

# Extending maintenance intervals of track switches utilising multi-channel redundancy of actuation and sensing

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## Abstract

A concept for a novel track switch arrangement has been developed at Loughborough University, which, through a novel locking arrangement, allows parallel, multi-channel actuation and locking functions for the first time. This switch has been developed as part of the REPOINT project, and is referred to as the REPOINT switch. Existing track switches generally use a single-channel actuator and lock, and undergo an intensive maintenance and inspection regime to ensure an acceptable level of reliability/availability. This paper demonstrates, through mathematical modelling with very conservative assumptions, that an increase in switch availability is possible alongside a corresponding decrease in ongoing maintenance intensity using the REPOINT multi-channel approach. The paper firstly introduces the theory behind the design of the REPOINT switch, using a switch with 2-out-of-3 redundant actuation and sensing channels as an example. An existing switch is analysed using real-world data as a benchmark. Availability is determined by the target time in which Maintenance Teams must have replaced any failed components, expressed herein as  $\tau$ . Availability measures are obtained as functions of  $\tau$  which show the range of possible switch availability against maintenance response times, for the given set of assumptions. The results show that for a REPOINT installation, gains in system availability are possible even when response times are set many times longer than current standards, indicating a significant reduction in ongoing maintenance cost.

**Key words :** Track Switch , Capacity, Reliability, Multi-channel Redundancy, Fault Tolerance, Maintenance

## 1. Introduction

It is commonplace in industries with safety critical or performance critical systems to replicate key components in order to increase whole-system life and reduce failure rates as per Isermann (2006). A project at Loughborough University called REPOINT has devised a novel arrangement for a railway track switch following this concept, described in Wright et al (2014) and in GB Patent 1322660. This new architecture of track switch enables multi-channel actuation to be used to provide improved switch performance in a way that is not possible with conventional switches. 'Performance', in this instance, refers to reduced lifecycle cost, increased availability, and improved maintainability. Alongside corresponding changes to the signalling system, it may allow for more capacity through existing junction layouts, when taken alongside signalling changes which allow a turnout to be treated more like plain line, in Bemment et al (2013). The design also eliminates several of the more common failure modes of traditional track switches. The architecture includes a condition monitoring scheme, which is designed to automatically reconfigure the control algorithm to isolate suspected faulty components, and enables the ongoing use of the switch with minimal degradation in performance until a repair becomes feasible. General arrangements of a traditional switch as presented by Morgan (2009), and a contrasting REPOINT switch are shown in Fig.1, described later.

The concept of replication of critical components in a system generally improves theoretical reliability; however

achieving the same in application requires consideration of human and economic factors. The fitment of a REPOINT switch is envisioned as part of a rail industry wide trend of moving to true condition-based maintenance, eliminating the need for regular and unrequired human intervention or inspection as in Bemment et al (2015), and Wright et al (2014). The asset manager must then decide on the required availability of the switch, which is determined by the target time in which Maintenance Teams must have replaced any failed components, expressed herein as  $\tau$ . As  $\tau$  decreases, the associated ongoing maintenance cost increases as more teams must be kept on standby, thus  $1/\tau$ , or 'maintenance intensity', can be taken as a general indication of the relative cost of maintenance. No attempt is made herein to quantify  $1/\tau$  in monetary terms as this value would be unique to the particular maintenance team arrangements at each specific locality.

This paper demonstrates, through mathematical modelling and conservative assumptions, that an increase in switch availability is possible alongside a corresponding decrease in ongoing maintenance intensity using the REPOINT multi-channel approach. The paper firstly introduces the theory behind the design of the REPOINT switch, using a switch with 2-out-of-3 redundant actuation and sensing channels as an example. A benchmark existing switch is analysed using data from real-world scenarios. Availability measures are obtained as functions of  $\tau$  which show the range of possible switch availability against maintenance response times, for the given set of assumptions. The results show that for a REPOINT installation, gains in system availability are possible even when response times are set many times longer than current standards, indicating a significant reduction in ongoing maintenance cost.

