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## Parallel simulation of railway pneumatic brake using openMP

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### ABSTRACT

The continuous growth of ore train lengths demands more efficient schedules, improved transit estimations and accident prevention schemes. Braking is a key component in achieving these objectives. Understandably, physical testing is potentially dangerous and costly. Meanwhile, the computational cost of calculating vehicle forces and brake airflow is high, both in computational effort and time. Therefore, strategies to improve analytical and simulation effectiveness efficiency are critical to achieve the goal of transporting more cargo safely and economically. This work implemented and compared the computational cost of a parallelization method against a traditional single-thread approach. The first model is based on lump parameters, while the second use Navier-Stokes conservation equations assuming an isothermal environment. Both models used OpenMP to execute on multiple cores. This implementation resulted in an 80% reduction in model solution time, when compared with the traditional single-thread approach.

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## 1. Introduction

Freight cars build and topology depend on the type of transported goods, track conditions, and local transportation standards [1]. The increase in commodity demand has led to longer trains [2]; also, freight car speed and capacity have also been increased to enhance the overall system efficiency [3,4]. However, increasing cargo and speed can lead to higher operational risks, such as derailments [5]. Bearing these in mind, several studies were carried to improve railway rolling stock and operation as highlighted in the work of Aly et al. [6].

Contemporary computational resources allow the use of optimization techniques on the railway simulations, especially on train longitudinal dynamics. The aim of the optimization is to find optimum control schedules and increase the overall energy efficiency [7]. Fortunately, the railway environment presents technical features that make the implementation of optimization algorithms possible and viable. The first of such is to assume that the route/track conditions are constant, considering the track degradation process is very slow for the time frame of a single trip [8]; the second feature is that the rolling stock

configuration does not often change [8], especially heavy-haul ore trains, such as the one analysed in this study. Despite these potential simplifications, the simulation of trains comprised of several freight cars is traditionally associated with prohibitive computational cost. This high cost comes from the calculations of the in-train forces between the cars [9], the airflow through the brake pipe, valves, and cylinders (that is converted in the braking forces applied to each vehicle) [10], that also compounds the in-train forces.

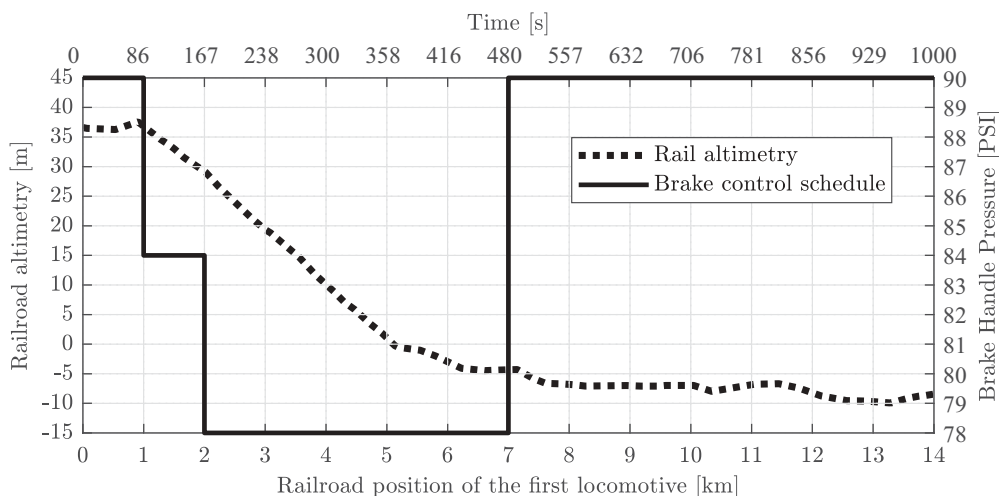
This paper focuses on a strategy to reduce the computational time for train braking simulations, which will be used to estimate the in-train forces for a dynamic model running in tandem. Faster simulation is key to develop an optimum train operational plan using iterative optimization algorithms. These aim at fuel consumption reduction and improved efficiency. This will be achieved after several iterations, testing different parameters from field tests and experimental evaluations. An adequate optimum operation will brake or accelerate just the necessary, for the less energy dissipated during the braking process, the less power is required to accelerate back the train. This simulation is particularly important because, on heavy-haul operations, the majority of vehicles still use automatic pneumatic brake valves [4,11]. For long compositions, this brake system has a well-known issue of delay braking application [12]. The delay in the time required by the main pipe pressure to reach the most distant cars control valves creates an unbalanced braking force distribution from the first to the last car [13] that, in turn, generates a longitudinal impact wave on the couplers [4], caused by the rear wagons pushing the front ones [14]. Also, the automatic pneumatic brake system has a limited number of applications until there is an unsafe chance of running out of air, thus losing brake power, which can cause accidents [15,16].

