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Modelling and Simulation Historical Tram Running in Modern Tracks

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Abstract

The restoration of historic trams is not only an operation of aesthetic and cultural preservation but also requires complex technical and engineering analyses to ensure the vehicle safety and efficiency. The restoration activity, if intended to bring these vehicles back to conditions to be made circulating and usable for tourist purposes, presents many complexities. In fact, the tramway infrastructure has changed significantly compared to the period in which these vehicles circulated and the regulatory framework to allow the approval of vehicles has become much stricter.
Often, the restoration of these vehicles requires the replacement of some components to make them compatible with the current infrastructure and the retrieval of data relating to the original projects and the characteristics of suspension, running gear and structure may require a reverse engineering activity as the original projects are often no longer available. The paper focuses on the dynamic simulation of tram 614, a Turin tram from the 600 series restored by the Associazione Torinese Tram Storici (ATTS). The main goal is to verify whether the main railway parameters, such as the derailment safety ratio, wheel unloading and the limit gauge, fall within the values required by current regulations when running on Turin tramways.

Keywords: historic trams, vehicle restoration, dynamic simulation, multibody, running safety, virtual homologation, digital twins, gauge limits.

1 Introduction

Retrofitting of railway vehicles and their primary components is typically undertaken to enhance energy efficiency [1] or to improve dynamic performances, thereby enabling higher operational speeds and/or increased axle load capacities [2]. However, when dealing with tramway vehicles, it should be kept in mind that historic trams are not only a means of transport, but also true witnesses of a bygone era, where technology and art meet on the rails. The restoration of these vehicles is not only an act of technical preservation, but a journey through time, which brings back to life the elegance and charm of a heritage that continues to flow through the streets of our cities [3].

Public transport in Turin began in 1846 with the introduction of omnibuses, horse-drawn carriages travelling on the road. However, it was in 1872 that the horse-drawn city railway service began in Turin. In 1897, the electrification of the urban network began, leading to the construction of the first electric trams and a significant expansion of the network. After the First World War, ATM (Azienda Tranviaria Municipale) took over the management of public transport in Turin, administering a network of 27 lines over 144 km, and during this period the first modern trams with bogies were built. The tram network continued to grow until the 1950s, when this type of transport suffered a sharp decline due to the increase in motor vehicles such as buses. Starting in 1973, with the oil crisis and a growing sensitivity towards environmental issues, the value of rail transport was rediscovered. This led to the renewal of the old lines and rolling stock, a process that continues today with the introduction of the new 8000 series trams produced by Hitachi Rail.

To preserve the historic trams as an integral part of the cultural heritage of the city of Turin, the ATTS (Associazione Torinese Tram Storici) is committed to the restoration of these vehicles, bringing them back to their former splendor. The association organizes tourist tours on their vehicles and events to allow the public to rediscover the charm of these trams of the past. Since 2023, with the support of CRT and GTT, the ATTS has begun the restoration of a 600 series tram, engine 614.

The 614 tram vehicle, built in the late 1920s in the ATM workshops in Turin, had a red-cream livery and remained in service until the early 1960s, when it was decommissioned to recover some of its parts, then reused in the construction of track-cleaning trams. The only surviving component was the carbody, which was preserved in a park along the Po, in the province of Alessandria, see Figure 1.

Figure 1: Carbody of Tram 614 and Wheelset of the 2700 series before restoration.

In 2013, ATTS acquired the body with the aim of restoring it. However, since many original components were missing, it was necessary to use components (bogies and wheelsets) from other series of trams similar and contemporary to those of the 600/2700 series, to complete the restoration.

The tram in question has characteristics that are currently very different from those of modern trams and therefore the verification of the dynamic performance of this rolling stock on the current infrastructure is of paramount importance. One of these characteristics is that the tram is supported by a single two-axle bogie, which could produce excessive transverse deviations of the carbody compared to the current tram vehicles.

