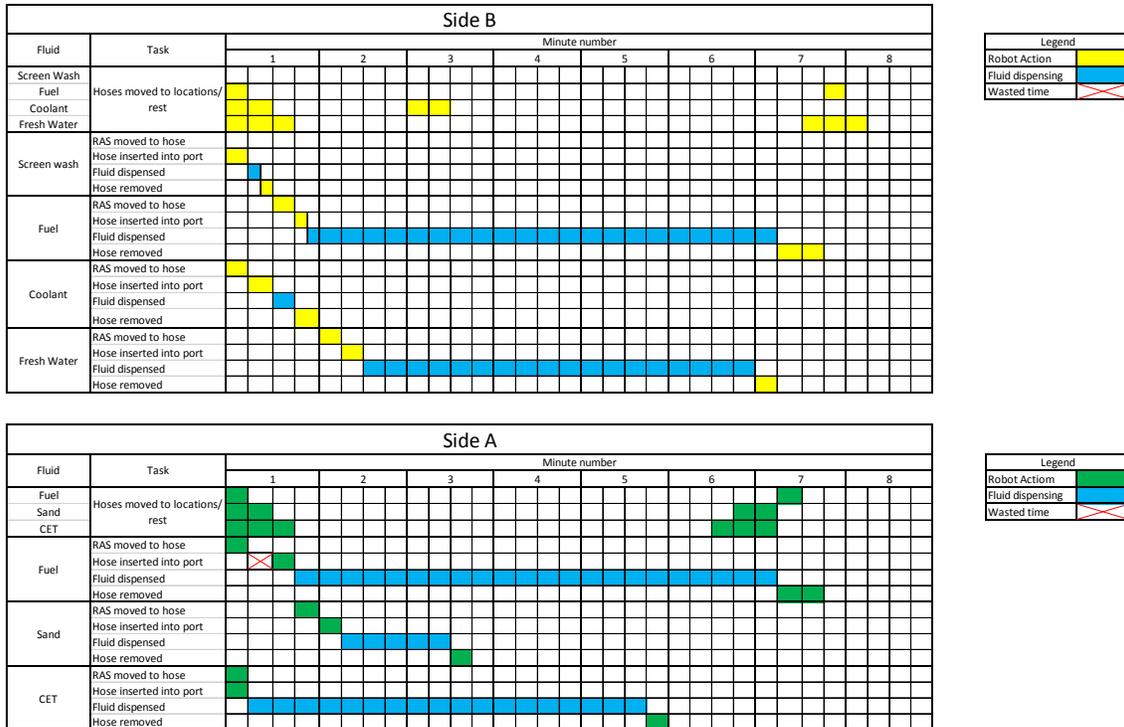


Figure 8: Timing diagram for Cartesian RAS fluid servicing

### 3.4.3 Articulator RAS service timing

The Articulator RAS concept allows hoses to be inserted simultaneously which reduces cycle time. Due to the complex motion of articulators and the varying angular speeds of the numerous axes, a conservative estimate of 15 seconds is enough time to pick up a hose and insert it into a port. Articulators are likely to be faster in reality. Using this information the timing diagram is shown in Figure 9.

