Assessing the potential cost savings of introducing the maintenance option of 'Economic Tyre Turning' in Great Britain railway wheelsets

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Abstract

This paper assesses the potential cost savings of introducing a maintenance option known as 'Economic Tyre Turning' (ETT) in railway wheelset maintenance in Great Britain. It first develops a life-cycle cost model and puts forward a Monte Carlo simulation procedure to assess the life-cycle costs of different maintenance strategies, including ETT. This Monte Carlo simulation procedure samples from statistical degradation models that estimate the evolution of wear and damage trajectories of different wheelsets, and the maintenance impact of wheel turning in the loss of diameter in a more realistic manner by controlling random effects related to unit, vehicle and month of measurement. The main findings suggest that ETT may provide potential savings of around 0.8% up to 4.4% when compared to a simple wheelset renewal strategy, and between 2.0% and 4.7% cost savings when ETT is used in association with more complex strategies.

Keywords: maintenance; railways; life-cycle costs; Monte Carlo simulation; wheelsets

1. Introduction

Any complex engineering system requires maintenance from time to time. The railway system is not an exception, and thus, the train system requires maintenance in a cost-effective way, while ensuring safety and availability constraints/requirements. The topic of maintenance models to support decision-making has been the focus of several research works in different areas and from different perspectives: from repair models, opportunistic models, maintenance models, maintenance/replacement models and up to inspection/maintenance models [1].

These models mainly explore decision-making regarding preventive and corrective maintenance [2], exploring maintenance grouping in multi-component systems [3, 4], assuming perfect or imperfect or minimal maintenance, and balancing overall costs. Their main objective is to support maintenance

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decisions leading to a risk-informed and optimized strategy. Moreover, very often these models assume a life-cycle cost perspective.

Uncertainty plays an important role in the maintenance modelling. Not only might components of the same type deteriorate at a different rate, but its inspection and/or maintenance action may involve some uncertainty, due to human factors or the accuracy of the inspection/maintenance instruments or machines. Assessing the impact of the uncertainty associated with deterioration, inspection, maintenance and renewal processes are vital for the determination of a robust strategy to maintain the system. Simulation-based approaches are very often used to conduct robust assessment of maintenance strategies/rules [31, 32, 33]. Nevertheless, mixed effects (fixed and particularly random effect) have not been considered explicitly and modelled in these simulation-based approaches. Rare exceptions are [34, 35, 36] in controlling explicitly for random effects on nuclear, aircraft engine or electrical engineering systems, and thus providing more realistic prediction of degradation for each unit/component. In this sense, our research puts forward a simulation procedure that controls for the random effects associated with each factor (train unit, individual vehicles within the unit, month of measurement, etc), for each predictive model explaining the evolution of each dependent variable, providing a more realistic simulation of the maintenance needs, and thus a more robust assessment of the life-cycle costs for each maintenance strategy.

Typically, the state-of-the-art and practice of maintenance for a given component or system is typically condensed into a technical standard or maintenance procedure that provides guidelines and technical requirements for that component or system. Nevertheless, when a change in a technical standard is proposed, an extensive analysis of the impacts of such a change is needed, demanding an economic, engineering and safety assessment of its impacts throughout its life-cycle, and on current preventive and corrective strategies, availability and other impacts. The present paper provides a discussion on the economic assessment associated with a change in the maintenance of railway wheelsets in on trains in Great Britain (GB).

Economic Tyre Turning (ETT) is a wheel maintenance action not currently allowed by the GB Railway Group Standard (RGS) GM/RT2466 [5]. In accordance with this standard, wheel turning actions must restore the full flange profile, which may pose significant losses in the wheel tread diameter. ETT is a maintenance action that allows the wheel maintainers to partially restore the wheel profile, as long as the minimum in-service limits for flange thickness and height are met. ETT typically lead to thinner flanges and to some savings in the diameter loss, extending the wheelset life.

Previous research work conducted within the Rail Safety and Standards Board (RSSB) research project T963 [6], which resulted in the development of the Wheel Tread Damage Guide, pointed out this unexplored opportunity of introducing ETT in GB, whilst RSSB research project T641 [7] showed that revised profiles with thinner flanges would still comply with current geometric limits in RGS, regarding safety and resistance to derailment. Nevertheless, previous research has not presented a business/economic case on the risks and benefits of including ETT as an option in the current standard. Therefore, this paper aims to explore the potential economic benefits of ETT as a maintenance action, as part of the evidence base which may be required to support a potential change to the current RGS GM/RT2466.

The outline of the paper is as follows: this first section introduces the need to study the economic benefits of ETT in the maintenance of railway wheelsets. Then, the second section explores the state of the art and practice in maintenance modelling of railway wheelsets, namely the ETT action. The third section puts forward a life-cycle cost (LCC) model to support maintenance decisions. Moreover, the fourth section specifies some statistical degradation models for the wear and the damage trajectories, providing a simulation procedure to assess the life-cycle of a railway wheelset and the fifth section puts forward a Monte Carlo simulation procedure to assess the life-cycle costs of a fleet of modern multiple units for different maintenance strategies including ETT. The final section highlights the main conclusions and 'paves the way' for future research.

2. State of the Art and State of the Practice in maintenance of railway wheelsets

2.1. State of the Art

The contact between wheel and rail must be monitored throughout the life-cycle of wheelsets and rails. Predicting the wear and damage of rails and wheelsets is a crucial aspect to ensure that both rail and wheelsets are maintained in a cost-effective manner. Data driven models to predict wear and damage trajectories for railway wheelsets have been put forward to support re-profiling strategies in metro systems [8, 17]. The optimisation of wheelset maintenance has considered not only the costs associated with wheelsets but also associated with the rail component [9]. Inspection intervals have also been optimized by considering reliability and availability components [10]. Moreover, mechanical engineering models have been put forward to estimate rolling contact fatigue (RCF) [18, 19] and wear [20] of railway wheels, and in locomotive wheels [21]. Statistical models were also proposed using a parametric Bayesian approach [22], discussing data analysis techniques for samples under unequal operating conditions [23] and with the aim to assess reliability of railway wheelsets [24]. Wheel profile parameters have also been used as indicators of increased risk of wheel defects [25] and as indicators for decision-making in condition monitoring at the wheel/rail interface [26].

