Impact of Design Methods and Maintenance Policies on the Dynamic Behaviour of Escalators

Helene Buet[1], David Courteille[2]

RATP, Station Maintenance Engineering, France
[1]Escalator Maintenance Engineer, helene.buet@ratp.fr
[2]Electromechanics Division Manager, david.courteille@ratp.fr

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Abstract: Throughout their service life, escalators undergo wear and tear that disrupt their dynamic behaviour and lead to faster deterioration or collision between components. Therefore, balancing the dynamic behaviour of escalators is one of the keys to longer life expectancy and safety. This requires thorough adjustments and regular part replacements. This paper assesses the impacts of internal and external parameters on the dynamic behaviour of escalators in order to enhance maintenance policies and design methods. Given the wide range of maintenance, design and environmental variables, this paper solely focuses on studying the most common parameters, the step chain lubrication and tension, the step design, the guide rail lubrication and the number of passengers carried on each step. For this purpose, a model is created using a multi-body dynamics' (MBD) system. Conducting Taguchi-designed experiments, the main effects of these factors and their interactions on the stress distribution and displacement of each moving parts of the model are studied. The results are then compared using ANOVA to determine the significant effects for each response. Heavy passenger flows greatly alter force distribution throughout the system, leading to reduced fatigue life of the steps, rollers and guide rails. Poor step chain lubrication and a maladjusted tensioning station have a significant impact on the step chain tension, yielding a higher collision risk between the steps and the combplates. Guide rail lubrication does not seem to significantly affect the system dynamics. No significant interaction between the studied parameters has been found and the responses are for the most part linear. This study showcases the major impact of passenger flows on the stresses applied on the moving parts and calls for an improved assessment of effective passenger flows in the dimensioning of escalators.

1 INTRODUCTION

Escalators undergo wear and tear throughout their service life, which inevitably leads to broken components, endangering users and reducing equipment availability. In addition, they are composed of thousands of moving parts connected to one another. Consequently, wear and tear not only damages the components but also modifies the force distribution through the entire system, altering its dynamic behaviour [1]. This can cause faster deterioration and collisions between components.

Balancing the dynamic behaviour of escalators throughout their service life is therefore one of the keys to longer life expectancy and safety [2].

This process requires thorough adjustments, the effectiveness of which when combined with design or environmental factors is not yet known.

This paper assesses the impact of design methods and maintenance policies on the dynamic behaviour of escalators under normal conditions of use.

2 METHOD

2.1 Selection of the study parameters

Design and maintenance parameters vary from one manufacturer to another but also throughout the escalator's service life. As a first approach, only the factors impacting the maintenance costs of the equipment were studied in this paper. Common environment configurations were also taken into account in order to study the impact of these parameters on escalators under normal conditions of use. The environment parameters were selected according to their occurrence.

Thus, the factors selected for this study are:

- The friction between the plates (which reflects the effectiveness of the step chains lubrication) is modelled as a viscous rotational damping moment in the link joints, as shown in the simplified model in Figure 1 :

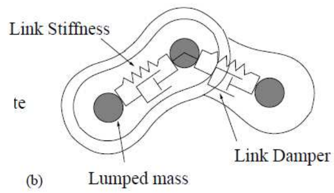


Figure 1: Simplified model of the chain link stiffness and damper

- The rolling friction of the polyurethane rollers on the steel step tracks (which depends on the step track lubrication),
- The steps weight,
- The tensioning station adjustment,
- The number of passengers carried and their position on the steps.

2.2 Creation of the dynamic model

To perform dynamic analyses, a model was created using a multi-body dynamics software enabling the modelling of fully functional chain driven systems.

This model represents a 4.8 meter rise escalator with a nominal step width of 1 meter. It operates in the upward direction at a speed of 0.6 m/s. These are currently the most common characteristics of the RATP fleet.

Given the high number of moving components in escalators, only the essential parts enabling transportation of passengers from the lower to the upper landings were modelled. This enabled simulation cost savings. Thus, the model is composed of:

- Two independent step chain systems (210 chain links, four sprockets, four chain guides) connected to each other by the use of two shafts,
- Two independent damping systems used as a tensioning station to pre-charge the step chain systems,
- Seventy steps and their rollers,
- One rail assembly.

Figure 2 shows the bottom part of the chain systems, the bottom shaft and the dampers.

