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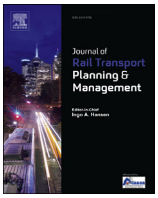

Using operational data to estimate the running resistance of trains. Estimation of the resistance in a set of Norwegian tunnels

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ABSTRACT

Two approaches to estimate the running resistance from operational data have been studied: A direct approach based on a measured/estimated acceleration to obtain a resistance time-series, and a velocity-fitting approach based on fitting a predicted to a measured velocity time-series. Two data sets have been considered: The first consists of a velocity time-series, extracted from the train event recorder. The second is logged from the vehicle control unit and includes a time-series of energy consumption and velocity. Velocity-fitting has been shown to be more robust with respect to the data resolution and is the recommended approach. The inclusion of energy consumption (or traction) data is recommended, resulting in more precise estimates. The approach is considered feasible in terms of data storage and transfer requirements, allowing a routinely collection of data from trains in operation.

The additional tunnel resistance has been evaluated for a set of 10 tunnels in Norway, giving resistance coefficients ranging from 2.4 to 16.0 kg/m for tunnels with an aerodynamic cross section of 87 to 27 m^2 respectively. The comparison to a set of predictions showed that there is a large spread in the predicted additional tunnel resistance. This demonstrates that the choice of prediction method and corresponding coefficients must be taken carefully.

1. Introduction

The running resistance of a train directly effects journey times and energy consumption, two key indicators for train operation. With increasing speed in the railway sector, the running resistance is getting more and more important for these indicators. This is both a result of the increased aerodynamic resistance at higher velocities, but also a result of an increase in the amount of tunnels for modern railroad tracks, where the running resistance is substantially higher than in open air. Being a mountainous country, the latter is a typical issue for the Norwegian railway network.

As a consequence, it is important to develop appropriate methods to estimate the running resistance and in particular the additional tunnel resistance. From our experience, there is a lack of clarity on the effect a tunnel has on the train resistance and subsequentially on the journey times and energy consumption. This is a paradox, since this effect has been the subject of

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numerous studies the last century and a large number of trains run through tunnels every day, where these effects are present and may be observed.

Typical full-scale train resistance measurements are performed with separate test runs, often with the use of special equipment and personnel, and are costly to perform and organize (Baker, 2014a). A method to utilize the operational data from trains in regular service will give access to a large set of measurements at a low cost, typically limited to logging equipment, data transfer and storage. An aim of this study was to develop methodology to estimate the running resistance from trains in regular service based on operational data that is (or can be) logged. This has the advantages that (*i*) there is no need to perform separate and cost-intensive test runs; (*ii*) the amount of available data for analysis is increased substantially and (*iii*) real-life conditions may be observed, such as variable weather conditions and interference with other trains. The main disadvantages are the lack of control of the test conditions and that the data logging possibilities may be limited.

A number of predictive equations have been proposed for the additional tunnel resistance. However, NSB experiences that in several cases the choice of equations and corresponding parameters is not given enough attention, leading to resistance predictions that do not correspond to reality. This study was initiated to document the tunnel resistance observed in a set of Norwegian railroad tunnels as well as to evaluate the precision of the predictive equations.

The main objectives include:

(i) Develop methodology to estimate the running resistance from trains in operation
(ii) Estimate the tunnel resistance for a set of Norwegian railway tunnels
(iii) Compare these estimates to a set of predictions.

2. Literature review

The running resistance of a train, and in particular the additonal resistance in a tunnel, has been addressed in numerous studies the last two centuries. Early measurements of the running resistance was performed already in 1818 by Stephenson and Wood (Clark, 1855) but was investigated in more detail in the 1840's by Harding (1846) and Gooch (1848a,b). The latter studies lead to early predictive equations for the running resistance (Clark, 1855). These early measurements reached velocities up to about 100 km/h, and during the next half-century the velocity range for resistance measurements was expanded, reaching up to 210 km/h in 1904 (Buhle and Pfitzner, 1904a, 1904b). The running resistance is commonly determined by employing traction measurements, typically at constant speed (Harding, 1846; Gooch, 1848a, 1848b; Sanzin, 1908) or by coasting or run-down measurements (Sanzin, 1908). Recent studies primarily focus on the latter technique (Bernard, 1974; Brockie, 1988; Peters, 1990; Rochard and Schmid, 2000; Lukaszewicz, 2001, 2007, 2009; Kim et al.,2006). The aerodynamic resistance may also be determined by wind-tunnel tests at reduced scale, however these require a correction to account for the difference in scale and the difference between experimental and full-scale conditions (Brockie, 1990; Baker and Brockie, 1991; Schetz, 2001).

Formulas for the running resistance were developed by numerous authors, among others Harding (1846), Clark (1855), Barbier (1898), Leitzmann and von Borries (1911), von Borries (1904), Frank (1907), Schmidt (1910) and Strahl (1913) (see Clark (1855), Sanzin (1908) or Sachs (1928) for a historical overview), all based on a formula describing the running resistance as a quadratic function of the velocity, in the general form as

$$R = A + Bv + Cv^2 \quad , \tag{1}$$

where R is the running resistance, v the velocity and A, B, C are coefficients determined from theoretical considerations or measurements. This equation is commonly known as the Davis equation (Rochard and Schmid, 2000; Davis, 1926). The coefficients of the Davis equation are related to different resistance contributions, where A can be related to the rolling resistance, B to other mechanical resistance as well as drag associated with ingested air and C to the aerodynamic resistance (Schetz, 2001; Baker and Brockie, 1990).

Due to the confined space, the aerodynamics for a train passing through a tunnel is different from the aerodynamics in open-air, which leads to increased running resistance. This increase can be related to the increase in skin friction drag and pressure drag (Vardy, 1996a, 1996b). The additonal resistance in a tunnel was estimated theoretically by Stix (1906) already in 1906, followed by wind tunnel experiments by Tollmien (1927), Langer (1927) in 1927 and full-scale measurements in two Swiss tunnels by Sutter in 1930 (Sutter, 1930). The additional tunnel resistance can be obtained with the same methods as for the resistance in open air (Peters, 1990; Kim et al., 2006), but may also be derived from pressure measurements (Sutter, 1930; Hara, 1965; Gawthorpe et al., 1979; Maeda et al., 1988; Vardy and Reinke, 1999). Early studies of the additional tunnel resistance assumed (quasi)-steady flow conditions to deduce global resistance coefficients for complete trains (Vardy, 1996a), typically on the form

$$R_{at} = C_{at} v^2 \quad , \tag{2}$$

where R_{at} is the additional running resistance inside a tunnel and C_{at} a coefficient. The value of C_{at} will in principle depend on a large number of factors, among others the train and tunnel length and aerodynamic cross section (including the blockage