## 2. Operational Reliability and Asset Management Measures

It is necessary to distinguish between the mean time between unsafe failures (i.e. system in an unsafe state), and the mean time between operational failures. Literature, especially industrially-focussed documents, can cause confusion by representing either by the term 'MTBF' or 'MTTF' (Meant Time Between/To Failure). The distinction is made here between MTBF, the mean time between unsafe failures, and MTBOF (Mean Time Between Operational Failures), which describes how often the system can be expected to suffer a failure which interrupts operations. The latter would generally be expected to be substantially lower, and reflects the service quality that the system must provide. This concept is explored by Goodall et al (2006), with further mathematical modelling work on the reliability of 'k-out-of-N' systems discussed in Dwyer et al (2011). To make this distinction for railway track switching systems specifically, the MTBF would be required to be of a level of a modern high-integrity system, around SIL-4 ( $10^8 - 10^9$  hours) – i.e. so high that one would not normally expect to encounter a failure within the working life of the population for systems the size of a railway network (see Standard BS:EN61508 for a further discussion of SIL levels and their calculation). However, the MTBOF – the mean time to a switch failure causing network disruption – is much lower, and of the order of  $10^4 - 10^5$  hours, as can be observed from Table 2. In practice, if a single fault causes an unsafe condition in any system then some level of functional replication or redundancy is essential. This will usually ensure a satisfactory level of safety but always compromises reliability in some manner. The formula  $MTBF/(MTBF + MTTR)$  takes account of repair time to predict system availability, but this is different from operational availability because, for a fault-tolerant system with redundancy, operation continues while the repair is being effected. It should be emphasised that the basic elements in the track switching system are Line Replaceable Units (LRUs). These will not be repaired: there will be a stock of functioning units that maintenance engineers can use to replace the faulty/failed unit (which may subsequently be repaired in the background). This paper continues to use the word 'repair', even though in practice it will usually mean 'replace'.

Accepting that the MTBF cannot be relaxed for safety reasons, there is still scope to provide an improved MTBOF by improving the track switching system and its associated maintenance practices. This may, or may not, come at additional financial cost. Mathematical modelling can be used to provide an indication of the potential change in MTBOF versus cost for a given set of maintenance regimes. Traditional reliability modelling of a system may deliver results which are somewhat abstracted from the realities of the day-to-day operation of a railway. The modelling herein takes a railway asset management perspective, in that the primary controlled variable is one which can be directly affected by the asset manager to bring about the level of availability required of the asset. This variable is  $\tau$ , which describes the target time period in which a failed (or isolated as identified faulty) unit must be replaced by a maintenance team to deliver a given system MTBOF. Repair times are assumed to follow some general distribution  $f(\tau)$ .

### 3. Track Switching Practice (UK)

Track switching, in UK signalling practice is extensively discussed in literature relating to the design - Morgan (2009), maintenance - Cope and Ellis (2002) and operation - Hadaway (1950) of switches. Switches are actuated remotely by electro-mechanical devices, of various designs, which are responsible for the setting of the switch blades, their locking in position, and the communication of that position back to the controlling system and therefore the operator. An arrangement of device and moving rails is shown in Fig. 1. These devices can be situated many miles from available maintenance/response teams. Any system failure, whilst not necessarily a safety risk due to the inbuilt controls and associated operational procedure, causes much disruption to the network whilst a team is despatched to repair the system. This disruption is magnified where no diversionary route around the failed switch can be established, an increasingly common occurrence as the switch population is minimised by infrastructure operators in order to cut costs.