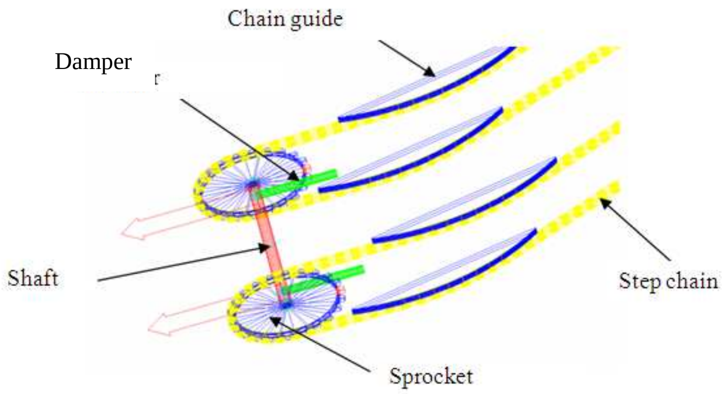


Figure 2: View of the tensioning station

The passengers loading, transport and unloading were modelled by applying a uniform distributed load on each step located between the lower and the upper combplates. The passengers' position on the steps was also taken into account by enabling the possibility to apply the distributed loads on the right half of the steps.

Figure 3 shows the complete model fully loaded. The green arrows represent the distributed loads applied to the steps, the red ones the reaction forces of the sprockets on the step chains.

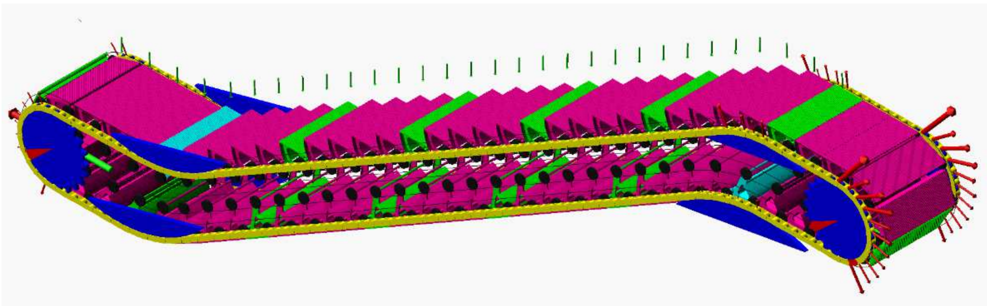


Figure 3: Fully loaded model

2.3 Validation of the simulation model

Part of the study was dedicated to ensure the simulation model was sufficiently accurate for the set of parameters previously identified.

The validation approach focused on comparing the outputs of the dynamic model described earlier to the outputs of a theoretical model specially built for the validation process [3]. This theoretical model was established using the manufacturers' static and dynamic design equations enabling the calculation of:

- The nominal motor torque required to run the escalator up to a speed of 0.6m/s,
- The steps chain links maximum dynamic tension,
- The normal contact forces of the steps and steps chain rollers on the rails.

These equations mainly depend on the following variables:

- The number of passengers,
- The step weight,
- The tensioning station adjustment,
- The rolling friction of the rollers on the rails.

Given that the design equations available do not take the step chains lubrication efficiency into account, the input-output transformation could not be validated for this particular parameter using this method and additional trials had to be run to determine the step chains rotational damping characteristics.

A Design Of Experiments (DOE) was conducted to optimize the simulation process [4, 5]. Considering that a first full factorial multilevel design had shown no significant interaction between the study parameters [6], a Taguchi method was used based on a L16 (2^{15}) orthogonal array, allowing the study of four parameters on two levels and taking into account all their possible interactions (up to the second order). This table requires 16 experimental runs.

The values assigned to each factor are the most commonly used by manufacturers in their design equations. They are given in Table 1.

Table 1: Factor levels defined for the validation runs

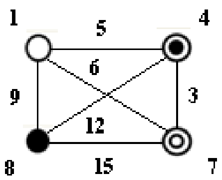
Level	**Number of passengers carried [passengers/step]**	**Tensioning station adjustment [mm]**	**Steps weight [kg]**	**Rolling resistance coefficient of the rollers on the tracks**
1	0	Min 169	Aluminium 15	Lubricated 0.04
2	2	Max 171	Steel 35	Non-lubricated 0.05

Table 2 gives the column assigned to each factor in the selected orthogonal array.

Table 2: Column of the L16 (2^{15}) array assigned to each factor

Parameter	Number of passengers carried	Tensioning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks
Column	1	4	7	8

Figure 4 gives the linear graph selected of the interactions for the L16 array.