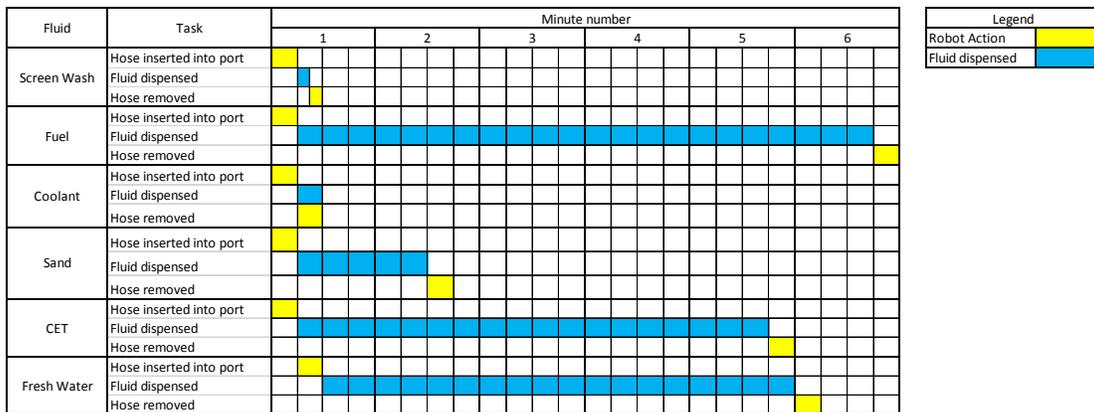


Figure 9: Timing diagram for Articulator RAS fluid servicing

From Figure 9 it can be seen that 5 vehicles can be serviced in 6 minutes by a 5-vehicle Cartesian RAS and adding an extra 5 minutes for vehicle movement, up to 25 vehicles

can be serviced per hour. These figures for both RAS are an increase on values previously reported by the authors<sup>18, 19</sup>, which were based on a 4-car RAS.

The fluid task timings of both RAS are summarised in Table 2 for comparison.

Table 2: Summary of fluid task times for both RAS options

Fluid Task	Cartesian RAS (aggregated)			Articulator RAS		
	Robot Action (secs)	Fluid Dispensing (secs)	Wasted Time (secs)	Robot Action (secs)	Fluid Dispensing (secs)	Wasted Time (secs)
Fuel	71	327	15	30	327	0
CET	54	258	0	30	258	0
Sand	71	66	0	30	66	0
Coolant	52	5	0	30	5	0
Fresh Water	74	258	0	30	258	0
Screen Wash	28	12	0	30	12	0
TOTAL	350	926	15	180	926	0

### 3.5 Economic evaluation

The upfront cost of new 10-car manual servicing facility will include purchasing of land, civil works and fitting out the building but excludes other costs such as signalling and sidings, which are assumed to be common to all the solutions compared here. The service staff costs will be four staff members at around £60,000 per annum<sup>20</sup>. These figures will be used to compare with those of both RAS concepts. Both RAS concepts are assumed to be housed in a heated shed, which keeps them protected from the weather but is not of the higher specification required for permanent human occupation. The capacity of a manual service facility is based on the number of vehicles serviced in an 8-hour shift, which based on manual servicing timing above will be around 64 vehicles per shift. Table 3 shows a summary of costs.

Table 3: Cost delta estimations for a new 10-car manual service facility

Cost Items	Value
Upfront	£15 million fixed
Staff Costs (per year)	£240,000 per annum
Facility Maintenance Costs (per year)	£70,000 per annum

The costs of the Cartesian RAS are based on an estimate of £150,000 for a ‘Ro-ber’ palletising gantry system<sup>17</sup> with an operating envelope of 30m x 4m x 2.7m which is generally larger than most rail vehicles. This gantry cost is multiplied by 10 (1 per side of vehicle, 5 vehicles).

The costs of the Articulator RAS are based on an estimate of £36,000 for a Kuka KR120 Quantec R2500 robot<sup>16</sup>, which is multiplied by 60 (6 robots per side of vehicle, 5 vehicles). A rugged outdoor version of the Kuka KR120 Quantec Artic is also available costing £56,000, which would not require a heated shed. The cost delta of a 5-car heated shed (£437,500) and non-heated shed (£312,500) are estimated from figures provided by a rail industry stakeholder<sup>20</sup>.

The cost of a powered hose reel is £6,000, obtained from a UK supplier<sup>21</sup> and made by a US company<sup>15</sup>.

By again using a cost delta, the figures for each RAS concept in Table 4 ignore items common to all solutions, such as civil works, cabling, drainage, etc., as including them in the economic comparison is not necessary.