The use of commercial multibody software to study the railway dynamic problem to predict the wheel wear evolution can be found in [27], in which the authors analysed how wheel wear progression was affected by some physical parameters related to vehicle characteristics. Regarding primary suspension stiffness, they found that a vehicle assembled with softer primary suspensions tends to produce less wheel wear on both tread and flange zones. Regarding the effect of rail inclination, they found that a track with a rail inclination of 1/40 had larger re-profiling intervals, though this finding had mainly to do with the fact that the wheels simulated (S1002 profiles) also had a tread inclination of 1/40. The complex nature of a wheel wear prediction model from a mechanical engineering perspective is also highlighted in [28], comprising: i) simulation of vehicle dynamics, ii) local wheel-rail contact model, iii) local wear model. The authors carried out some experimental tests using a twin disc machine to validate a wear rate function according with a $T.\gamma/A$ parameter (also known as wear index), in which T is the contact force in the contact plane, A is the contact area and γ is the relative slip. This wear law has been used extensively in other studies [29, 30].

2.2. Current Maintenance Practices

Although in Great Britain, ETT is not allowed, it is currently conducted in several European railway administrations as it is accommodated by the European standard EN 13715 [11]. For instance, Northern Ireland Railways (NIR) has some experience on extending wheel life allowing thinner flanges. In 2003, NIR approved the possible offset of the P1 profile by up to 2 mm so that it allows the further use of worn wheels, which would have gone below the scrapping diameter, and thus providing some additional life. Moreover, Pascual and Marcos reported on the US experience of Talgo on wheel wear management of 'high-speed' passenger trains [12]. Talgo developed a maintenance program called Total Logistic Care (TLC) that keeps the flange thickness within an 'optimal' range of operation, instead of waiting until the wheel is out of the specifications. The French train operating company SNCF reportedly allows ETT as part of its maintenance strategy. SNCF uses multiple criteria for turning wheels as defined by EN 13715 [11]. Their maintenance rules appear to be developed using a risk management system, called REX [13]. It seems to attempt to benefit from the experience of the people who run the system, rather than solely based on the historical analysis of incidents and accidents. Apparently, REX adds a subjective dimension to risk assessment to tackle organizational issues with multiple decision-makers and multiple criteria. Nevertheless, no specific information on the practical maintenance rules could be found. The Portuguese train operating company CP has already been using 'economic' profiles, i.e. profiles that were turned using ETT. As a criterion, they set a minimum flange thickness of 28.0 mm post-turning, though several wheels are leaving the wheel lathe with a higher flange thickness (e.g. 29.0 or 30.0 mm), depending on the amount of wheel diameter it has to be removed due to damage defects. However, it seemed that no proper study or optimization model has been used, and in fact, it seems that a lot of the practical decision rules are derived from the experience of wheel maintainers. The German train operating company DB has also been using ETT as a maintenance action. For instance, for S1002 profiles, wheels have been turned with a 1.0 mm reduction in the flange thickness compared to the new wheels, i.e. flange thicknesses changing from Ft=32.5 mm to Ft=31.5 mm, due to running stability reasons rather than to optimize the material removed in the lathe. No further details on any decision support system to plan the maintenance actions were obtained.

3. Life-cycle cost model to support maintenance decisions

This section puts forward a life-cycle cost (LCC) model to support different maintenance strategies, namely to assess the potential cost savings for ETT actions when compared to other current options. A wheelset life-cycle cost model (WLCC) should include renewal costs ($\mathrm{C_R} = \mathrm{c_R}$), total maintenance costs ($\mathrm{C_M} = \mathrm{c_M}.N_M$), inspection costs ($\mathrm{C_I} = \mathrm{c_I}.N_I$) and unavailability costs ($\mathrm{C_{un}} = \mathrm{c_{un}}.N_{un}$).

$$\mathrm{C_T} = \mathrm{C_R} + \mathrm{C_M} + \mathrm{C_I} + \mathrm{C_{un}} = \mathrm{c_R} + \mathrm{c_M}.N_M + \mathrm{c_I}.N_I + \mathrm{c_{un}}.N_{un} \quad (1)$$

In which: $\mathrm{c_M}$, $\mathrm{c_I}$ and $\mathrm{c_{un}}$ are the unit costs for maintenance/turning action, inspection action and unavailability occurrence, respectively; N_M, N_I and N_{un} are the number of maintenance/turning actions, the number of inspection actions and the number of unavailability occurrences in a life-cycle. Note that in a life-cycle, the renewal cost is incurred only once so $\mathrm{C_R} = \mathrm{c_R}$.

The wheelset life-cycle is usually measured in distance units, instead of time, in our example in wheelset mileage. As a typical wheelset life-cycle (L) is not that long, when compared to that for railway track for example, it was assumed that working with discounted costs would not represent an important advantage, and thus, no discount rate was considered in the cost calculations.

Moreover, it is necessary to choose the objective function to be minimized. Typical choices are the minimization of the total life-cycle costs ($\mathrm{C_T}$) and the minimization of the total life-cycle costs per mileage ($\mathrm{C_T}/\mathrm{L}$). In our example, we used the minimization of the total life-cycle costs per mileage.

Based on the previous RSSB research project T792 [14], several LCC inputs were collected and adapted to Table 1. These unit costs will vary depending on the train operating companies and on the fleet under analysis, though they represent a typical interval for inspection (l_I) and the average costs for renewal ($\mathrm{c_R}$), maintenance ($\mathrm{c_M}$), inspection ($\mathrm{c_I}$) and unavailability ($\mathrm{c_{un}}$). Note that all costs in Table 1 are costs per wheelset, except the unavailability cost, which is a cost per train.