The dots are labelled with the corresponding array column number for factors and the connecting lines are labeled with the corresponding array column number used for the interaction. These arrays are determined using the Taguchi interaction table for the L27 (3^{13}) orthogonal array.

Figure 4: Linear graph for the Taguchi design matrix

Results show a mean disparity of 10% between the dynamic model and the analytical model. This disparity principally impacts the nominal torque output: the 3D model takes into account coefficients of friction in the joints connecting parts whereas the theoretical model only considers the rolling friction between the roller and the rails. Therefore, the rolling friction variations have more impact on the analytical model than on the dynamic model.

This validates that the simulation model correctly reproduces the system behaviour (i.e. within acceptable bounds).

No significant interaction between the studied parameters has been found.

2.4 Impact evaluation of the study parameters

The same DOE process was conducted to assess the impact of the five study parameters but using a Taguchi method in order to optimize the number of simulations.

Since the passenger's position on the steps is a non-linear factor, it was important that our table provided for the study of the linearity of the system. At the same time, given that no significant interaction between the studied parameters has been found during the validation process, it was not necessary that the Taguchi table selected enabled the study of all the interactions between the parameters.

Thus, a L27 (3^{13}) orthogonal array was selected, enabling the study of five factors on three levels and the study of four interactions. This requires 27 simulation runs.

Table 3 summarizes the values assigned to each factor. Since our simulation model is not used for design purposes, the rolling resistance coefficient was set to its theoretical literature values [7].

Table 3: Factor levels defined for the Taguchi design matrix

Level	Number of passengers carried [passengers/step]	Tensioning station adjustment [mm]	Steps weight [kg]	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping[1] [N.mm.s/rad]
1	0	Min 169	Aluminium 15	Highly lubricated 0.015	Highly lubricated 1
2	1 Standing on the right side of the steps	Mean 170	Heavy Aluminium 25	Lubricated 0.0225	Lubricated 2000
3	2	Max 171	Steel 35	Non-lubricated 0.03	Slight corrosion damages 4000

[1]The step chain lubrication effectiveness and thus the factor levels are determined by increasing the step chain rotational damping up to the point where a discontinuity appears in the rotational oscillation of the step chain links.

Table 4 gives the column assigned to each study parameter in the L27 (3^{13}) orthogonal array.

Table 4: Column of the L27 (3^{13}) orthogonal array assigned to each factor

Parameter	Number of passengers carried	Tensioning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping
Column	1	4	6	8	9

Figure 5 gives the linear graph selected of the interactions for the Taguchi design matrix. The confounding scheme chosen is considered acceptable since the previous validation array revealed that there was no significant interaction between the main study parameters.

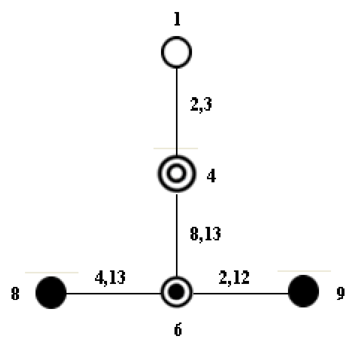


Figure 5: Linear graph for the Taguchi design matrix

3 RESULTS

3.1 Selection of the study outputs

Studying the system's dynamics involves going through the forces and displacements of each component all the way along the escalator. Given the high number of outputs, this study mainly focuses on covering the following aspects, selected according to their impact on the maintenance costs:

- The life expectancies of the steps chains, chain guides, steps, rollers and tracks,
- The risk of collision between the steps and the combplates,
- The nominal torque required to operate the system.

The following table lists the effects analysed during this study and briefly explains how they were used.