Train operational procedures and limits are defined by simulations; therefore, the braking calculations must accurately represent the real response of the system as the engineer commands the brake handle on the locomotive [17].

Empirical lump parameter functions have been used to simulate the brake system behaviour. They are adequate for representing the non-linear delay of the airflow pressure wave propagation; nonetheless, models considering transient dynamical pressure propagation can generate substantially more realistic results [18].

In the previous work, Teodoro et al. [19] implemented the simulation in C programming language to simulate the train pneumatic brake system in real-time. The first approach was based on the Navier-Stokes equations [20,21], assuming conservation of mass and momentum for the fluid transversal flow and an isothermal environment. The second approach in Teodoro work was the lumped method adapted from Pugi et al. [22] that simulates the brake system using pneumatic elements such as orifices, reservoirs, and cylinders, harmonized by solving the conservation of mass laws. Both methods were compared with a legacy software and showed satisfactory agreement. Furthermore, the models were able to simulate the braking process in real time i.e. each step in simulation time represented the same step in wall time; however, the lumped method was more than 10 times faster. The methods were very accurate, but they presented a high computational cost. This hampers their application in optimizations, where it is required that the model run at compressed time, i.e. the simulation takes less than the actual phenomena. The optimization algorithm should search for the best conduction procedures in a reasonable time, especially for control strategies.

In order to reduce the computational time, this work uses a modified version of the solver that incorporates the lumped parameters and Navier-Stokes methods, as presented by Teodoro et al. [19], to execute most of the calculations in a parallel processing



**Figure 1.** Train braking schedule according to the railroad position.

environment. The multi-thread strategy is built by executing each independent loop in a different core of the Central Processing Unit (CPU).

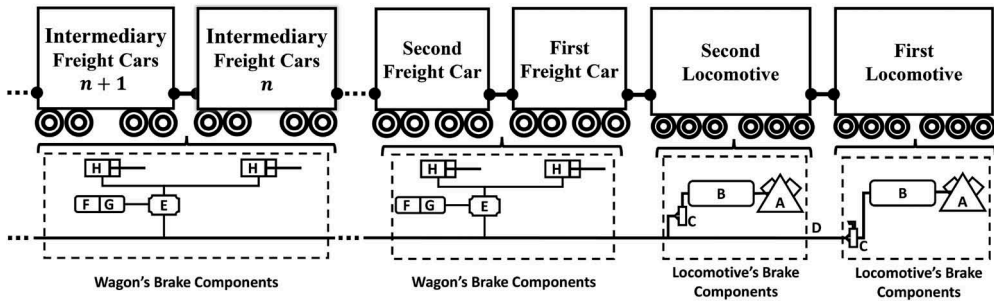
The algorithm was built using open Multi-Processing (openMP). It allows the execution of the code in multiple cores of the CPU and is easy to implement. The program requires a single command line before the loop to start the parallelization [23]. OpenMP is common in Computational Fluid Dynamics (CFD), and normally yields adequate results [24].

The openMP tool is used for several problems of fluid dynamics complex models, such as predicting the airflows for the planning and installation of windmill power plants [25], airflow pollutant dispersion in cities [26], mixing of fuel and the compressed airflow in hypersonic jet engines [27] and CFD model of an air-blown coal-fired updraft gasifier [28]. However, there is no application of the openMP related to the airflow simulation for train braking systems.

Therefore, the objective of this paper is to parallelize the Navier-Stokes [20,21] and the lumped [22] models using openMP (written on C) and analyse the efficiency of the computational time of this parallel implementation. The case selected for this evaluation is based on a standard braking procedure for a heavy-haul train (2 locomotives followed by 168 freight cars with 100 tons of ore each) on a downhill grade of the EFVM (Vitória-Minas Railroad) in Brazil, as presented in Figure 1.