To counter any failures, switches undergo a labour-intensive maintenance programme. A typical set of maintenance interventions (UK) is shown in Table 2. More recent efforts include an extensive rollout of basic remote condition monitoring equipment since 2009 with much academic input into algorithm design, for instance in Silman and Roberts (2010). This effort has, in part, been responsible for a downward trend of switch failures over the intervening period, which can be observed in Table 1. However, whilst this downward trend may have caused a corresponding falling trend in reliability fines to the infrastructure owner, it does not correspond to a downward trend in maintenance costs. This is because the switches are now subject to periodic *and* condition based maintenance, primarily because the condition monitoring technology is not capable of monitoring the state of all safety-critical elements of the switch, necessitating the continuation of regular human inspection. For a conventional switch all significant failures create an unsafe condition and are therefore accommodated at a system level by the signalling system, i.e. an operational failure because functional redundancy in the switch itself is not possible. However the functional redundancy enabled by REPOINT means that an operational failure is when there is only one good actuation channel remaining. The balance of probability is that the single remaining actuator will probably still be working, but a single further failure is unsafe. Herein is the subtle distinction between MTBF and MTBOF, as defined in Section 2.

### 4. The Repoint Project

An ongoing project at Loughborough University, called 'REPOINT', has devised a novel architecture of track switch which allows multi-channel actuation of the movable track elements. The engineering detail of this design is omitted here for brevity, but [is](#) provided in several previous publications as cited above. The locking function is provided passively, such that each actuator can operate the switch alone, and with no performance degradation, with other channels isolated. A 1-in-3 schema is provided for analysis herein, but it is possible that the number of actuation channels could be adjusted for the requirements of a particular junction/route. Local condition monitoring is able to isolate any single unit in the event of a suspected fault. Each individual actuator is designed to have a standardised and line replaceable active element which can be exchanged trackside in the order of 2 minutes. These features open up the possibility of a truly condition-based maintenance regime. One option, explored here, is that two channels are required to actuate the switch, and provide reliable position feedback. Three channels are provided, whereby if a fault was suspected the faulty channel is immediately isolated and the other two could continue operation with performance unaffected. The active elements in the first channel could then be replaced at will by a passing maintenance team. A failure of a second channel, during the downtime of the first, would cause an operational failure, as defined in section 2.

A 384mm gauge demonstrator of this concept is currently operational in a laboratory at Loughborough University, UK, and is shown in Fig. 2.