Furthermore, given that the restoration in this case is not limited to restoring the characteristics of a vehicle that had already circulated but requires the use of subsystems derived from different vehicles, it was considered important to address additional checks including the dynamic analysis of the vehicle in operation. For this purpose, ATTS has specifically established a collaboration with Politecnico di Torino to carry out numerical simulations of the running behaviour of the reference vehicle on the current city network. Please note that for the specific tram vehicle considered in this work, the virtual homologation of the running behaviour is essential, as the vehicle is intended to run in the urban city of Turin, so that its safety must be verified in advance. Therefore, the numerical models developed in this activity can be considered as the digital twin of the physical object [4,5], that are used to assess the running safety of the restored tramway vehicle.

To carry out dynamic simulations, the approach of the railway standard EN14363 [6] was considered, since light rail regulations is also recently referring to this approach. Although the use of the vehicle requires a reduced speed (<50 km/h) such as to exclude a large part of the tests normally required by this standard, verifications were carried out relating to the running safety to determine the risk of derailment on curves and the wheel unloading. Another critical simulation is the verification of the limit gauge that in the city area could cause impacts with infrastructure elements or other vehicles. For this simulation it was necessary to detect the main obstacles present on the Turin city network and simulate them in the numerical routes, referring to the standard. UNI 7156 [7].

2 Multibody model

This section presents the numerical model developed in this paper, with details on the vehicle model, track layout, and wheel-rail contact elements. The railway vehicle model, sketched in Figure 2, is implemented in the SIMPACK commercial multibody (MB) code and it includes the following main rigid bodies:

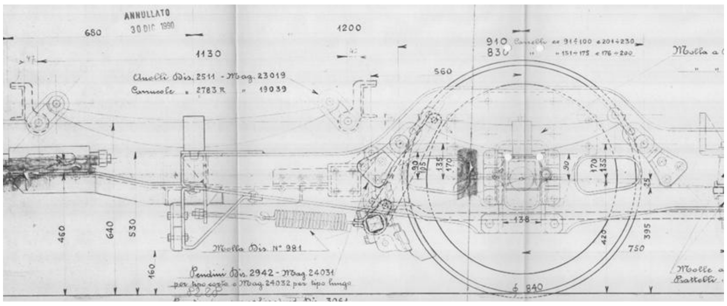
- one carbody (represented in yellow).
- one bogie frame (in grey).
- four axle boxes (in red).
- two wheelsets (in light blue).

The carbody, bogie frame and wheelsets are connected to the inertial reference system by means of specific joint types with 6 degrees of freedom (DOFs), while the axle-boxes have a single rotational DOF with respect to the wheelsets.

(a) (b)

Figure 2: Reference tramway vehicle: (a) CAD drawing and (b) MB model with reference system axis.

To obtain the CAD model of the vehicle and build the SIMPACK MB model, that coincide with the digital twin of the physical vehicle, a data collection and reverse engineering stage was required. Data was collected from archive drawings of the recovered vehicle components, see Figure 3(a), as well as from direct measurements on the physical parts, such as the primary suspension sketched in Figure 3(b).



(a)

(b)

Figure 3: Data collection. Examples of: (a) archive drawings and (b) recovered components (primary suspension leaf spring).

The vehicle includes two suspension stages: a primary suspension, connecting the axle-boxes to the bogie frame, and a secondary suspension, between the bogie frame and carbody. The primary suspension of the vehicle includes one leaf spring with shackles mounted on each axle-box, see again Figure 3(b). The vertical, lateral and longitudinal stiffness values of the primary suspension were estimated from technical data and drawings of the primary suspensions and validated with finite element (FE) models. Longitudinal and lateral stiffness values were corrected by accounting for the combined effect of the shackles and main spring. The determined equivalent stiffness values, listed in Table 1, are applied in the model through the definition of a lumped stiffness element (SIMPACK element type: *43 - Bushing Cmp*).

Stiffness component	Value
Kx	900 kN/mm
Ky	30 kN/mm
Kz	1.4 kN/mm
Kθ	0.1 kNm/rad
Kφ	200 kNm/rad
Kψ	5.497 kNm/rad

Table 1: Stiffness values for primary suspension.