## 2. Material and methods

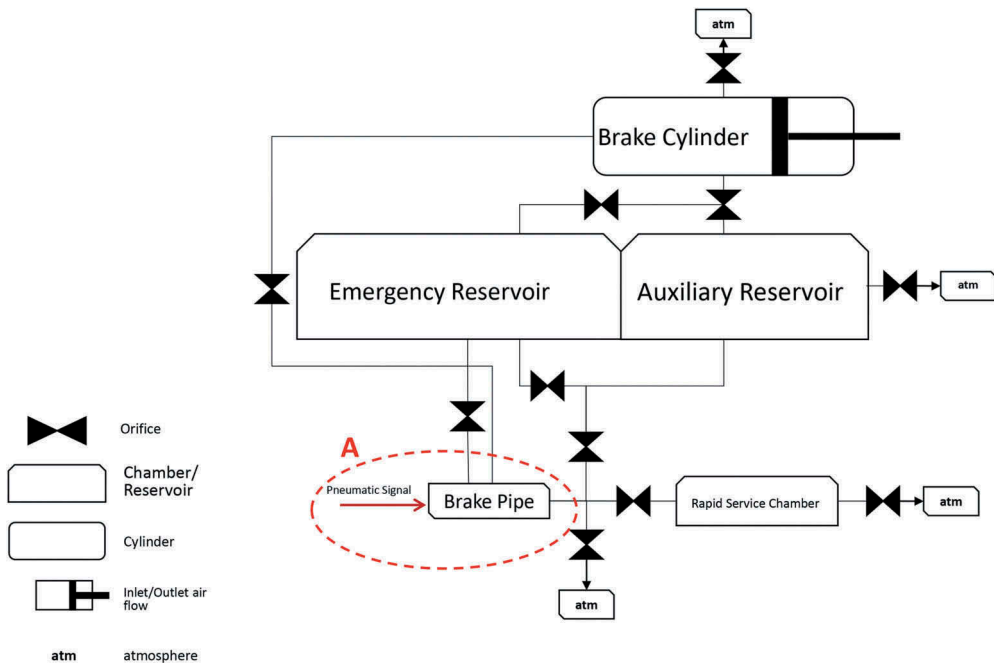
The heavy-haul train type considered for this exercise has two locomotives pulling 84 pairs of ore wagons (168 freight cars total). Each freight car pair shares a single brake valve (either AB, ABD, ABDX or EL-60), as shown in Figure 2. Both locomotives are equipped with a compressor, reservoirs, and a brake handle on an NYAB 26L topology. The compressor feeds the reservoirs with compressed air, while the brake handle commands brake pipe that controls the pressure in the whole system. The handle commands the pressure of the equalizing reservoir, that in turn, opens and closes valves to control and adjust the pressure on the brake pipe and, thus, the system.



**Figure 2.** Schematic of the pneumatic brake system composed by: (a) compressor, (b) main reservoir, (c) brake handle, (d) brake pipe, (e) control valve, (f) emergency reservoir, (g) auxiliary reservoir and (h) brake cylinder.

For this experiment, all remaining components of the brake system are considered to be located on the freight cars: brake cylinder, auxiliary and emergency reservoir, the automatic brake control valve. Among these, the control valve has the role of identifying the pressure difference and variation between the car reservoirs and the brake pipe, connecting the reservoirs to the brake cylinder to apply or release brake force.

The model used to emulate the freight car components is similar to the model implemented by Teodoro et al. [19]. It uses volumes and orifices to calculate the flux that passes through the components depending on their pressure. This model is shown in Figure 3, where the orifices connecting the chambers open or close depending on the command of the control valve. That valve, in turn, evaluates the pressure difference and variation



**Figure 3.** Wagons brake system model. (A) is the brake pipe pressure entry.

between the brake pipe and the auxiliary and emergency reservoir to take its decision in a totally mechanical implementation. The model uses three mathematical equations that define the pressure along time: volume, cylinder and orifice, i.e. one for each component.

The pressure of the brake pipe is the input parameter for the model of each car pair. It is calculated by the two different approaches adopted, the lumped characteristics and the isothermal Navier-Stokes equations. Both approaches are presented in detail along this text.

### 2.1. Volume

The volume is an idealization that represents a limited enclosure ( $V_C$ ) which accumulates pressure. It uses the summation of the in-and-out mass flows ( $\dot{m}$ ) to determinate the pressure ( $p_c$ ) inside itself, using the ideal gas Equation (1). In that equation,  $t$ ,  $R$ , and  $T_{env}$  represent time, specific gas constant, and environmental temperature, respectively.

$$\frac{\partial p_c}{\partial t} = \frac{R \cdot T_{env} \cdot \sum_{i=1}^n \dot{m}_i}{v_c} \quad (1)$$

### 2.2. Cylinder

The (brake) cylinder is a chamber with a variable volume. Therefore, the equation used to define its pressure is similar to (1), considering volume variation. The instantaneous variable volume is estimated by multiplying the piston area ( $A_p$ ) by the displacement ( $X$ ), as shown in Equation (2).

$$\frac{\partial p_c \cdot A_p \cdot X}{\partial t} = R \cdot T_{env} \cdot \sum_{i=1}^n \dot{m}_i \quad (2)$$

The displacement changes with the pressure variation. Therefore, to calculate the displacement value a dynamic equation of the movement for the piston is used (Equation 3).

$$M_p \cdot \ddot{X}_{t+dt} = A_p \cdot (p_c - p_{atm}) - C_p \cdot \dot{X}_t - K_p \cdot X_t \quad (3)$$

A numerical iterative solution was employed to address Equation 3. In that equation,  $M_p$  is the mass of the piston and  $A_p$  is its area. Besides, the viscous friction  $C_p$  and spring elastic  $K_p$ , are assumed to be constants for each time step. The equation also considers the pressure inside the cylinder  $p_c$ , the environment pressure  $p_{atm}$ , the previous displacement  $X_t$ , and the velocity  $\dot{X}$  of the piston. The values are then updated in the next time step and the calculation continues.