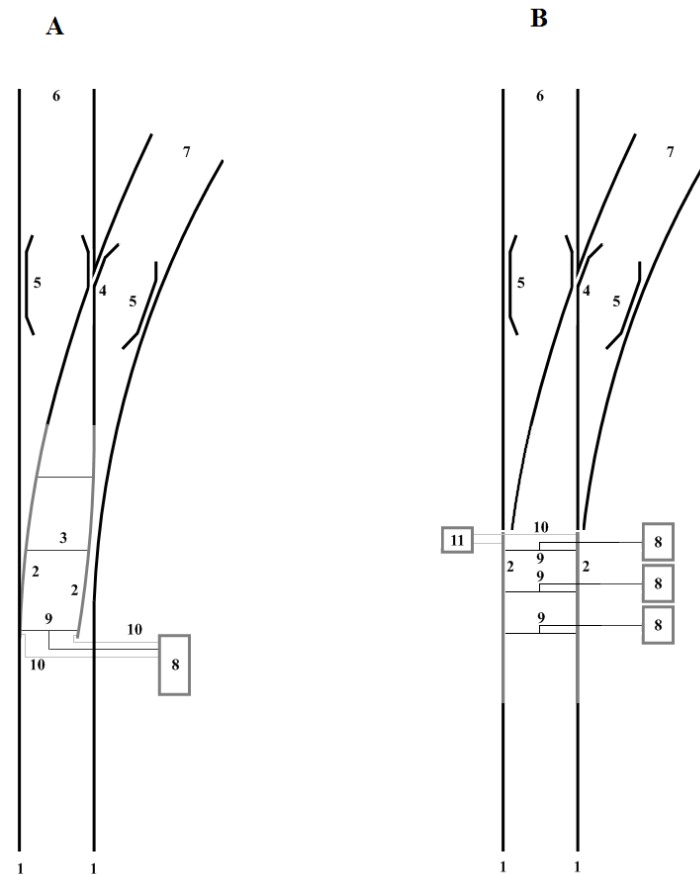


Fig. 1 Traditional (A) switch arrangement and proposed REPOINT (B) switch arrangement. 1 Stock Rails; 2 Moveable Switch Rails; 3 Stretcher Bars; 4 Common Crossing; 5 Check Rails; 6 Straight Route; 7 Turnout Route; 8 POE (Points Operating Equipment), line-side type shown; 9 Drive Bar and Drive Stretcher ; 10 Detection Rods, 11 Supplementary Sensor.



Fig. 2 Photograph of the 384mm gauge demonstrator in the laboratory at Loughborough University

Table 1: Incident count for infrastructure assets between 2017-2012 upon UK mainline, for top 18 incident categories (by count), including mean number of 'delay minutes' incurred per incident. Source: Office of Rail Regulation (2013)

Infrastructure type	Incident Count $I_c$						Mean	Mins/Incident Mean
	08-09	09-10	10-11	11-12	12-13	13-14		
<b>Track</b>	<b>7750</b>	<b>6665</b>	<b>5879</b>	<b>5519</b>	<b>5346</b>	<b>5997</b>	<b>6193</b>	<b>137</b>
Speed Restrictions	1428	1278	932	717	685	747	965	122
Track Faults	6322	5387	4947	4802	4661	5250	5228	139
<b>Non-Track</b>	<b>32001</b>	<b>30109</b>	<b>27157</b>	<b>25767</b>	<b>25121</b>	<b>25491</b>	<b>27608</b>	<b>97</b>
Points	8022	7118	5803	5162	5021	4376	5917	106
Level Crossings	2261	2162	2003	1932	1857	1936	2025	49
OLE/Third Rail	1458	1241	1281	1276	1265	1259	1297	205
Signals	6559	6202	5116	5018	4449	4278	5270	48
Track Circuits	5381	5145	4567	4243	3902	3729	4495	123
Axle Counters	1096	913	648	683	706	799	808	117
Signalling/Power	3750	4016	4422	4202	4494	4684	4261	114
Other Signalling	1495	1430	1513	1505	1300	1338	1430	41
Telecoms	1406	1352	1252	1176	1513	2406	1518	46
Cables	573	530	552	570	614	686	588	281
<b>Other</b>	<b>12633</b>	<b>9303</b>	<b>9084</b>	<b>9212</b>	<b>9289</b>	<b>10753</b>	<b>10046</b>	<b>74</b>
Structures (Civils)	397	436	385	279	444	574	419	253
Other Infra.	5478	3772	3455	3774	3612	4739	4138	62
Track Patrols	3362	2565	2269	1949	2213	2075	2406	16
Mishaps	1839	1183	1493	1838	1836	2009	1700	93
Fires	197	221	250	257	116	218	210	145
Bridge Strikes	1360	1126	1232	1115	1068	1138	1173	129
<i>Total</i>	<i>52384</i>	<i>46077</i>	<i>42120</i>	<i>40498</i>	<i>39756</i>	<i>42241</i>	<i>43846</i>	<i>97</i>

Table 2: Typical scheduled maintenance operations for UK switch installations, and total labour time. Note labour time does not include travel to site. Source: Network Rail/Interview.