The number of inspections (N_I), the number of maintenance/turning actions (N_M) and the number of unavailability occurrences (N_{un}) are estimated assuming periodic inspections between maintenance actions, and using the set of simulated values of the wheelset mileage since last turning action ($m_1, \dots, m_n$) for all maintenance/turning cycles throughout the life-cycle of the wheelset. The simulation procedure that computes a set of wheelset mileages since last turning ($m_1, \dots, m_n$) for all the maintenance cycles in a wheelset life-cycle is put forward in Section 5. For example, the number of inspections is estimated by rounding down the quotient between the wheelset mileage and the inspection interval (l_I) and summing it over all maintenance/turning cycles, i.e. $N_I = \sum_n \lfloor m_n / l_I \rfloor$.

4. Statistical modelling of wear and damage trajectories

Quantitative statistical models were added to model the evolution of the main geometrical variables of the wheel and the occurrence of wheel tread damage defects. Details are provided on a set of statistical models that predict the evolution of the flange height and thickness as well as the occurrence of other defects like rolling contact fatigue (RCF), wheel flats and cavities. These statistical models will then feed the simulation procedure developed in section 5 and the LCC model from section 3, providing a quantitative basis to assess the impact of introducing ETT in the maintenance strategies and in the life-cycle costs per mileage.

These statistical models are used to predict the evolution of wear and damage trajectories. The comparison of different model specifications within the Linear Mixed Models (LMM) and the Generalized Linear Mixed Models (GLMM) is discussed elsewhere [15], and the use of Stochastic Frontier Analysis (SFA) to account for different technical efficiencies of the wheel lathe operators is also discussed in more detail in [16]. Therefore, this section describes the 'best' models from our previous work [15, 16], according to the Akaike Information Criterion (AIC), that are used in the Monte Carlo simulation procedure proposed in section 5.

The following variables were statistically modelled to describe the wear and damage trajectories:

- On the wear trajectory: the change in the flange thickness (ΔF_t), the change in the flange height (ΔF_h) and the change in the tread diameter due to wear (ΔD) were modelled using LMMs;
- On the damage trajectory: the occurrence of other wheel defects, such as rolling contact fatigue (Y_{RCF}), wheel flats (Y_{FLAT}) and cavities (Y_{CAV}) were modelled using GLMMs (particularly the Binomial distribution with logit link function).

Table 2 shows the estimated coefficients for the fixed effects and random effects for each dependent variable: ΔF_t, ΔF_h, ΔD, Y_{RCF}, Y_{FLAT}, Y_{CAV}. Further details are provided in [15] with extensive comparisons between alternative model specifications for each dependent variable. So, for instance, the change in the flange thickness (ΔF_t) and the probability of an RCF defect (p_{RCF}) would be estimated using the following expressions 2 and 3:

$$\Delta F_t = \beta_0 + \beta_M M + \beta_{M^2} M^2 + \beta_{M^3} M^3 + \beta_W W + b_{M_n} + b_U + b_V + \varepsilon \qquad (2)$$

In which: b_{M_n}, b_U and b_V are random effects and ε is the typical random measurement noise, so that $b_{M_n} \sim N(0, d_{M_n})$, $b_U \sim N(0, d_U)$, $b_V \sim N(0, d_V)$, $\varepsilon \sim N(0, \sigma^2)$ and independent of each other. Note that in the expression $b_{M_n} \sim N(0, d_{M_n})$, the symbol '$\sim$' means that b_{M_n} follows a certain probability distribution, in this case the Normal (N) probability distribution with mean equal to zero and variance equal to d_{M_n}. The same is valid for b_U, b_V and ε with different variances. M is the wheelset mileage since turning (and three terms are used: linear M, quadratic M^2 and cubic M^3), W is a nominal variable that assumes one of the wheelset types: Motored, internal Trailer or Leading; in each case $\beta_W W$ is equal to β_{Motor}, or $\beta_{Trailer}$ or $\beta_{Leading}$, respectively.

$$p_{RCF} = P[Y_{RCF} = 1] = \frac{1}{1 + \exp\left(-(\beta_0 + \beta_M M + \beta_D D + \beta_W W + b_{M_n} + b_U + b_V)\right)} \qquad (3)$$

Note that the remaining dependent variables would have similar expressions to the previous ones in accordance with Table 2. Another variable (Y_{other}) was included for any other type of defect not covered by the RCF, wheel flats and cavities, and thus a simple value was assigned to the probability of occurring this defect $p_{other} = 0.5\%$ as no reasonable model was found to model that dependent variable.

Furthermore, an additional dependent variable referring to the diameter loss due to turning (ΔD_T) must be added to the statistical modelling. The diameter loss due to turning was modelled through a Stochastic Frontier Analysis (SFA) model, considering the occurrence of damage defects and controlling for other variables, including inefficiencies of wheel lathe operators. More details are provided in [16] with an extensive comparison between alternative specifications and using a LMM approach. Table 3 shows the estimated coefficients for the parameters associated with each explaining variable and the associated standard deviations in parenthesis. In terms of the error components, σ_v is the standard deviation for the random error component associated with the measurement noise, i.e. $v \sim N(0, \sigma_v^2)$, and σ_u is the standard deviation of the error component associated with inefficiencies, i.e. $u \sim N_+(0, \sigma_u^2)$, so that u is always positive and follows a one-sided distribution (e.g. a half-normal distribution, denoted by N_+). Then, the following expression can be used to estimate the diameter loss due to turning:

$$\Delta D_T = \beta_0 + \beta_{F_t} F_t + \beta_{RCF} Y_{RCF} + \beta_{FLAT} Y_{FLAT} + \beta_{CAV} Y_{CAV} + \beta_W W + \beta_{M\times RCF} M.Y_{RCF} + \beta_{M\times FLAT} M.Y_{FLAT} + \beta_{M\times CAV} M.Y_{CAV} - v + u \quad (4)$$