### 2.3. Orifice

The orifice connects one volume or cylinder to another and determines the airflow between them, acting as a concentrated pressure drop between the two components. Equation (4) calculates the airflow from high pressure ( $p_{hi}$ ) to low pressure ( $p_{lo}$ ), assuming the temperature of the high-pressure component ( $T_{hi}$ ) and the area of the orifice ( $A_o$ ).

$$\dot{m} = A_o \cdot C_m \cdot C_q \cdot \frac{p_{hi}}{\sqrt{T_{hi}}} \quad (4)$$

The coefficients  $C_m$  and  $C_q$  are correction factors responsible to guarantee that the mass flow calculation is close to reality. The factor  $C_m$  is calculated for subsonic flow and uses the heat capacity ratio  $\gamma$ , the high pressure ( $p_{hi}$ ) chamber and the lower pressure chamber ( $p_{lo}$ ), as shown in Equation (5) [22].

$$C_m = \sqrt{\frac{2\gamma}{R(\gamma-1)}} \sqrt{\left(\frac{p_{lo}}{p_{hi}}\right)^{\frac{2}{\gamma}} - \left(\frac{p_{lo}}{p_{hi}}\right)^{\frac{\gamma+1}{\gamma}}} \quad (5)$$

The factor  $C_q$  is an empirical coefficient calculated using Equation (6) [22].

$$C_q = 0.814 - 0.1002 \left(\frac{p_{lo}}{p_{hi}}\right) + 0.8415 \left(\frac{p_{lo}}{p_{hi}}\right)^2 - 3.9 \left(\frac{p_{lo}}{p_{hi}}\right)^3 + 4.6001 \left(\frac{p_{lo}}{p_{hi}}\right)^4 - 1.6827 \left(\frac{p_{lo}}{p_{hi}}\right)^5 \quad (6)$$

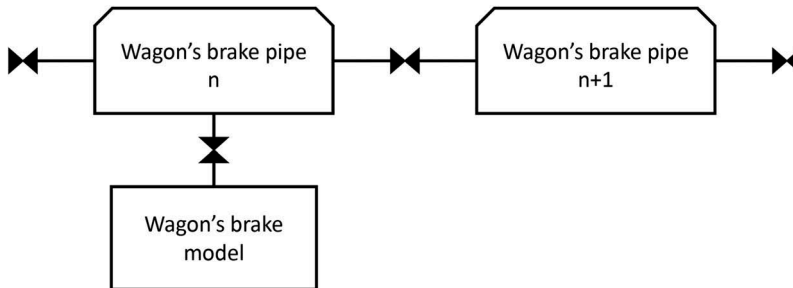
## 2.4. Brake pipe

The brake control valve responds according to the pressure variation in the brake pipe, that connects each individual car. Therefore, the brake pipe mathematical model is a major task, for it has to account for the wave propagation along the trains 186 cars, while mass flow is added and subtracted from it.

As mentioned before, two approaches are used in this component as well: the overall lumped parameters, to calculate the pressure along the pipe, which is a simple and fast solution; and the isothermal Navier-Stokes equation, which is more complex and slow to calculate but carries fewer errors in the numerical solution and approximations.

## 2.5. Lumped characteristic approach

In the lumped approach, the brake pipe is considered as series of volumes connected via orifices, as shown in Figure 4. Each chamber represents the portion of the volume of the brake



**Figure 4.** Schematic representation of the lumped method. The volume represents the section of the brake pipe in each wagon connected by orifices with its neighbour wagons and with the wagons model.

pipe at each individual car and the orifice emulates the pressure loss between two vehicles. The model calculates the pressure variation along time using Equations (1) and (4).

## 2.6. Navier-stokes approach

In this approach, the brake pipe is a duct that passes through all the wagons of the train. Assuming that we can use a one-dimensional model to represent the flow through this pipe, and assuming an isothermal system, the brake pipe can be represented by Equations (7) and (8). These equations are the mass and momentum conservation equations, where  $\rho$  is the air density,  $u$  is the velocity of the flow,  $P$  is the brake pipe pressure and  $x$  is the position along the brake pipe,  $A_b$  is the pipe transversal area, and  $D_b$  is the pipe diameter.

$$\frac{\partial p}{\partial t} + \frac{\partial pu}{\partial x} = \frac{\partial}{\partial x} \sum_i \dot{m}_i \quad (7)$$

$$\frac{\partial(pu)}{\partial t} + \frac{\partial(pu^2)}{\partial x} = -\frac{\partial P}{\partial x} + \frac{\rho f_x u^2}{2D_b} C_x \quad (8)$$

Equation (7) adds the contribution of the balance of mass, i.e., the in-and-out flow at the pipe ( $\dot{m}$ ), while Equation (8) is responsible for the pressure loss along the pipe by calculating frictional losses considering the friction coefficient of the pipe ( $f_x$ ) and a pressure loss coefficient ( $C_x$ ) that modulates the influence of the loss term depending on how many components downstream that interact with the flow [19]. In addition to these, the ideal gas equation (Equation (9)) is used to determine the relationship between pressure and density.

$$P = \rho RT \quad (9)$$

All the differential equations were calculated using finite differences as the numerical solver.