Table 4: Estimated costs of 5-car Cartesian and Articulator RAS service facilities

<b>Cartesian RAS</b>			
<b>Item</b>	<b>Item Cost</b>	<b>No of Items</b>	<b>Total Cost</b>
Ro-ber gantry robot	150,000	10	1,500,000
Hose reels	6,000	40	240,000
100L reservoir	100	20	2,000
Heated Shed	437,500	1	437,500
			<b>2,179,500</b>
<b>Articulator RAS</b>			
Kuka KR 120 Quantec Arctic	56,000	60	3,360,000
Hose reels	6,000	210	1,260,000
Non-heated Shed	312,500	1	312,500
			<b>4,932,500</b>
Kuka KR 120 Quantec R2500	36,000	60	2,160,000
Hose reels	6,000	210	1,260,000
Heated Shed	437,500	1	350,000
			<b>3,857,500</b>

## 4. Discussion

### 4.1 Economic evaluation

Using summary values (Table 5) to compare the proposed Cartesian RAS and Articulator RAS 5-car fluid service concepts with the equivalent (10-car) manual service facility, the RAS can be seen to be more commercially attractive. Generally a RAS comfortably outperforms manual fluid servicing facility, more than doubling the throughput compared to current services for 15% of the cost. The increase in service capacity is compelling given the prospect of considerable growth in rail traffic. The cost delta of a new 10-car manual fluid service point is much greater than that of a RAS.

Table 5: Summary of business case

	<b>Cartesian RAS</b>	<b>Articulator RAS</b>	<b>Manual</b>
Capacity (vehicles/hr)	20	25	8
Number of staff	1	1	2-4
Cost delta	£2.2million	£3.9million	£15million

Either RAS solution requires only 1 operator and the RAS operators will have an improved quality of work due to the reduced handling of fluid port interfaces and engagement with operating and maintaining the RAS. This upskilling will be relevant to other technological advances that are developing in the rail industry.

Consideration of projected UK fleet expansion will highlight the economic demand for RAS fluid service facilities. An initial estimate of the number of RAS required in the UK can be based on the expected fleet size changes for the UK passenger fleet up to 2046, which are estimated for low, medium and high scenarios<sup>1</sup>. The current vehicle numbers are assumed to be adequately served by existing manual servicing facilities as a baseline. Let us assume that the projected new vehicles,  $V$ , are assumed to be on average connected as a 5-car train length and to visit a facility for fluid servicing twice per week. Table 6 estimates the number of additional trains requiring fluid servicing per week,  $TSW$ , at each census date based on:

$$TSW \left[ \frac{(\text{trains serviced})}{(\text{week})} \right] = \frac{2V}{5} \left[ \frac{\left( \frac{(\text{services})}{(\text{week})} \right) (\text{vehicles})}{\left( \frac{(\text{vehicles})}{(\text{train})} \right)} \right] \quad (1)$$

Table 6: Estimated trains to be serviced per week

Census date	Scenario	Total vehicle fleet	Equivalent 5-car trains	Extra trains from previous date	Fluid services per week
					TSW
2017		13377	2675	0	5351
2019	H	15212	3042	367	734
	M	15091	3018	343	686
	L	14986	2997	322	644
2024	H	16488	3298	255	510
	M	15916	3183	165	330
	L	15643	3129	131	263
2029	H	18722	3744	447	894
	M	17322	3464	281	562
	L	16348	3270	141	282
2034	H	21248	4250	505	1010
	M	18969	3794	329	659
	L	17440	3488	218	437
2049	H	24943	4989	739	1478
	M	21136	4227	433	867
	L	18527	3705	217	435

The RAS working day assumes 16 hours to allow for human RAS operator availability and train scheduling constraints; and the working week to be 6 days in order to allow for planned maintenance and other track closures. The number of each facility option required,  $N_M$  (or  $N_C$  or  $N_A$ ), is calculated by taking the respective facility capacity,  $C$ , from Table 4, such that:

$$N_M; N_C; N_A = \frac{TSW}{\left(C * \frac{1}{5} * 16 * 6\right)} \left[ \frac{\left(\frac{\text{trains serviced}}{\text{week}}\right)}{\left(\frac{\text{vehicles}}{\text{hour}}\right) \left(\frac{\text{train}}{\text{vehicles}}\right) \left(\frac{\text{hours}}{\text{day}}\right) \left(\frac{\text{days}}{\text{week}}\right)} \right] \quad (2)$$