The secondary suspension of the vehicle employs four groups of leaf springs without shackles and lateral side bearers. The leaf springs only provide a vertical stiffness, while the lateral side bearers allow a maximum lateral displacement of 5 mm due to the presence of bumpstops mounted between the bogie frame and carbody. In the current configuration of the vehicle to be restored, the original traction linkage system, providing the required longitudinal stiffness during traction and braking operations, could not be recovered. Therefore, during the numerical simulation activity, an additional Watt's linkage with silent blocks was specifically designed, to obtain a natural frequency of 6.5 Hz for the carbody longitudinal motion, thus not interfering with the other vibration modes. The leaf springs are modelled using lumped spring elements (SIMPACK element type: *43 -Bushing Cmp*), with stiffness values in all directions except for the longitudinal one, see Table 2. Frictional damping at the sliding interfaces of the side bearers is modelled through stick-slip elements (SIMPACK element type: *194 - Stick-slip 2D Cmp*), with static and dynamic friction coefficients set equal to 0.1 and 0.05, respectively, to account for grease lubrication. Finally, the Watt's linkage providing the longitudinal stiffness is modelled using two point-to-point spring-damper elements (SIMPACK element type: *4 – Spring-Damper Parallel Ptp*), with stiffness of 8 kN/m each.

Stiffness component	Value
Kx	0
Ky	15 kN/mm (after free displacement of 5 mm).
Kz	0.577 kN/mm
Kθ	200 kNm/rad
Kφ	200 kNm/rad
Kψ	200 kNm/rad

Table 2: Stiffness values for secondary suspension.

The track is modelled using a one-stage elastic foundation approach to account for the track flexibility. As the goal of the activity is to prove that the restored tramway vehicle can operate on the urban tramway lines in Turin, different sections of the Turin tramway are modelled. Precisely, the sections with the tightest curve radii (between 15 and 20 m) are modelled, such as Rondò Rivella, Piazza Sabotino, Piazza Statuto, Piazza Vittorio Veneto, Abruzzi-Peschiera, and Arsenale-Vittorio. Track layout data, including length of straight and circular sections, curve transitions and curve radii were extracted from the historical archives of GTT, namely the Turin transport company. The track has nominal gauge of 1445 mm, measured 8.5 mm below the top of rail, with widening of 5 mm in tight curves. No superelevation is applied in curves, and the rail cant is always zero. As the GTT rules [8] prescribe using the 60R2 rail profile for straight sections and the 62R2 profile for curved ones [9], see Figure 4, the numerical model exploits SIMPACK capabilities to define rail profiles that vary with the position along the track (*s-variable* rail profiles). The wheel profile corresponds instead to the UNI 3332 tramway wheel profile [10]. At the initial stage of the activity, the nominal wheel and rail profiles are considered, thus neglecting wear [11].

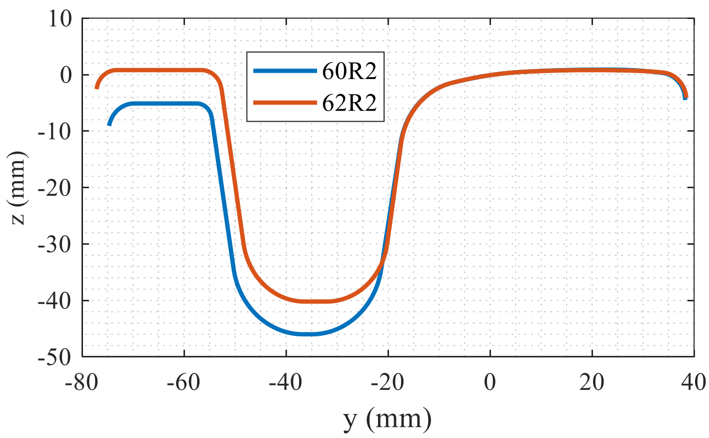


Figure 4: Rail profiles for straight (60R2) and curved (62R2) sections.