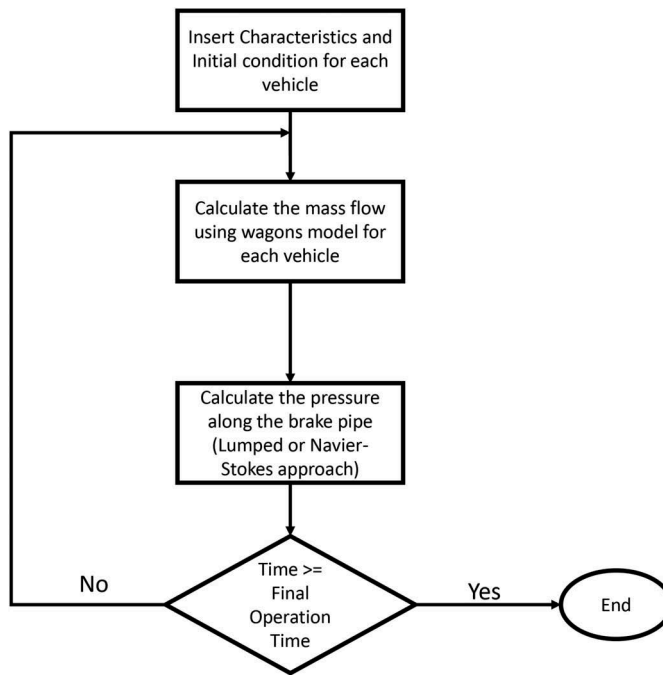
## 2.7. Algorithm

In order to link all the equations and generate the desirable simulation, we built the algorithm presented in Figure 5. The process starts a loop allocating all initial entry data (constant coefficients, initial data, etc.). After that, a time-controlled loop is used to calculate the pressure of all components in each step. Nested inside this time loop, there are two other internal loops.

The first internal loop calculates all the mass flows that enter and exit the brake pipe and the pressure of the components in the specific freight car through the brake system model, according to the selected simulation approach (Lumped characteristics or Isothermal Navier-Stokes). After that, the second internal loop uses the mass flows obtained in the previous loop to simulate the pressure along the brake pipe, and so on.

For the problem at hand – the simulation of multiple vehicles – the time step has to be small (as little as 0.5 ms) in order to achieve numerical accuracy, and thus, the computational cost becomes very high, especially, when processed by a single CPU core. Therefore, this work will parallelize the algorithm presented in Figure 5

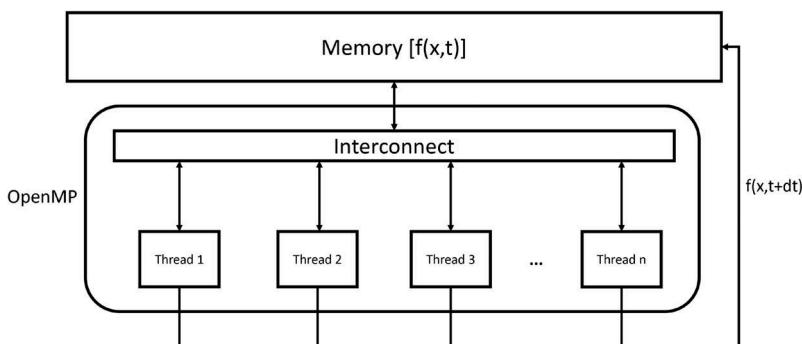




**Figure 5.** Linear algorithm.

distributing the execution of each loop on several CPU cores, applying the tools of openMP, in an attempt to reduce overall simulation time.

OpenMP is an Application Programming Interface (API) that enables shared-memory parallel execution, i.e. it allows different threads to access the same information in the memory synchronously. The API decides the amount of code each thread (and core) will execute, allowing for the parallelization of the code blocks. For example, suppose a function  $f(x, t)$  that needs the previous iteration values to determinate the current step. OpenMP will act as presented in Figure 6., i.e. the API will determinate that the idle thread calculates the value of the next time step for each  $x$ . If the number of  $x$ s is higher than the number of threads, the application