ID	Type	Interval	Intervention time (Hours) ( $t_m$ )	Possession Required
1	Track Component Inspection	Weekly	0.1	No
2	Track Gauging, Adjustment	4-weekly	1	No
3	Track Element Renewals	5-yearly	10	Yes
4	Signalling 'A' Service	4-weekly	1	No
5	Signalling 'B' service	13-weekly	1	No
6	Signalling 'C' Service	Yearly	4	Yes
7	Location Case Inspection	13-weekly	1	No

## 5. Modelling Operational Reliability – Traditional Switches

### 5.1 Establishing a Baseline

In order to provide a comparator for the modelling of the Repoint switch, there first needs to be estimated some baseline figures for switches as currently deployed. This estimate can, in the first instance, come from the data provided in Table. 1 and Table. 2. The population of UK switches is 21602 (2013).

$$\begin{aligned} \text{MTBOF} &= (\text{Population} / I_{c\_mean}) * \text{Hours\_in\_year} \\ &= (21602 / 5917) * 8766 \\ &= \underline{\sim 32003\text{hrs} (\sim 3.65 \text{ years})} \end{aligned} \quad (1)$$

There are two significant unknown variables for further calculation.

Firstly, the actual repair time for operational failures (i.e. the time the switch is unavailable following a failure in use). For this modelling exercise, the mean number of ‘delay minutes’ per incident will be used. Delay minutes are a measure used in the UK to establish the severity of impact upon the network due to an asset failure. The calculation, and attribution, of delay minutes to particular faults is not through a particularly scientific process, but the mean magnitudes provided in Table- 1 provide a good first estimate. This repair time includes transit to site for emergency responses only.

Secondly, the transit time  $t_t$  of maintenance teams to site is unknown, and may be widely variable depending on the particular switch, depot location, time of day (e.g. rush hour) team utilisation, etc. From interviews with network operators, it has been established that 1 hour *per switch* is a typical figure. This has previously been modelled as a Poisson distribution, as per Rausand and Hoyland (2004), but as the goal is a benchmark figure this mean value has been assumed. Note transit time is not included for item number 1 in Table- 2, as the weekly visual inspection is part of the ‘track walk’ conducted by operations staff, therefore transit time is essentially zero. Availability is indicated by considering the sum of downtime (delay minutes incurred, from Table 1) from operational failures and scheduled maintenance (where the asset is out of use, ‘under possession’ only), as:

$$\begin{aligned} \text{Availability} &= (\text{MTBOF} / (\text{MTBOF} + \text{MTTR})) - \sum(t_{m\_peryear} / \text{Hours\_in\_year}) \quad (2a) \\ &= (32003 / (32003 + 1.77)) - (6 / 8766) \quad (2b) \\ &= \underline{0.999260} \end{aligned}$$

This availability is alternatively termed “three nines”, as there are three nines after the decimal point. It is achieved with a given direct given labour commitment time, consisting of the sum of time spent on interventions ( $t_{m\_peryear}$  of given frequency  $F_i$ , and associated transit time  $t_t$  (where  $t_t$  is multiplied by 2 to give out and back transit time). Note direct labour does not include management, overheads etc. Including emergency responses from above, this gives:

$$\begin{aligned} \text{Labour\_time} &= \text{Maintenance\_time} + \text{Transit\_time} + \text{Emergency\_response\_time} \quad (3a) \\ &= \sum F_i * t_{m\_peryear} + \sum F_i * 2t_t + ((1/\text{MTBOF}) * (\text{MTTR}_{\text{hours}} + t_t)) \quad (3b) \\ &= 45.20 + 35.20 + 0.62 \quad (3c) \\ &= \underline{\sim 81 \text{ hours/year}} \end{aligned}$$