Regarding the diameter loss due to 'economic tyre turning' action (ΔD_{ETT}), no data is available and thus some assumptions had to be made to specify a statistical model. A typical assumption is that the flange will wear with a constant flange angle (qR=68º-70º), so that a 1 mm of reduction in flange thickness (i.e. a 1 mm horizontal shift) will translate into a 1mm×tan(qR) of reduction in radius (i.e. a 2.48-2.75 mm vertical shift). This quantity has to be multiplied by two as a wheel diameter has two radii, which leads to approximately 5.00 mm of diameter loss per millimetre of reduction in the flange thickness. This geometrical argument shows then that the diameter loss due to turning can be approximated with a linear relationship to the flange thickness, as pointed out in the Wheel Tread Damage Guide [6]: 'it is typically about five times the flange wear (depending on the flange angle and shape)'. The following expression for the diameter loss due to 'economic tyre turning' (ΔD_{ETT}) combines this rule of thumb with some findings from the SFA model for the diameter loss due to simple turning (ΔD_T):

$$\Delta D_{ETT} = \begin{cases} \max(5 \times (F_t^{ETT} - F_t), \Delta D_T), & F_t < F_t^{ETT} \\ Damage, & F_t \geq F_t^{ETT} \end{cases} \quad (5)$$

In which: F_t^{ETT} is the flange thickness post-turning (e.g. 26.0 mm), $Damage$ is the component relative to damage in the SFA model for the diameter loss due to turning (i.e. the part of the SFA expression where any dependent variable Y_{RCF} , Y_{FLAT} or Y_{CAV} is directly present, so that $Damage = \beta_{RCF}.Y_{RCF} + \beta_{FLAT}.Y_{FLAT} + \beta_{CAV}.Y_{CAV} + \beta_{M\times RCF}.M.Y_{RCF} + \beta_{M\times FLAT}.M.Y_{FLAT} + \beta_{M\times CAV}.M.Y_{CAV}$); ΔD_T is the diameter loss due to turning computed based on the SFA model in Table 3.

Note that if the flange thickness is higher than the value set for the flange thickness post-turning (e.g. 26.0 mm), and for the cases that no damage defect occurs, ΔD_{ETT} would be equal to zero. Otherwise, i.e. if the flange thickness is lower than the value set for the flange thickness post-turning, ΔD_{ETT} is the maximum between: the diameter loss given by the rule of thumb and the diameter loss if the full flange turning was conducted.

5. A Monte Carlo simulation procedure to assess different maintenance strategies

Having specified several statistical models that can predict the evolution of the main variables describing wear ($\Delta \mathrm{F_t}$, $\Delta \mathrm{F_h}$ and ΔD), and the probabilities of occurrence of damage defects ($\mathrm{p_{RCF}}$,

$\mathrm{p_{FLAT}}$, $\mathrm{p_{CAV}}$ and $\mathrm{p_{other}}$), as well as the maintenance impact in the diameter loss due to turning ($\Delta\mathrm{D_T}$ and $\Delta\mathrm{D_{ETT}}$) in Section 4, this section will explore a Monte Carlo simulation procedure to assess different maintenance strategies using the LCC model developed in Section 3.

The main idea behind this Monte Carlo simulation procedure is that the simulation procedure samples from the statistical models specified above, for each maintenance cycle, but controlling for the random effects associated with the unit, the vehicle and the month of measurement, so that the wear and damage trajectories and the associated maintenance needs and unavailability impacts are as realistic as possible for a generic fleet of modern multiple units.

Figure 1 provides a schematic representation of a unit, with three vehicles (DMC, MS and DMS), four axle positions for each vehicle (AP1-AP4) and their associated wheelset type (M – motor, T – internal trailer and L – leading trailer).

To make the simulations more realistic, the assumption of fixed turning intervals is relaxed and, based on a sample collected for a fleet of modern multiple units, a simple cumulative distribution is defined, for the mileage since turning for each turning cycle, as shown in Figure 2. It represents two examples to illustrate how the turning cycles are simulated for a fixed turning policy defined by the interval s, for s=120,000 and s=150,000 miles. Setting the fixed turning interval s equal to s=120,000 miles truncates the cumulative probability distribution at s=120,000 miles, i.e. 40% of the wheelsets will have mileage since turning below 120,000, and the remaining 60% of the wheelsets will have exactly 120,000 miles; whereas if the fixed turning interval s is set equal to s=150,000 miles, 40% of the wheelsets will have mileage since turning below 120,000 miles, 40% will have turning cycles with mileage since turning between 120,000 and 150,000 miles, and the remaining 20% will have exactly 150,000 miles. Therefore, the cumulative probability distribution represented in Figure 2 is then truncated at different points for different values for the fixed turning interval s.

Table 4 describes different maintenance strategies that are compared later using the ratio of the average life-cycle costs per thousand miles run per wheelset ($\mathrm{C_T}/\mathrm{L}$ in £/10^3 miles). Four possible actions are defined: (a) R – renewal, (b) KIR – keep it running without turning, (c) T – simple full flange turning and (d) ETT – economic tyre turning; and different alert limits (AL) to trigger each action are set using the wheel diameter as the main triggering variable, i.e. D_{KIR}^{AL} and D_{ETT}^{AL}. The scrap diameter, i.e. the last admissible diameter (D_s), triggers wheelset renewal action for any strategy. In this sense, Table 4 provides different combinations of strategies defined by different Alert Limits for the wheel diameter. For example, strategy 'ETT 795' would mean that the Alert Limit D_{ETT}^{AL} would be set equal to 795 mm, i.e. if the pre-turning wheel diameter goes below 795 mm, then that wheel is turned using

Economic Tyre Turning, otherwise a simple full flange turning is conducted. Moreover, the mixed strategy 'ETT 800 + KIR 795' would mean that the Alert limits D_{ETT}^{AL} and D_{KIR}^{AL} would be equal to 800 and 795 mm respectively, resulting in the following prescribed actions: if the pre-turning wheel diameter is above 800 mm, a simple full flange turning is conducted, if it is between 800 and 795 mm, that wheel is turned using ETT, and finally if it goes below 795 mm, then that wheel is kept running without turning till any required limit is violated. Note that in any strategy when the wheel diameter goes below 790 mm, it must be renewed.