**Figure 6.** OpenMP function flowchart.

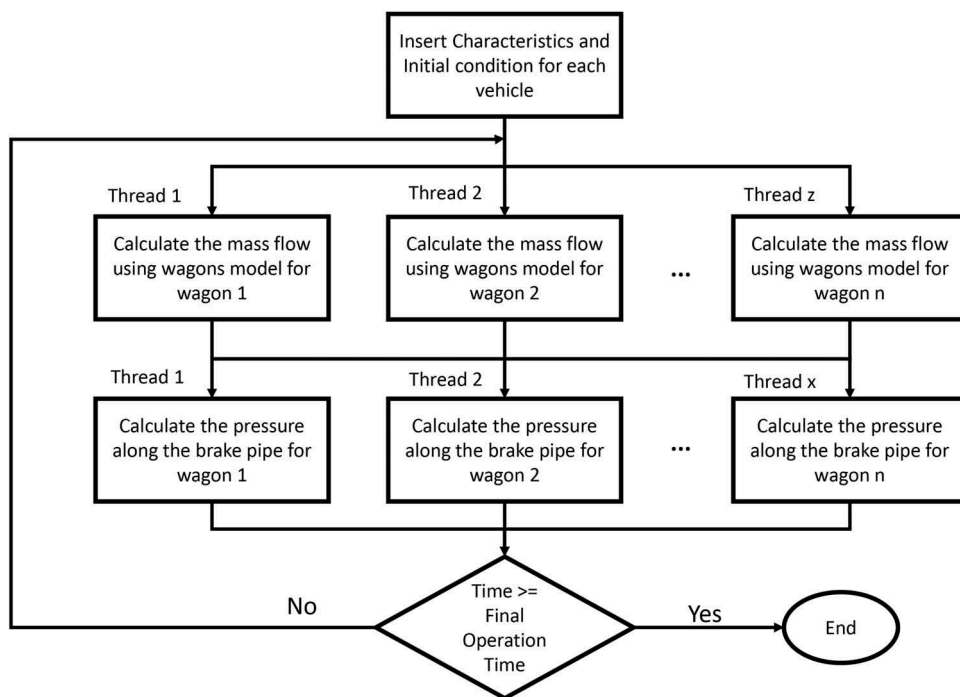
will hold the calculation of the remaining  $x_s$  until there is an idle core, thus, improving speed, for there are several steps being calculated at the same clock cycle.

Another good reason to choose the openMP is that little rewrites are required to parallelize an existing code, as shown in [Figure 7](#). In this figure, both internal loops were parallelized, in order to allow each processor executes the model equations for a specific wagon. Once the number of processors is lower than the number of wagons, any processor that finishes the calculation will change for the next-uncalculated wagon, until all freight cars are processed.

## 2.8. Simulation parameters

As mentioned before, the typical train chosen for this analysis has two locomotives followed by 168 freight cars and travels on a downhill section of a Brazilian railroad ([Figure 1](#)). During this voyage, the train executes a two-step brake application with a brake release at the end of the downhill stretch. The brake application starts at 86 s when the brake pipe pressure drops to 84psi. Afterwards, a large drop of pressure in the brake pipe increases the brake application at 167 s, when the pressure on the brake pipe is 78psi. Finally, at the end of the downhill, the brake pipe is pressurized to 90psi, making the system release the brakes.

Each wagon has 12.1 m of the brake pipe, with a diameter of 31.75 mm. Each section can be isolated by two cocks, one at the beginning and another at the end of each wagon. Additional parameters intrinsic to the model are listed in [Table 1](#).



**Figure 7.** Parallelized algorithm ( $n$  is the total number of vehicles and  $x; z$  are the number of processor cores).

**Table 1.** Characteristics of the brake system adopted for the simulations.

Auxiliary reservoir volume	0.041 m <sup>3</sup>
Emergency reservoir volume	0.057 m <sup>3</sup>
Brake cylinder mass	0.25 kg
Elastic constant of the brake cylinder	100 N/m
Brake cylinder Area	0.065 m <sup>2</sup>
Maximum displacement of brake cylinder	0.1868 m
Minimum displacement of brake cylinder	0.0627 m

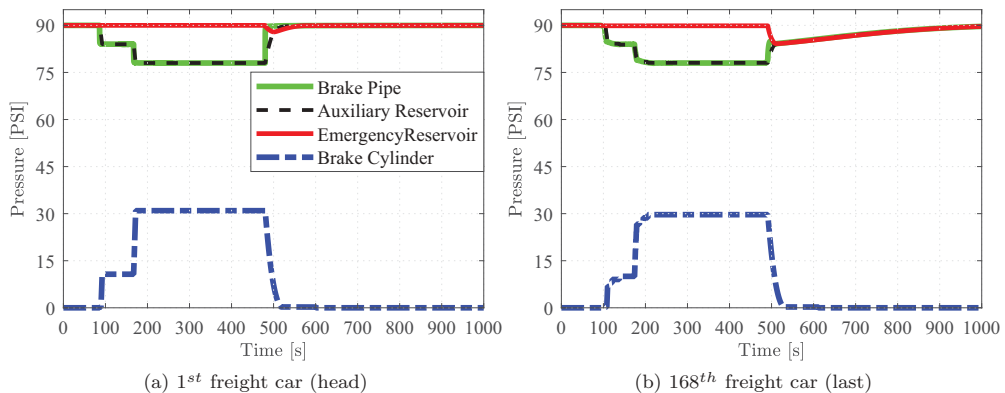
To extend the scope of this study, the simulations were performed and compared based on two different CPU types. The first, an Intel i7-8700 with 6 processor cores and the second, a Ryzen 1700 with 8 processor cores. The results are discussed in the next section.