### 5.2 Discussion: Variables and Limiting Factors

The labour value quoted in 5.1 is somewhat misleading in that it still relies upon teams being on standby to respond to faults within the prescribed 106 minutes; they are essentially still ‘working’ when on standby. Section 2 introduced  $\tau$ , the time in which a maintenance team must fix any failed components, and return the switch to a functional state. For a system without parallel redundancy of mission-critical components, the system is safe but the asset is out of use during this period, and the target  $\tau$  must be as small as possible as it is equivalent to MTTR. Eqn (2b) shows the relative importance of unscheduled and scheduled maintenance with regards the availability figure. Because MTTR is much

less than MTBOF there is a linear relationship between MTTR and availability. This relationship is shown in Fig. 3a. There is limited opportunity to relax  $\tau$  whilst still maintaining “three nines” due to the relative frequency of failure, but, over 10h is achievable. However, unscheduled failures in the UK typically incur a monetary cost around 100x scheduled maintenance downtime (through performance-related fines) meaning this approach to cost saving would be counter-productive in practice. The number of teams required on standby for a given geographical area can be deduced from a Poisson distribution and is the subject of further work.

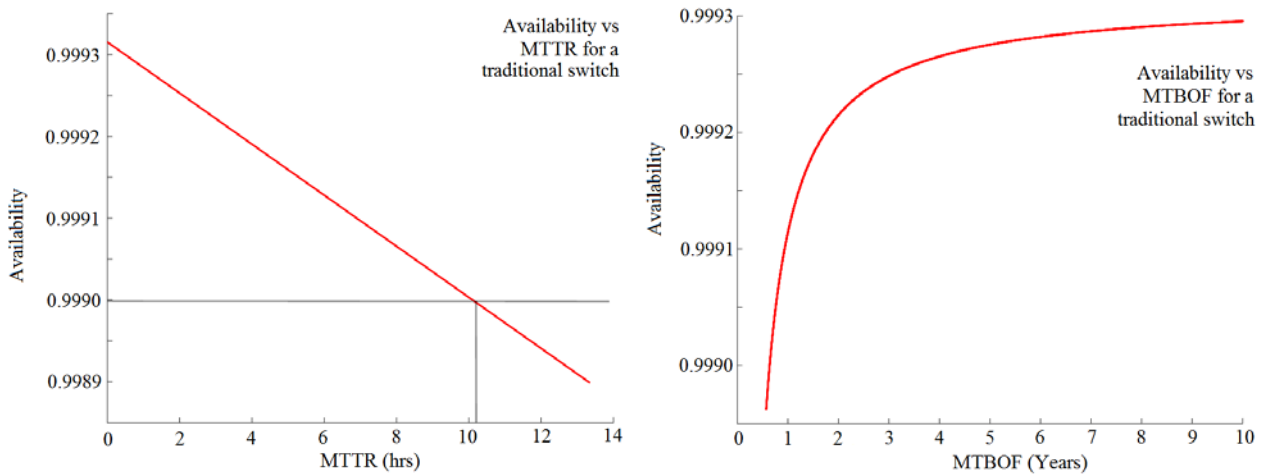


Fig. 3: Plots showing variation of asset Availability vs MTTR (a, left) and MTBOF (b, right) for a traditional switch installation

Figure 3b shows that even by working to improve the MTBOF to the order of 10 years, the availability figure is plateauing well within the bounds of “three nines”. This is because the remaining unavailability is taken up by preventative maintenance practices, which are necessary for an asset which cannot be ‘run to failure’. This ceiling is of significance as it represents the practical performance limit of the traditional approach with a single actuator. Improving the MTBOF has been the subject of much academic and industrial work, for instance Silmon and Roberts (2010), yet this plot indicates returns are significantly diminishing as the gradient levels out beyond around 4 years MTBOF.

## 6. Modelling Operational Reliability – REPOINT Switches

### 6.1 Mathematical Model

Consider the case of a triplex system, in which the failures of each subsystem are modelled by IID (independent, identical) exponential distributions, with a constant failure rate  $\lambda$ . This is the modelling approach taken by Goodall et al (2006), and a full derivation can be found therein. The system can be described by a state machine, with parameter  $S$ , equal to the number of units currently non-operational, or in repair. The system starts at time  $t=0$  with  $S=0$ , meaning all units are fully functional. When a unit fails, the state becomes  $S=1$ , with a response and repair time given by  $\tau$ . Provided there are no further failures, the system will progress through this state, returning to  $S=0$  after time  $\tau$ .  $\tau$  could be considered an IID exponential distribution in the same way, or else a constant target which is the maximum allowed repair time, as here, in order to indicate a lowest availability bound (assuming the target is met). If a further failure occurs, then  $S=2$ , and an operational failure is considered to have occurred, necessitating an emergency response. This is described in the state diagram shown in fig. 4.