Table 7 estimates the number and cost of providing RAS fluid servicing facilities required for the projected increases in UK fleet size of the next three decades. The number of manual/RAS facilities are rounded up to the nearest integer for calculating the cost of systems required at a given census date. 2017 cost estimates are used throughout.

$$\text{Cost} = \text{CostDelta} * \text{Roundup}(N) \quad (3)$$

Table 7: Estimated manual and RAS facilities costs for projected UK fleet increases

Census date	Scenario	Fluid services per week	10-car manual facilities required (1.6 trains/hr)	5-car Cartesian RAS required (4 trains/hr)	5-car Articulator RAS required (5 trains/hr)	10-car Manual facility cost £M	Cartesian RAS cost £M	Articulator RAS cost £M
Symbol		TSW	N <sub>M</sub>	N <sub>C</sub>	N <sub>A</sub>	Cost <sub>M</sub>	Cost <sub>C</sub>	Cost <sub>A</sub>
2017		5351	34.8	13.9	11.1	525	30.8	46.8
2019	H	734	4.8	1.9	1.5	75	4.4	7.8
	M	686	4.5	1.8	1.4	75	4.4	7.8
	L	644	4.2	1.7	1.3	75	4.4	7.8
2024	H	510	3.3	1.3	1.1	60	4.4	7.8
	M	330	2.1	0.9	0.7	45	2.2	3.9
	L	263	1.7	0.7	0.5	30	2.2	3.9
2029	H	894	5.8	2.3	1.9	90	6.6	7.8
	M	562	3.7	1.5	1.2	60	4.4	7.8
	L	282	1.8	0.7	0.6	30	2.2	3.9
2034	H	1010	6.6	2.6	2.1	105	6.6	11.7
	M	659	4.3	1.7	1.4	75	4.4	7.8
	L	437	2.8	1.1	0.9	45	4.4	3.9
2049	H	1478	9.6	3.8	3.1	150	8.8	15.6
	M	867	5.6	2.3	1.8	90	6.6	7.8
	L	435	2.8	1.1	0.9	45	4.4	3.9
TOTAL	H					480	31	51
	M					345	22	35
	L					225	18	23

From Table 7 it can be seen that the Cartesian RAS is easily the most economic option, apart from two Low scenarios in 2034 and 2049. In practice, it is likely that the actual numbers of RAS required will be significantly greater due to geographic and operational factors increasing UK service capacity well beyond demand and thus offering a degree of contingency across the rail network. However, it is important to note that the calculations made regarding the capacity increases do not take into account external factors such as getting vehicles to the RAS service area, driver availability and maintenance workshop signaling capabilities.

## 4.2 Technical evaluation

The RAS options considered will be able to service different fleets than the BR Class 168 considered here. The main issue in depot arrangements will be space available for a RAS. Modifications are required to vehicle fluid ports in order to make them more suitable for RAS fluid servicing. We envisage modifications to existing fleet and design changes for new fleet in terms of fluid port interfaces suited to RAS while maintaining manual servicing if required in unexpected circumstances. There are fluid coupling products that are already in use in various industries that could be adapted for this application with minimal technological risk. For example, Parker Hannifin produce a range of products that include quick fit coupling mechanisms used in demanding environments<sup>22</sup>. Relevant standards on vehicles and infrastructures would need to be revised accordingly.

Although electrical power for the RAS is readily available on the rail network, electrical-powered RAS solutions are generally designed to operate indoors and therefore an insulated and heated shed is needed to house the RAS. Otherwise robust electrical robots such as the Kuka Artic designed for outdoor use will use a non-heated shed just to make their servicing by humans more practical in extreme weather. The KR 120 Quantec Arctic can operate in temperatures down to  $-25^{\circ}\text{C}$ , the KR 120 Quantec R2500 operates above  $10^{\circ}\text{C}$ . Both models have the same payload.