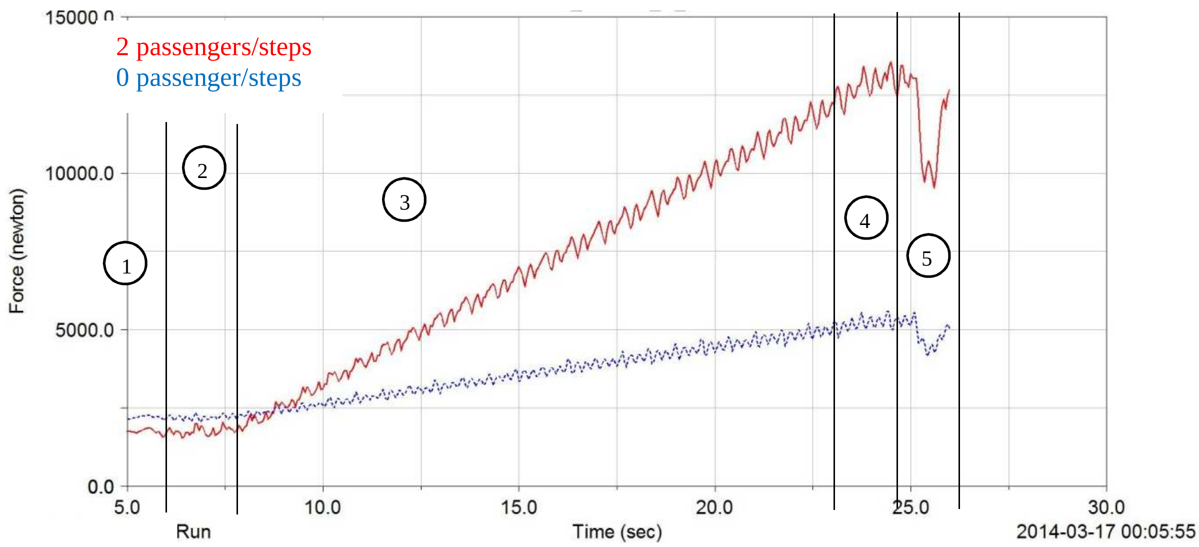
Table 5: Studied effects and examples of use

Studied effects [Unit]	Example of use
Nominal torque applied on the shaft [N.m]	Evaluation of the motor power required to move the escalator in the upward direction at a nominal speed of 0.6m/s
Step chain links tension [N]	Determination of the step chain fatigue life : the tension is used as an input to determine the cycle stress
Normal contact forces of the step rollers on the rails [N]	Evaluation of the risk of collision between the steps and the combplates : the steps have a higher propensity to raise and hit the combplates when the contact forces of the rollers on the rails are low
Projected contact forces of the step rollers on the rails [N]	Determination of the step rollers deformation: the contact forces are used as inputs to determine the polyurethane deformation
Restoring forces and displacements of the damping systems [N]	Determination of the tensioning station behaviour
Normal contact forces of the steps shaft on the steps [N]	Determination of the step fatigue life (normal contact forces used as inputs)
Normal contact forces of the steps chains on the chain guides [N]	Determination of the step chain fatigue life (normal contact forces used as inputs)
Roller speed variations [m/s]	Evaluation of the track wear which can be caused by the rollers variation of speed

3.2 Impact of the parameters on the studies effects

To reduce the simulation time, the outputs of only two steps (coloured in blue in figure 3) and their four attached chain links were recorded. This way, the behaviour of the steps and the step chains can be assessed by only computing half of an entire cycle run.

Figure 6 shows an example of the tension evolution within the step chains from the bottom to the upper landings on an escalator moving in the upward direction.



1 – Lower landing 2 – Lower transition curve 3 – Inclined plane 4 – Upper transition curve 5 – Upper landing

Figure 6: Step chain tension evolution under two different load cases

The blue curve represents the chain tension when no passengers are using the escalators and the red one shows the tension evolution when two passengers are standing on each step. The regular vibration on the curves is due to the polygon effect.

Depending on the output, the min, max or mean value of these graphs was used to complete our DOE table.

An ANalysis Of Variance (Chi² test) was used to determine which factors were significantly impacting our studied effects. The following table gives the percentage relative to the contribution of each significant parameter to the outputs.

Table 6: Chi-square contribution

Output \ Input	Number of passengers carried	Tensionning station adjustment	Steps weight	Rolling resistance coefficient of the rollers on the tracks	Step chains rotational damping
Nominal torque	98.0 %	Negligible[1]	Negligible	Negligible	2.0 %
Step chain links tension	97.1 %	Negligible	2.4 %	Negligible	Negligible
Normal contact forces of the step rollers on the rails	97.1 %	Negligible	2.7 %	Negligible	Negligible
Contact forces projection of the step rollers on the rails	89.8 %	Negligible	Negligible	Negligible	9.2%
Normal contact forces of the steps shaft on the steps	75.5%	Negligible	2.4%	Negligible	21.6%
Restoring forces and displacements of the damping systems	59.1%	16.8%	7.7%	Negligible	16.4%
Normal contact forces of the steps chains on the chain guides	71.7%	Negligible	2.7%	Negligible	24.8%
Rollers speed	Negligible	Negligible	Negligible	Negligible	Negligible

Once more, no significant interaction between the studied parameters has been found.