For a maintenance/turning cycle n, Figure 3 provides the sequence of simulated and computed values for a maintenance cycle. It starts by simulating a mileage since turning (step 1) from the truncated distribution in Figure 2 given a choice of a fixed turning interval s; then, it simulates variables describing the damage trajectory (step 2) and afterwards the variables describing the wear trajectory (step 3). Then, it calculates the pre-turning geometrical variables (step 4) and simulates the impact of turning in the loss of diameter (step 5). Finally, it calculates the post-turning geometrical variables that are the new values for the next maintenance cycle (step 6). This process is repeated continuously depending on the strategy chosen till the post-turning diameter is lower than the scrap diameter, i.e. when a renewal is needed. The following groups of expressions are used respectively for the steps 4 and 6 on the calculation of pre-turning and post-turning geometrical variables:

$$D_{n+1}^{pre} = D_n^{post} - \Delta D_{n+1} \qquad (6)$$

$$F_{t_{n+1}}^{pre} = F_{t_n}^{post} + \Delta F_{t_{n+1}} \qquad (7)$$

$$F_{h_{n+1}}^{pre} = F_{h_n}^{post} + \Delta F_{h_{n+1}} \qquad (8)$$

$$D_{n+1}^{post} = D_{n+1}^{pre} - \Delta D_{T_{n+1}}.(1 - K_{n+1}) \qquad (9)$$

$$F_{t_{n+1}}^{post} = F_t^{new}.T_{n+1} + F_t^{ETT}.ETT_{n+1} + F_{t_{n+1}}^{pre}.K_{n+1} \qquad (10)$$

$$F_{h_{n+1}}^{post} = F_h^{new}.T_{n+1} + F_h^{ETT}.ETT_{n+1} + F_{h_{t+1}}^{pre}.K_{n+1} \qquad (11)$$

For: $n = 0,1,2,\dots,N$; $D_0^{post} = D_{new}$; $F_{t_0}^{post} = F_t^{new}$ and $F_{h_0}^{post} = F_h^{new}$

ETT_n, T_n and K_n are decision binary variables that define the mutually exclusive maintenance actions: ETT_n- Economic Tyre Turning, T_n - full flange Turning and K_n- Keep It Running without turning.

The following decision rules apply to each maintenance strategy defined previously in Table 4, depending on the alert limits (D_S, D_{ETT}^{AL}, D_{KIR}^{AL}):

$$d_{R_n}\left(D_n^{post}\right) = \begin{cases} R_n = 1, & D_n^{post} < D_{scrap} \\ R_n = 0, & otherwise \end{cases} \qquad (12)$$

$$d_{T_n, ETT_n, K_n}\left(Z_n, D_n^{pre}\right) = \begin{cases} T_n = 1, E_n = 0, K_n = 0, & Z_n = 1 \wedge D_n^{pre} > D_{ETT}^{AL} \\ T_n = 0, E_n = 1, K_n = 0, & Z_n = 1 \wedge D_n^{pre} \le D_{ETT}^{AL} \\ T_n = 1, E_n = 0, K_n = 0, & Z_n = 0 \wedge D_n^{pre} > D_{ETT}^{AL} \\ T_n = 0, E_n = 1, K_n = 0, & Z_n = 0 \wedge D_{KIR}^{AL} < D_n^{pre} \le D_{ETT}^{AL} \\ T_n = 0, E_n = 0, K_n = 1, & Z_n = 0 \wedge D_n^{pre} \le D_{KIR}^{AL} \end{cases}$$

(13)

In which:

$$Z_n = \begin{cases} 1 & Y_{RCF_n} = 1 \vee Y_{FLAT_n} = 1 \vee Y_{CAV_n} = 1 \vee Y_{other_n} = 1 \vee F_{t_n}^{pre} < F_t^{lim} \vee F_{h_n}^{pre} > F_h^{lim} \\ 0 & otherwise \end{cases}$$

Note that if any defect occurs or any flange wear limit is passed ($\mathrm{Z_n} = 1$), then the 'Keep it Running' option is not available ($\mathrm{K_n} = 0$), and depending on the Wheel Diameter pre-turning, turning ($\mathrm{T_n} = 1$) or Economic Tyre Turning ($\mathrm{ETT_n} = 1$) is triggered. If no damage defect occurs nor any flange limit is passed ($\mathrm{Z_n} = 0$), then the three options are available depending on the wheel diameter pre-turning.

For each simulation, the fixed turning intervals were set equal to s=120,000; 140,000; 160,000; 180,000; 200,000; 220,000 and 240,000 miles; and a total of 100 units were simulated, each with 3 vehicles and a total of 12 wheelsets (4 per vehicle).

Figure 4 presents the average life-cycle cost per thousand miles ($\mathrm{C_T/L}$) per wheelset for the different maintenance strategies identified in Table 4. Figure 4 shows that the renewal strategy exhibits the larger value for the ratio of average life-cycle cost per mileage per wheelset regardless the value chosen for the fixed turning interval (s). The 'Economic Tyre Turning' strategies without KIR actions tend to present lower life-cycle costs per mileage per wheelset than the simpler one (i.e. renewal), representing a cost saving per mileage of around 0.8%, 2.4%, 3.6% and 4.4% on average, respectively for ETT 795, ETT 800, ETT 805 and ETT 810. Comparing the 'Economic Tyre Turning' (ETT) strategies with the 'Keep it Running' (KIR) strategies for the same alert limit $\mathrm{D_{KIR}^{AL}}$, the KIR strategies tends to provide higher cost savings. Comparing the strategy 'KIR 795' with the corresponding Economic Tyre Turning strategies for the Alert Limit $\mathrm{D_{KIR}^{AL}} = 795$ mm, i.e. 'ETT 800 + KIR 795' and 'ETT 805 + KIR 795', they represent cost savings per mileage of around 2.0% and 3.5% respectively on average. Finally, comparing the strategy ‘KIR 800’ with the corresponding Economic Tyre Turning strategy for the Alert Limit $\mathrm{D}_{\mathrm{KIR}}^{\mathrm{AL}} = 800$ mm, gives the largest cost saving per mileage of around 4.7% on average.