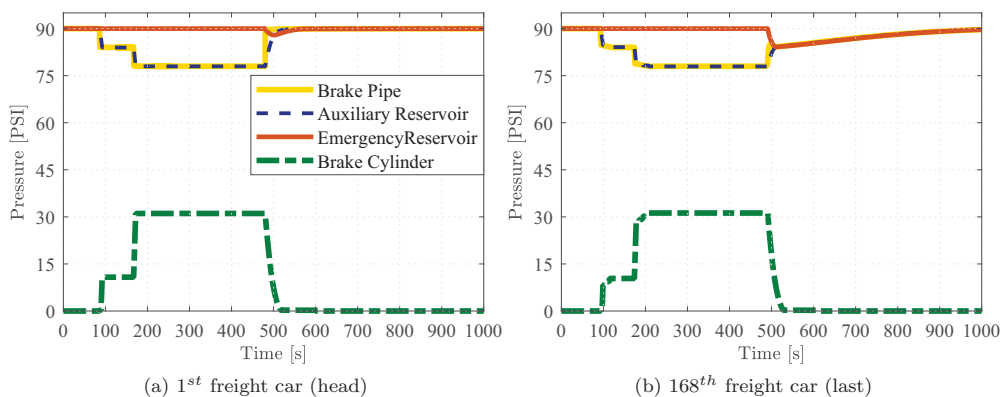
### 3. Results

All the simulation results presented in this section were compared and validated with the commercial software TOS (Train Operation Simulator), in the same way as performed by Teodoro et al. [19]. On both approaches, the results are similar and they are presented in Figures 8 and 9, for the first and last freight car. In either figure, when there is a drop in the pressure of the brake pipe; the auxiliary reservoir pressure responds to this drop by sending its air to the brake cylinder, which generates an increase in the brake cylinder pressure and, subsequently, the brake force. The same action happens on the second pressure drop. Upon the release of brake force, during the pressurization of the brake pipe, the reservoirs and the brake pipe are connected and increase their pressures together. This generates a little drop in the pressure of the emergency reservoir and subsequently connects the brake cylinder to the atmosphere reducing the brake force to zero.

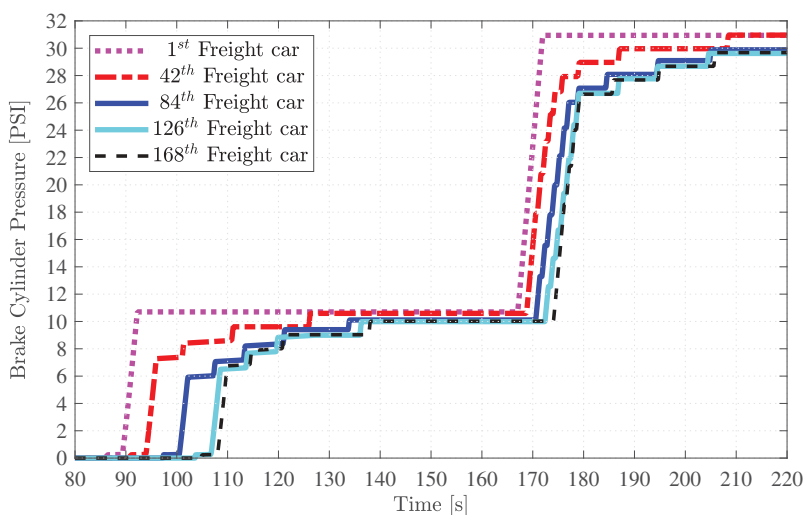
The main difference between the results from the first and the last wagons, according to Figures 8 and 9, is the delay of the pressure variation and the velocity of it, as highlighted in Figure 10. This braking delay is not only common but expected in long trains with several freight cars.

The braking delay in the freight cars (Figure 10) happens because the valves receive the pressure variation (trigger signal) from the locomotive handle (head of the train). This

**Figure 8.** Pressure behaviour in the components of the brake system Lumped characteristic approach



**Figure 9.** Pressure behaviour in the components of the brake system according to the Navier-Stokes approach.



**Figure 10.** Pressure behaviour in the components of the brake system in the 168<sup>th</sup> wagon (Lumped approach).

pressure depression signal has to travel through the whole brake pipe (approximately 2 km) to reach the wagons located throughout the train. Due to this pressure variation delay, the equalization between the auxiliary reservoir and the brake pipe pressures happens faster than the brake pipe pressure drops, delaying the airflow to the brake cylinder until the main pipe pressure difference is sufficient again to trigger the valve.