[1]The level of significance is set to 0.02.

4 DISCUSSION

The number of passengers carried is the most significant factor of the study in terms of impact on the dynamic behaviour and stresses of the escalator. The high variation of stress passengers create while standing on the steps transfers through the step chains and its connected parts. It modifies the forces distribution within the whole model and impacts the life expectancy of all the components connected to the loaded steps and to the steps chain.

The passengers' location on the steps, however, does not seem to imbalance the dynamics of the escalator, although it affects the stress distribution in the steps.

To a lesser extent, the step weight significantly impacts the dynamics of the system.

However, evidence that the use of lighter step material could increase the steps unexpected rising leading to the collision between the steps and the combplates has not been found.

The use of lighter steps (e.g. aluminum steps instead of steel steps) does not affect the nominal torque.

The step chain lubrication does not have a significant impact on the step chain tension. However, poor lubrication generates unpredicted forces on the step chain increasing the stress and displacement of its connected parts, potentially reducing their life expectancy and increasing the risk of collision.

The tensioning station has a negligible impact on all of the studied effects according to the one-way ANOVA table. This result contrasts with the forces distribution mechanism observed under steps load, steps weight and steps chain lubrication quality variations. For these three factors, the forces transfer through steps chains and are then absorbed by their connected parts, putting the steps chains at the centre of the dynamic mechanism. Due to the fact that the tensioning station's purpose is to preload the steps chain, a similar effect should occur when the tensioning station is adjusted to a different value. However, this did not occur in any of the DOE simulation runs. It can be explained by the fact that the three millimetre range of adjustment selected for the DOE is the one specified by the manufacturer; consequently, no chain tension adjustment within this range should disturb the dynamics of the system.

Additional simulations in which the tensioning station was incorrectly adjusted were run to tackle this issue. They tend to showcase that the tensioning station adjustment is the non-environmental parameter that has the greatest impact of the study.

Rails lubrication is a quite recent maintenance operation in the field of escalators. Manufacturers recommend lubricating the tracks to prevent premature damages caused by the rollers' speed variations. However, over the 27 simulations, no variation of the roller speed was noticed.

5 CONCLUSION

Because they are composed of a high number of moving parts, escalators require thorough adjustments to help control their dynamics. A better understanding of these adjustments when combined with design or environmental factors is a key to longer life expectancy and safety.

This study solely focuses on assessing the impact of the most expensive maintenance operations and common environmental parameters:

- The step chains lubrication efficiency
- The lubrication of the tracks
- The weight of the steps
- The tensioning station adjustment
- The number of passengers carried

To perform dynamic analysis, a model composed of the essential parts enabling transportation of passengers from the bottom to the top landing platforms was created using a multi-body dynamics software enabling the modelling of fully functional chain driven systems.

Part of the study was dedicated to validating this model by comparing its outputs to the outputs of a theoretical model established using the manufacturer's static and dynamic design equations. The disparity between the dynamic and the analytical model outputs is mostly due to the more complex definition of the simulation model.

Once the simulation model was validated, a series of 27 simulations was run using the DOE Taguchi methods to assess the impact of the 5 study parameters on 7 effects previously identified. These effects were selected according to the amount of information they give about the force distribution variations through the entire escalator system.

The steps chain appeared to be the main component of the mechanism controlling the escalator's dynamics. All the forces applied to one of its connected parts are transmitted through the steps chain impacting the stresses and displacements of the entire system.

This study showcases the *major impact of passenger flows on the force distribution through the whole model* and calls for *an improved assessment of effective passenger flows in the dimensioning of escalators* [8]. Finally, this study invites us to *optimise the maintenance policies regarding step chain lubrication and tensioning station adjustments* in order to reduce the escalator cost of ownership.

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BIOGRAPHICAL DETAILS

Hélène Buet is Escalator Maintenance Engineer in the Station Maintenance Engineering unit of the Equipment and Transport Spaces Maintenance department of RATP. She received her Master's degree in Mechanical Engineering from IFMA (French Institute for Advanced Mechanics).

David Courteille is Electomechanics, Civil and Climatic Engineering division manager in the Station Maintenance Engineering unit of the Equipment and Transport Spaces Maintenance department of RATP. He received a Master's degree in Mechanical Engineering from INSA (National Institute for Applied Sciences) Lyon and a postgraduate Advanced Studies Diploma from the doctoral school MEGA. He's been working for 11 years for RATP and is currently a member of the working group WG2 (Escalators and moving walks) of CEN/TC10.