Although in past activity the authors developed in-house codes to deal with the wheel-rail contact problem [12,13], the MB model uses SIMPACK built-in routines. More in detail, the normal problem, which deals with the identification of the location of the contact points and calculation of contact patch area and normal load, is solved with the SIMPACK equivalent elastic approach, which is based on semi-Hertzian contact methods. The tangential problem is then solved with Kalker's FASTSIM algorithm [14], ensuring an excellent compromise between calculation accuracy and efficiency.

3 Results

A first analysis was carried out to obtain the maximum values of derailment ratio on the sections with the tightest curve radii in the Turin urban tramway line. Simulations were run at 3 different speed levels, namely 7, 10 and 12 km/h, which correspond to lateral accelerations of 0.25, 0.5 and 0.75 m/s^2 on the tightest curves, respectively. The derailment ratio for each track was extracted using the filtering strategy prescribed by the EN 14363 standard [6], which includes: a 20 Hz low-pass filter, a sliding mean with averaging window of 2 m and sampling period of 0.5, and finally the selection of the maximum (in absolute value) between the 99.85% and 0.15%-th percentile values. Figure 5 provides the values of derailment ratio Y/Q extracted for each critical section of the Turin urban tramway line. It is found that the maximum speed in the critical sections should always be below 10 km/h in order not to exceed the limit prescribed by the standards and set to 0.8.

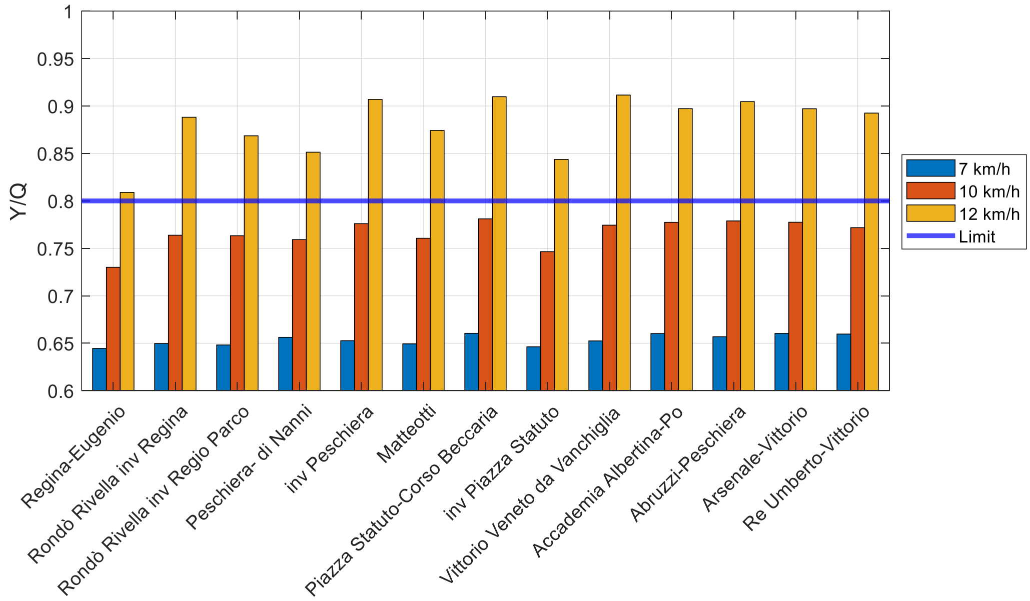


Figure 5: Pitch values for emergency braking and restart scenario.

Additional simulations were run to investigate the respect of the gauge when negotiating tight curves. To verify compliance with the limit gauge, three critical intersections in the city of Turin, shown in Figure 6, were considered:

- the intersection between Via dell'Arsenale and Corso Vittorio Emanuele, where an arch is present.
- the intersection between Via Accademia Albertina and Corso Vittorio Emanuele, where a tree is located.

- The intersection between Corso Vittorio Emanuele and Via XX Settembre, where there is an arch.