The hose reels identified have 15m reach, as this is the only motorised single wrap reel size available (3" inner diameter hose), which will be sufficient for the Cartesian RAS. The hose reels for the Articulator RAS need only be about 5m maximum length, which would reduce the cost although it is not expected by much. Hose reels account for 33% of the cost of the Articulator RAS concept.

Both RAS concepts at least double the throughput compared to manual fluid servicing, and both concepts are highly technically feasible, as the core automation and robotics technology exists in other commercial sectors. The main technological risk is the potential for hosing to tangle and fray, which is mitigated by the powered reels.

The Cartesian RAS to be just over half (57%) the cost of the Articulator RAS, and with its simpler design and less cluttered operational envelope is attractive from an economic and operational viewpoint.

### 4.3 HTA for RAS

This work has applied a human error identification technique to the process of RAS as a means of preventing error or reducing the effects of error. Each concept required a modification of the initial HTA process trees which combined with SHERPA allowed to identify potentially unforeseen errors and the error reduction strategies.

To help display the modifications made to the initial tree, the processes for which the RAS will differ from the manual methods HTA tree are highlighted in green in Figure 10. The use of the HTA combined with SHERPA has helped to reduce the process of identifying the vehicle to only one task '1.3 RFID Tag is read and vehicle information is obtained' (See Figure 10). Also the fluid processes have been changed and have been generalised. However, these changes based on the HTA results will need further reiteration and revision since the potential for the tasks to be completed simultaneously by two or more RAS will mean that the speed with which the fluids are serviced should be increased. Further iteration of the HTA sub-goal hierarchy and plans are thus needed.

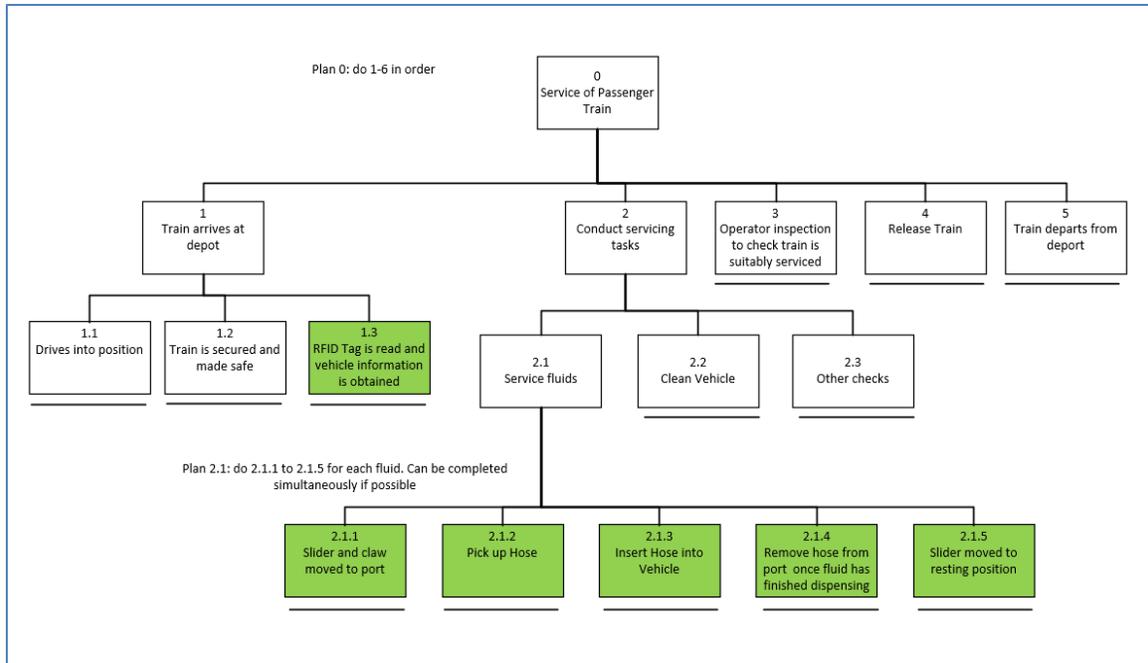


Figure 10: HTA for RAS with processes that differ to manual approach shown in green