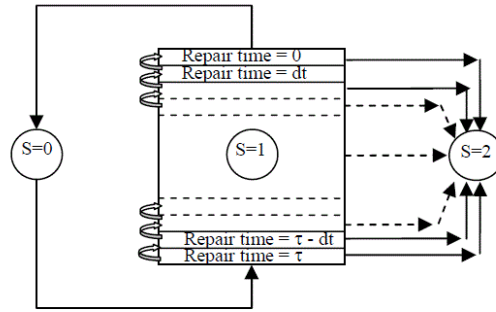


Fig. 4: State transition diagram for a triplex system, as per Goodall et al (2006).

The availability is still given by Eqn. (2b). The MTBOF value is now derived from the state machine model as below. A full derivation of this formula is provided in Goodall et al (2006), but excluded herein for brevity:

$$\text{MTBOF} = 1/(3\lambda(1-e^{-2\lambda\tau})) + 1/(2\lambda) \quad (4)$$

There are now several assumptions made about the system:

- That there is no scheduled maintenance apart from a weekly visual inspection (as in Table 2 ID1, and mandated by law) and a 5-yearly replacement of worn track elements (ID3), but at 3hr possession cost due to the concept utilising redesigned rail ends that can be quickly changed without major work to the structure of the switch.
- That the probability of failure during this 5-yearly, 3 hour maintenance window is negligible and can be ignored for simplicity.
- That the  $\lambda_{\text{Repoint}}$ , the subsystem failure rate, is higher than  $\lambda_{\text{Traditional}}$  for two reasons. Firstly, there is no scheduled maintenance. Secondly, the condition monitoring system has a necessarily high sensitivity (and subsequent false positive rate) in order to isolate faulty units before they fail in use. A very conservative estimate is that:

$$\lambda_{\text{Repoint}} = 20 * \lambda_{\text{Traditional}} \quad (5a)$$

$$\begin{aligned} \lambda_{\text{Repoint}} &= 20 * 1/32003 \\ &= 6.25 * 10^{-4} \end{aligned} \quad (5b)$$

- The MTTR is estimated equivalent to a traditional switch (106 mins). This is again a conservative estimate, as the REPOINT system is designed to have line-replaceable units to make repair almost instantaneous.

## 6.2 An asset management approach

Section 2 introduced  $\tau$ , the time in which a maintenance team must fix any failed components, and return the switch to a S=0 state. For a system without parallel redundancy of active components, the asset is out of use during this period, and the target  $\tau$  must be as small as possible as it is equivalent to MTTR (see section 5.2). If we assume each subsystem failure is treated as an emergency, as now, then using Eqns. (2a) and (4), values for the MTBOF and availability of a Repoint switch under the current maintenance/response regime can be calculated:

$$\begin{aligned} \text{MTBOF} &= 1/(3\lambda(1-e^{-2\lambda\tau})) + 1/(2\lambda) \\ &= 2.43*10^5(\text{hours}) \quad (=27.6 \text{ years}) \end{aligned} \quad (6)$$

$$\begin{aligned} \text{Availability} &= (\text{MTBOF} / (\text{MTBOF} + \text{MTTR})) - (5/8766) \\ &= 0.99992 \end{aligned} \quad (7)$$