An important finding from analysing Figure 4 is that when we increase the fixed maintenance interval s, the ratio of average life-cycle cost per mileage for each wheelset decreases, rapidly for the interval between 120 to 150 thousand miles and more smoothly from 150 to 200 thousand miles and it tends to stabilize from 200 to 240 thousand miles. Conclusions from Figures 4 and 5 should be taken cautiously, as other impacts may arise when we increase the fixed interval to 240 thousand miles (particularly for the KIR strategies), such as safety impact and its associated reliability. In this sense, we believe that it only makes sense to compare maintenance strategies that have intrinsically similar safety impacts, such as ETT 800 + KIR 795 vs. KIR 795. In our opinion, one should be cautious when comparing average LCC costs per wheelset for ETT 805 + KIR 800 with the ones for simple renewal, as both strategies may have completely different safety risks. Note that safety risks have not been discussed in the present paper and they are left for further research. Nevertheless, note that all strategies respect the limits specified in the BS EN 13715 standard, so at least the minimum safety requirements are observed in all strategies.

6. Conclusions and further research

This study reported the potential cost savings of introducing ‘Economic Tyre Turning’ in the current railway wheel maintenance strategies in the British practice. A life-cycle cost model was developed, and several statistical models were specified based on previous research with maintenance data from a fleet of modern multiple units [15, 16]. These statistical models support the predictions of the wear and damage trajectories, as well as the effect on wheel diameter loss of maintenance/turning . A simulation procedure was proposed to assess the maintenance needs and the evolution of the wear and damage trajectories of a given wheelset. The simulation procedure also accounts for random effects included in the statistical models like the unit, vehicle and month of measurement, so that the simulation is as realistic as possible for a typical multiple unit passenger train fleet in GB.

Simulation results identified that ‘Economic Tyre Turning’ could provide potential savings of around 0.8% up to 4.4% when compared to a simple renewal strategy, and between 2.0% and 4.7% cost savings for more complex strategies. The modelling suggests that for a typical fleet of 50 trains with 12 wheelsets per train, running an average of 120,000 miles/year, ‘Economic Tyre Turning’ could reduce the total annual wheelset maintenance costs by around £12K - £70K in a budget of £1.51M. A simple extension of these cost savings to the existing UK passenger train fleet of 11,000 vehicles would represent a potential cost saving per year of £880k-£5.1M. Therefore, these findings clearly support the interest in Economic Tyre Turning, making it worth taking the next steps, namely the engineering investigations necessary to build evidence for a change to the Railway Group Standard.

It is important to mention that the constraints of the problem under analysis were not modelled directly (e.g. maximum time of maintenance workers' shifts, maximum capacity of maintenance yards – number of lines, number of under-floor wheel lathes, lathe productivity rate, etc). This represents a limitation of our analysis, and thus the inclusion of these constraints is left for further research, and in this paper, we assumed that the inclusion of ETT maintenance action will not dramatically change the constraints that are now active in practice.

Regarding future research, there are a number of further steps which could provide a more comprehensive understanding of this topic: i) repeating the simulations for other types of trains (e.g. some freight vehicles), ii) assessing the impact of a larger portion of wheelsets running with thinner flanges in the network particularly with regard to the potential for lower conicity leading to increased rail wear, iii) assessing the potential changes in the safety risks, i.e. the derailment risks in switches and crossings and finally, iv) considering potential logistical constraints with the development of an optimization model to support maintenance decisions for the train operating companies and/or wheel maintainers.

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Notation list:

C_T - Total life-cycle costs (in £)

C_R – Renewal Costs (in £)

C_M - Maintenance Costs (in £)

C_I – Inspection Costs (in £)

C_{un} - Unavailability Costs (in £)

L – Wheelset life-cycle (in £)

N_R – Number of Renewals

N_M – Number of maintenance actions

N_I – Number of inspection operations

N_{un} – Number of times train is unavailable

ΔF_t – Evolution of the flange thickness (in mm);

ΔF_h- Evolution of the flange height (in mm);

ΔD – Evolution of the diameter (in mm);

ΔD_T – Diameter loss due to wheelset turning (in mm);

ΔD_{ETT} – Diameter loss due to Economic Tyre Turning (in mm);

Y_{RCF} – Occurrence of Rolling Contact Fatigue (RCF);

Y_{FLAT} – Occurrence of a wheel flat;

Y_{CAV}- Occurrence of wheel cavities;

Y_{other}- Occurrence of other type of defect;

p_{RCF} – probability of occurrence of RCF

p_{FLAT} – probability of occurrence of FLAT

p_{CAV} – probability of occurrence of cavities

p_{other} – probability of other damage defect

β_0 – intercept parameter

β_j – parameter for each explaining variable j

M – Mileage since last turning (in miles)

W – Nominal variable defining wheelset type: motor; trailer or leading.

b_{M_n} – random effect associated with month of measurement factor

b_U – random effect associated with unit factor

b_V – random effect associated with vehicle factor

ε – random measurement error

u – random error associated with inefficiency

v – random measurement error

σ_u^2 – variance of the random error associated with inefficiency

σ_v^2 – variance of the random measurement error

N – Normal probability distribution

N_+ - Truncated Normal probability distribution

F_t^{ETT} – Flange thickness after ETT action

F_t – Flange thickness

s – turning interval (in miles)

D_{KIR}^{AL} – Diameter Alert Limit for "Keep It Running" action (in mm)

D_{ETT}^{AL} - Diameter Alert Limit for "Economic Tyre Turning" action (in mm)

D_s - Scrap Diameter (in mm)