As both simulation approaches (using a parallelized or serial algorithm) produced the same results, the comparison between the methods is then focused on computational cost, measured by the processing time to perform each simulation.

The analyses are divided into four conditions, that simulate the train braking behaviour, according to the presented control schedule. The first two results use the Lumped equation method considering the serial (LSA Lumped Serial Algorithm), and parallel (LPA Lumped Parallel Algorithm) solver approaches. The last two methods correspond to the Isothermal

Navier-Stokes approach with the serial (NLA Navier-Stokes Serial Algorithm) and parallel (NPA Navier-Stokes Parallel Algorithm). Figure 11 presents a bar graph that shows the processing time for each algorithm/solver strategy and the values are shown in Table 2.

From the presented results, there is a clear difference between the serial and the parallel implementations. In both approaches (lumped and Navier-Stokes) the computational time in parallel implementations was reduced by nearly 80%. This expressive improvement allows faster simulations that can accurately reproduce system behaviour and optimize the conduction procedures in a shorter period of time, allowing for a more efficient trip.

Regarding computing time by using different processors, it is clear that the Intel i7 processor performed better for these selected simulations, finishing all the simulations faster than the AMD Ryzen 7. Nonetheless, when we compare the sheer processing time reduction, the AMD Ryzen 7 improved simulation time by around 82% in the parallelization of both analysed methods, while the Intel i7 reduced the computational cost by 81% for the lumped parameters and only 77% for the Navier-Stokes method. This difference in the parallelization reduction time happens because of the difference in the number of cores of each processor and their different internal architectures and implementation. The AMD Ryzen has less computational capability; however, it has more cores.

Thus, as the number of freight cars in the trains increase, the parallel approach will become ever more necessary in dynamic simulations. Therefore, it shows a promising solution that ensures simulation accuracy associated with lower processing time as compared to the standard serial solution.

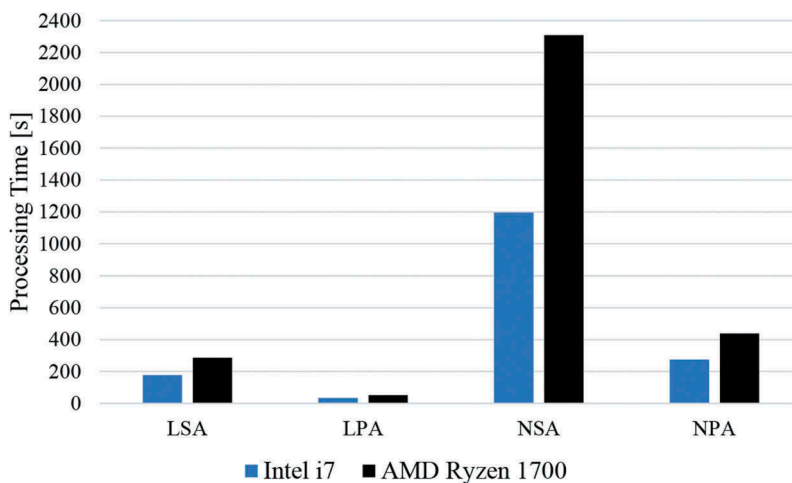


Figure 11. Pressure behaviour in the components of the brake system in the 168<sup>th</sup> wagon.

Table 2. Comparison among the processing times for the strategies adopted.

Algorithm Method	Computer Processor	
	Intel i7	AMD Ryzen 7
Lumped Serial	177.6 s	286.2 s
Lumped Parallel	34.3 s	52.4 s
Navier-Stokes Serial	1196.1 s	2309.4 s
Navier-Stokes Parallel	274.7 s	438.2 s

## 4. Conclusions

With the focus in pneumatic brake system of ore heavy-haul trains, this work presented models to simulate the dynamic behaviour of the brake system components located in the freight cars for a selected section of a Brazilian railroad. Moreover, two different approaches were employed to calculate the pressure along the brake pipe, each with a different mathematical treatment. These two approaches were implemented in a serial and parallel manner in order to assess the time necessary to perform the proposed simulation.

The parallelization method results in an evident improvement regarding the processing time, which makes it possible to perform several simulations for further development or optimization, in an acceptable overall processing time. The results show an average of 80% of reduction in the processing time due to parallelization, regardless of the mathematical method.

In addition, the results show that a larger number of processor cores leads to a greater processing time reduction. However, this also depends on the internal architecture and implementation of the CPU in question; i.e if the CPU has a great number of cores, but the communication between the cores and the memory is poorly made, the delay produced by this communication will interfere in the performance of the algorithm. Thus, as the number of freight cars in the heavy-haul ore trains increase, the parallelization procedure will become a necessity for future detailed/precise simulations.

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