Simulations were run for the three intersection and the distance between the tram boarding steps and the obstacles was recorded. Table 3 provides the distance values recorded for each critical intersection together with the minimum value that should be guaranteed according to the Italian UNI 7156 standard [7]. It is found that the restored tram can safely run through the Accademia Albertina – Vittorio Emanuele and Vittorio Emanuele – XX Settembre intersections, while it is recommended that the tram trip avoids the Arsenale – Vittorio Emanuele intersection.

(a) (b) (c)

Figure 6: Critical intersections considered for gauge assessment: (a) Arsenale – Vittorio Emanuele; (b) Accademia Albertina –Vittorio Emanuele and (c) Vittorio Emanuele – XX Settembre.

Intersection	Obstacle type	Minimum distance (mm)	Recorded Distance (mm)
Arsenale – Vittorio Emanuele	Fixed and continuous (Arch).	650	576.25
Accademia Albertina – Vittorio Emanuele	Fixed but discontinuous (Tree)	350	706.5
Vittorio Emanuele – XX Settembre	Fixed and continuous (Arch).	650	677.45

Table 3: Recorded distances in the critical intersections for gauge assessment.

Finally, the last simulation shown in this paper deals with the investigation of the pitch angles of carbody and bogie frame during traction/braking phases. Figure 7 shows the pitch angles for the simulation of an emergency braking operation from 30 km/h to stop with mean deceleration of 1.3 m/s^2 followed by a restart with speed rising to 30 km/h with acceleration of 1 m/s^2. It is found that the maximum pitch angle of the carbody is slightly above 0.25 deg, while for the bogie frame, the maximum value is around 0.17 deg. Therefore, it is concluded that limit traction/braking operations can be performed enduring safety and a good feeling for the passengers.

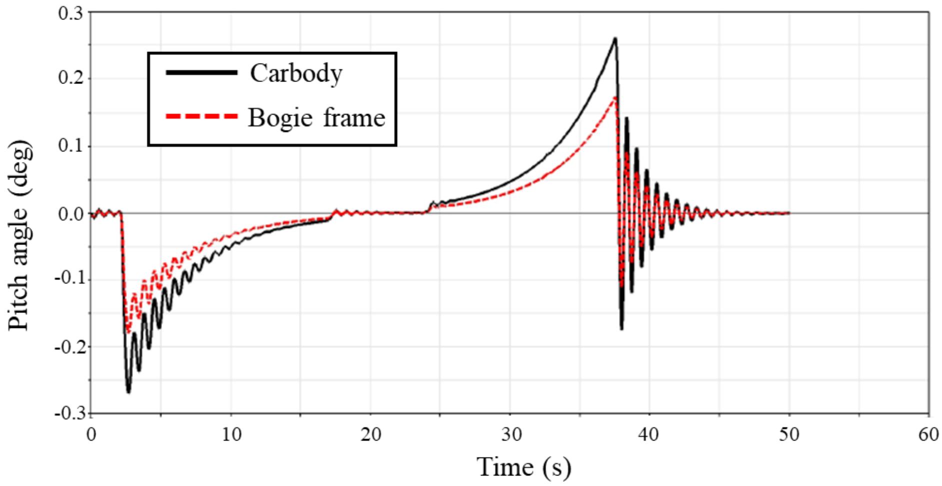


Figure 7: Pitch values for emergency braking and restart scenario.

4 Conclusions and Contributions

The work illustrated the simulation and virtual homologation activity according to the techniques provided by the EN14363 standard for a historic tram vehicle circulating on a modern tram network.

From the results obtained following the dynamic simulations on the SIMPACK multibody software, it is clear that the 614 tramway vehicle can be restored and subsequently put into operation as a tourist vehicle in the city of Turin. In fact, it emerged that the main parameters relating to the safety of the 614 tram comply with the regulations in force, guaranteeing safety for passengers.

The simulations carried out and the model created can be used as a reference for the organization of the experimental tests necessary for the commissioning of the vehicle once restored.

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