D_{n+1}^{pre} - Pre-turning Diameter (in mm) for maintenance/turning cycle n+1

D_n^{post}- Post-turning Diameter (in mm) for maintenance/turning cycle n

${F_t}_n^{post}$ – Post-turning Flange thickness for maintenance/turning cycle n

$\Delta F_{t_{n+1}}$ - Evolution in the Flange thickness for maintenance/turning cycle n+1

${F_h}_n^{post}$ – Post-turning Flange height for maintenance/turning cycle n

$\Delta F_{h_{n+1}}$ - Evolution in the Flange height for maintenance/turning cycle n+1

$\Delta D_{T_{n+1}}$ – Diameter loss due to turning for maintenance/turning cycle n+1

ETT_n – Economic Tyre Turning Action, $ETT_n = 1$ if ETT action is conducted at the end of maintenance cycle n and $ETT_n = 0$ otherwise;

T_n – Full flange Turning Action, $T_n = 1$ if Full flange Turning action is conducted at the end of maintenance cycle n and $T_n = 0$ otherwise;

K_n - Keep It Running Action (i.e. Do nothing), $K_n = 1$ if $ETT_n = 0$ and $T_n = 0$, i.e. no action is conducted at the end of maintenance cycle n;

d_{R_n} – decision rule

		Mean Interval (l_I) **(10^3 miles)**	**Average Cost components per Wheelset** **(in £)**
Renewal (c_R)	Trailer		5650
	Powered		9050
Maintenance/Turning (c_M)		-	320
Inspection (c_I)		16	33
Unavailability (c_{un}) (cost of train out of service)		-	1550

Table 1 – Main inputs for LCC model based on the RSSB Wheelset Management Model T792-07 [9].

		Dependent variables					
		Wear trajectory (LMM)			Damage trajectory (GLMM)		
Explaining Variables	Parameters	ΔF_t	ΔF_h	ΔD	Y_{RCF}	Y_{FLAT}	Y_{CAV}
Fixed Effects							
1	β_0	-0.4936 (0.02538)	0.4791 (0.03597)	1.394 (0.09236)	31.769104 (4.287260)	-0.785229 (0.412802)	47.736476 (11.006983)
M	β_M	-0.007469 (0.0005391)	0.008076 (0.0006305)	-0.0005329 (0.0008854)	0.012609 (0.001264)	-0.021362 (0.001215)	-0.011628 (0.002635)
M^2	β_{M^2}	5.778×10^{-5} (5.719×10^{-6})	-6.999×10^{-5} (6.689×10^{-6})	3.560×10^{-5} (4.382×10^{-6})	-	-	-
M^3	β_{M^3}	-1.366×10^{-7} (1.770×10^{-8})	2.621×10^{-7} (2.070×10^{-8})	-	-	-	-
D	β_D	-	-	-	-0.042256 (0.005168)	-	-0.062783 (0.013314)
W	β_{Motor}	0.03527 (0.007570)	0.03175 (0.008855)	-0.01270 (0.03050)	-1.614640 (0.142675)	-0.444594 (0.143837)	0.061992 (0.282116)
	$\beta_{Trailer}$	0.08746 (0.008174)	-0.09271 (0.009582)	-0.2277 (0.03302)	-0.783396 (0.142534)	-0.353106 (0.155126)	-0.789285 (0.328704)
	$\beta_{Leading}$	0^b	0^b	0^b	0^b	0^b	0^b
Random Effects							
M_n	$\sqrt{d_{Mn}}$	0.139	0.170	0.317	1.486	2.175	2.291
U	$\sqrt{d_U}$	0.047	0.073	0.172	0.636	0.818	1.327
V	$\sqrt{d_V}$	0.015	0.036	0.111	0.695	0.398	-
Scale (LMM and GLMM)	σ	0.204	0.238	0.821	-	-	-
-2 Restricted Log Likelihood		-1697.65	264.31	15576.67	-	-	-
Log Likelihood		-	-	-	-1589.64	-1404.32	-464.63
AIC value		-	-	-	3195.27	2822.64	943.25
Number of parameters		10	10	9	8	7	7

Table 2 – Estimated results using the Linear Mixed Models (LMM), the Generalized Linear Mixed Models (GLMM) and the Stochastic Frontier Analysis (SFA) for the dependent variables: change in the flange thickness (ΔF_t), change in the flange height (ΔF_h), change in the diameter due to wear (ΔD) and the occurrence of rolling contact fatigue defects (Y_{RCF}), wheel flats (Y_{FLAT}) and cavities (Y_{CAV}).

Explaining Variables	Parameters	ΔD_T
1	β_0	52.290 (2.0379)
F_t	β_{F_t}	-1.714 (0.0738)
Y_{RCF}	β_{RCF}	0.530 (0.2726)
Y_{FLAT}	β_{FLAT}	0.698 (0.1251)
Y_{CAV}	β_{CAV}	0.684 (0.3228)
W	β_{Motor}	-0.059 (0.0736)
	$\beta_{Trailer}$	-0.462 (0.0812)
	$\beta_{Leading}$	0[b]
$M \times Y_{RCF}$	$\beta_{M\times RCF}$	0.009 (0.0021)
$M \times Y_{FLAT}$	$\beta_{M\times FLAT}$	0.006 (0.0015)
$M \times Y_{CAV}$	$\beta_{M\times CAV}$	0.013 (0.0037)
Scale	σ_v σ_u	0.6884 3.6610
	λ	5.318 (0.1697)
Log Likelihood		-13529.82
AIC value		27083.64
Number of parameters (df)		12

Table 3 – Estimated results using the Stochastic Frontier Analysis (SFA) for the dependent variable diameter loss due to turning (ΔD_T).

	Alert Limits		
Strategy	D_s (mm)	D_{ETT}^{AL} (mm)	D_{KIR}^{AL} (mm)
Renewal	790	-	-
ETT 795		795	-
ETT 800		800	-
ETT 805		805	-
ETT 810		810	-
KIR 795		-	795
KIR 800		-	800
ETT 800 + KIR 795		800	795
ETT 805 + KIR 795		805	795
ETT 805 + KIR 800		805	800

Table 4 – Definition of the different maintenance strategies based on the Alert Limits (D_{KIR}^{AL} and D_{ETT}^{AL}).