The REPOINT approach shows a MTBOF an order of magnitude higher than traditional solutions. Availability has improved to ‘four nines’ standard, though largely through the removal of scheduled maintenance due to the ability to run-to-failure for individual subsystems. Whilst such availability may be attractive to most infrastructure owner/operators, of equal interest may be the labour saving. The labour hours to achieve such availability are again given by Eqn. (3a/b):

$$\text{Labour\_time} = \text{Maintenance\_time} + \text{Transit\_time} + \text{Emergency\_response\_time} \quad (8)$$

$$= \sum F_i * t_{m\_peryear} + \sum F_i * 2t_t + ((\lambda_{\text{Repoint}}) * (\text{MTTR}_{\text{hours}} + t_t)) \quad (9)$$

$$= \sim \underline{16.4 \text{hours/year}}$$

However, the labour value above is again misleading in that it still relies upon teams being on standby to respond to faults. By selecting a value of  $\tau$  many times longer than the emergency repair time, flexibility is increased, and teams formerly on emergency standby can build replacing individual units into the daily, weekly or monthly maintenance plan. Figure 5 shows a plot of  $\tau$ , in hours, against availability for values of  $\tau$  up to 4 weeks. This indicates a ‘three nines’ availability, equivalent to existing installations, can be achieved with a 525h  $\tau$  policy. It is, of course, up to the local asset manager to decide the particular value of  $\tau$  and therefore labour spend vs availability, but the plot in Fig.5 shows all values are an order of magnitude higher than the traditional solution. This demonstrates that the REPOINT approach, even with very conservative estimates, can offer savings in maintenance costs alongside improved availability across a range of possible maintenance staffing scenarios.

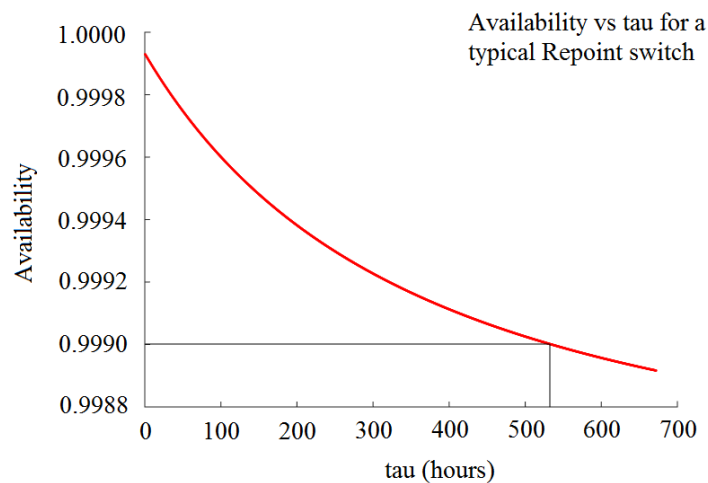


Fig. 5: Availability achieved for a given  $\tau$  value, in hours. ‘Three nines’ is still achieved with a 525h maximum replacement time.

## 7. Conclusions

A concept for a novel track switch arrangement has been developed at Loughborough University, which, through a novel locking arrangement, allows parallel, multi-channel actuation and locking functions for the first time. This paper has demonstrated, through mathematical modelling and conservative assumptions, that an increase in switch availability is possible alongside a corresponding decrease in ongoing maintenance intensity using the REPOINT switching concept. The results show that for a REPOINT installation, gains in system availability are possible even when response times are set many times longer than currently achieved, indicating a significant reduction in ongoing maintenance cost.

## 8. Future Work

The work presented herein is a first approximation for a piece of modelling work regarding the operational performance of a REPOINT installation, for which there are, in reality, many more variables. In particular, the individual failure rates shall be modelled as IID exponential distributions, and the measure of maintenance intensity  $\tau^{-1}$  shall be used to model the cost saving possible from a parallel subsystems, run-to-failure maintenance regime, through the use of monte-carlo simulation. An important measure to be deduced from  $\tau$  will be the number of maintenance teams necessary, for a given geographical area, to give a level of availability equivalent to existing practice.

## 9. Acknowledgements

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