A key benefit for staff of adopting RAS for fluid servicing will be reduction in exposure to harmful substances and reduction of dirty and menial work. A tool for human error quantification in the railway industry called Railway Action Reliability Assessment<sup>23</sup> has been developed using information from an existing human error quantification approach, the Human Error Assessment and Reduction Technique (HEART)<sup>24</sup>. HEART, used in the field of human reliability assessment (HRA), involves the use of qualitative and quantitative methods to assess the human contribution to risk<sup>25</sup>. The Railway Action Reliability Assessment method<sup>26</sup> is intended to be used when human reliability needs to be quantified for risk assessment or as part of the process of making safe decisions by providing information on the likelihood of human error.

#### 4.4 Potential wider benefits

As well as the advantages of increasing capacity cost effectively and improving the servicing quality, a RAS could bring other wider benefits. For example, it could incorporate additional new technologies, such as intelligent vehicle and fluid monitoring, to benefit the train operators.

Retaining a single operator to oversee the RAS operation would ensure an additional element of robustness and reliability. This operator would be able to monitor the fluid servicing and make sure that the RAS carries out the operational tasks without error. This would also bring a reduced likelihood of vehicle damage due to errors such as hoses being left coupled to the vehicle. The dependence on sensory equipment would also be reduced and robustness of the system increased by the presence of an operator, leading to fewer train recalls due to unfinished or incorrect servicing. The human operator would also be able to instigate troubleshooting in the case of a fault or if issues are detected by the RAS with aspects of the fluid servicing system. (Example: if excessive levels of

moisture are observed in the sand reservoir then the operator would be able to take action on this).

Another benefit of a RAS in this application would be the potential to bring additional monitoring functionality. As the RAS would need information about the level of fluid in the vehicle tank and the quantity it delivers, accurate data on the volume of fluid dispensed and used could be compiled. This data can include quantities of other fluids such as gearbox oil or engine oil that are not initially serviced by the RAS. Through analysis and interpreting this data, faults could be diagnosed and identified early, leading to a more proactive fault finding system. The data could also be combined with existing maintenance scheduling computer software, leading to further improvement of the process of fluid servicing. Early recognition of vehicles with lower levels of fluid could enable them to be put into a service schedule more rapidly. Fluid contamination is a big problem and use of a RAS with monitoring of fluid quality would further contribute to more reliable servicing of fluids, and fewer vehicle recalls as a result of contamination or lack of fluids.

## Conclusions

The RAS concepts considered are both technical and economically feasible for train fluid servicing, particularly the Cartesian RAS concept. They remove the need for humans to perform repetitive or hazardous fluid servicing tasks and significantly reduce the potential for errors, which are currently encountered during in fluid servicing thus contributing to a more reliable and punctual rail service. Some modest technological challenges need to be overcome in terms of developing a fluid port interface that works faultlessly and reliably with the RAS, plus hose management to avoid entangled and damaged hoses. Overall, a RAS will at least double fluid servicing capacity for approximately 15% of the cost of an equivalent manual servicing facility.

Further research would be needed to quantify the benefit from a reduction in human error and improved safety. The consideration of the contribution of human error probability to risk is of paramount importance since incident analyses identify that human error is the key contributor to railway incidents<sup>27</sup>. The benefit of reduced risk and improved safety for staff would be to obtain improvement in the human performance of the operator. It would particularly benefit dull and repetitive tasks that require little conscious effort, for example, inserting numerous hoses and waiting for fluid to dispense. In addition, some rule-based processes, where the operator applies previously learned rules to tasks, for example, targeted maintenance involving part replacement or inspection.

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