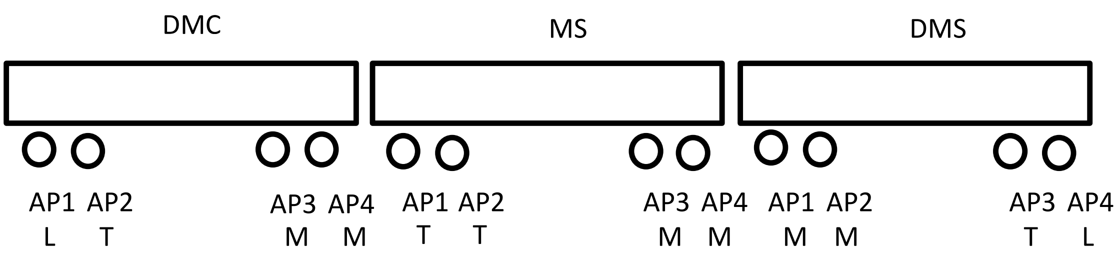

Figure 1 – Schematic representation of a three car unit (DMC, MS and DMS) and with four axle positions each (AP1-AP4).

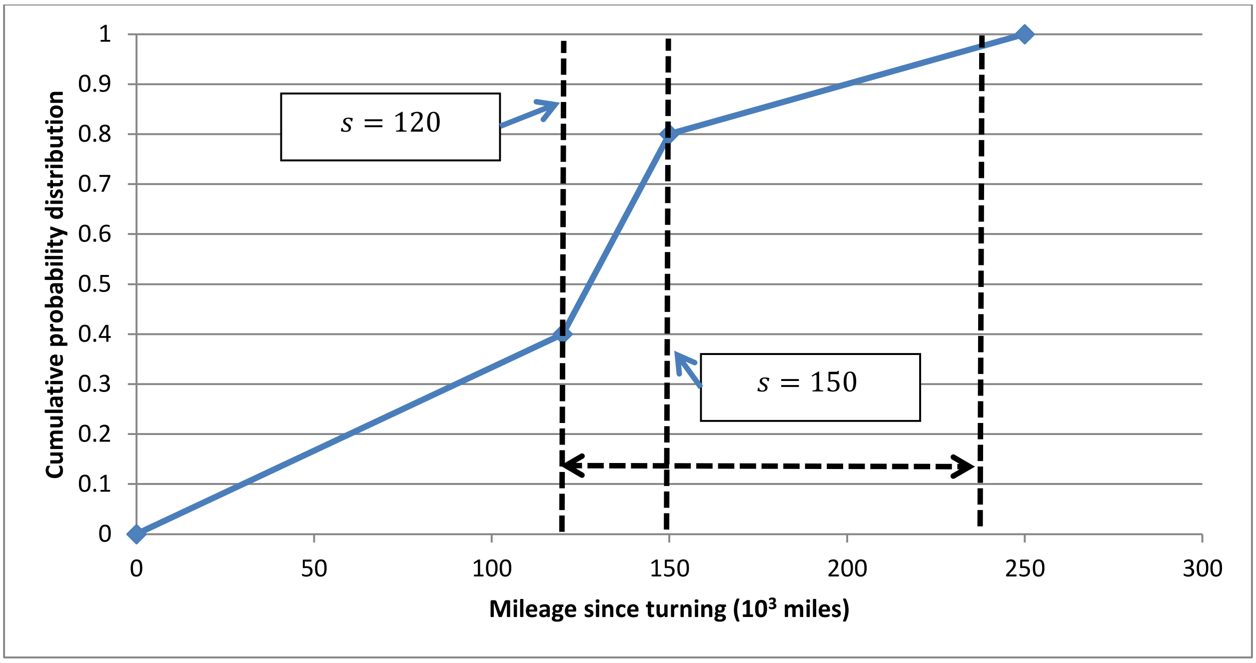

Figure 2– Cumulative probability distribution truncated at different fixed turning maintenance intervals (s=120,000 and s=150,000 miles).

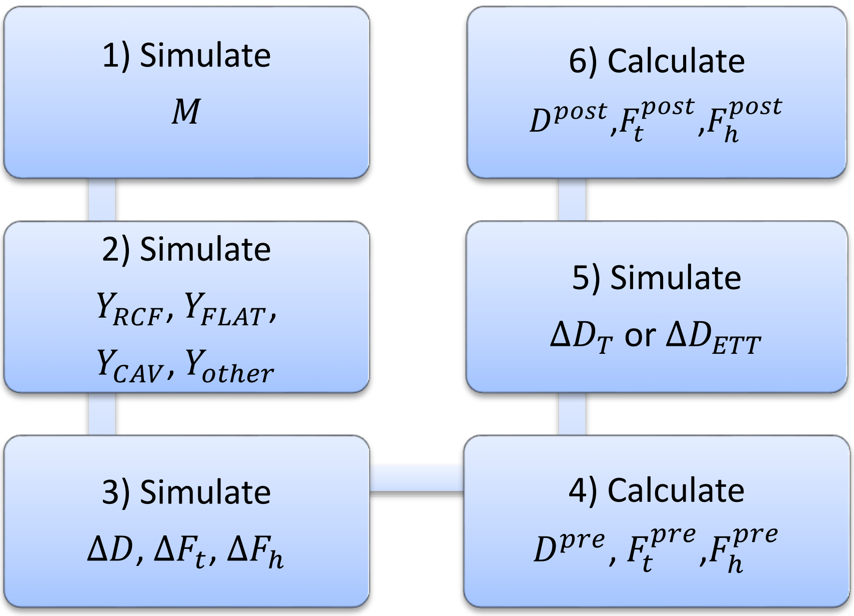

Figure 3 – Cycle of simulations/calculations for a maintenance cycle n.