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## Road and Rail Infrastructure III

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## WELL-TO-WHEEL ENERGY COMPARISON OF US AND EUROPEAN RAIL FREIGHT

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### Abstract

Worldwide, about 30% of the final energy and 62% of final oil is consumed by the transport sector. Reducing global fuel consumptions is one of the highest priorities for all countries for both energy security and greenhouse gas emission implications. With globalization, transport of goods increased significantly and then pressure on the environment. If the departure and arrival of the goods are on the same continent, transportation can be done by air, road or rail. Between this three means of transport, it is usual to consider that rail freight transportation allows reducing energy consumption per ton transported. United States and Europe have developed an important railway system to transport goods and people. These two systems are very different in terms of infrastructure, rolling stock and operation. They are specialized; the American in freight transportation while the European in people transportation. In a first part of this article, these differences are compared and analyzed. Then, a well-to-wheel reasoning is carried out on various types convoy (container or bulk) in Europe and US. Length, mass, propulsion, train resistance, speed, track profile, gauge, electricity generation etc. are taken into account. Train is modeled as a point with a mass. Newton's second law is applied on this point. The total force to the drive wheels provided by the electric motor is computed by a dynamic simulation. Finally, US and Europe rail freight are compared with an energy per ton transported indicator. This energy comparison shows the advantages of the American system on the environment despite the use of diesel locomotive.

*Keywords: rail freight, energy, well-to-wheel, Europe, United States*

### 1 Introduction

Globally, transportation activities are using more than 30% of the primary energy consumption, (33% in EU 27, [1]), they cause more than 25% of greenhouse gas emissions [1] and the trend is increasing as shown in Fig. 1.

In a world where energy is becoming more costly, and where global warming is making violent climatic episodes (floods, storms, etc.) more and more common, using environmental friendly freight transportation will soon be a necessity. Freight trains have now, in Europe, a modest market share for long distance transportation, but they are thought as being more efficient both in energy consumption and in greenhouse gas (GHG) emissions than other transportation modes as shown in Fig. 2.

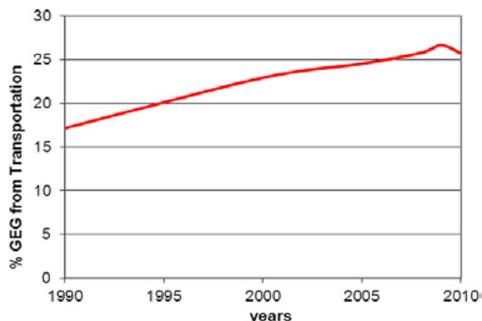


Figure 1 Greenhouse gas from transport in Europe, according to [2]

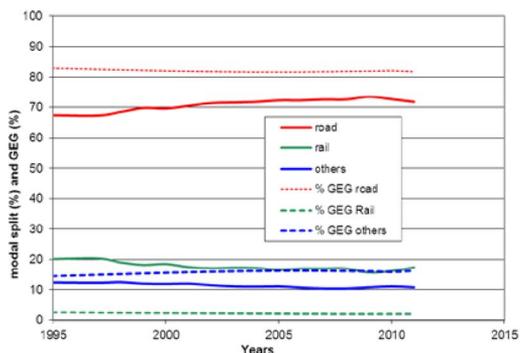


Figure 2 Internal transport modal split in Europe Market share and Greenhouse gases share, according to [1]

## 2 Typical train

Freight trains come in many varieties and a comparison between typical European and non-European freight trains shows the differences in Tab. 1.

Table 1 European and freight train comparison

	European freight	Non european freight	Impact
<b>Motorisation</b>	1 or 2 Electric engines	Up to 5 Diesel engines	· speed sensitivity to track profile · acceleration and transit time
<b>Couplers</b>	UIC couplers	Automatic couplers	· train length number of engines · aerodynamic resistance
<b>Gauge</b>	GA to GC	Double stack	· competitiveness · aerodynamic resistance
<b>Max length</b>	500 to 750 m	2,500 m and more (ECB)	· line capacity competitiveness
<b>Speed</b>	100 km/h	60/80 km/h	· transit time · energy consumption
<b>Traffic management</b>	Passenger train priority	Freight train priority	· transit time, number of stops/ starts, energy efficiency

As seen above, the two types of freight trains are quite different, and it is a legitimate question to ask if one is more efficient than the other in primary energy use or in greenhouse gas effect.

To check what type of train is more efficient in terms of energy consumption or GHG (or both), we tested 4 typical European and US trains:

- An heavy mineral train 87 waggons and 2 engines, 900 m and 10,440 t, named US-t-1 in this paper;
- A double stack container train, 105 waggons and 2 engines, 2,050 m and 10,500 t, named US-t-2;
- An European heavy freight train on a mixed passenger/freight network, 215 m, 1 engine, 1,300 t, noted EU-t-1;
- An european container train, 390 m, 1 engine, 1,300 t, noted EU-t-2.

### 3 Train resistances

The running resistance has a direct impact on energy consumption of trains. It is important to evaluate it correctly. Hence, in a first step we compare the different formulas proposed in the literature. In a second step, we choose one running resistance formula and we calculate the running resistance for the 4 trains selected in our European/US comparison.

#### 3.1 Formula train resistance comparison

Four train resistance formulas are compared. The first one is proposed by Lukaszewicz [2], data comes from full-scale tests with freight trains in Sweden. The second is proposed by Rochard [3] which summarizes various formulas. The third one comes from Allenbach [4] and the last one is the so called “Davis equation” summarized by Hay [5]. The 4 running resistance formulas are consistent and similar. We found a difference of less than 15% at a speed of 100 km/h for a standard freight train. Subsequently, only the Davis is then presented.

Particular attention should be paid to convert the “Davis equation” into international system units. Indeed, it is necessary to convert the speed in m/s, the mass in kg (US ton is equal to 907 kg) and force in N (1 lbf is equal to 4.45 N). The formula used is express in the equation (1).

$$R_{\text{Davis}} = 2.943 \times 10^{-3} \cdot W_{\text{Sl}} + 88.96 \cdot n + 1.097 \times 10^{-4} \cdot W_{\text{Sl}} \cdot V_{\text{ms}} + 22.26 \cdot K \cdot V_{\text{ms}}^2 \quad (1)$$

where:

- $R_{\text{Davis}}$  is the resistance in N for one car;
- $V_{\text{ms}}$  is the speed in m/s;
- $W_{\text{Sl}}$  is the car weight in kg;
- $n$  and  $K$  are number of axle and drag coefficient.

#### 3.2 Train resistance calculation

Davis equation is used to calculate the running resistance of the 4 trains used in the US/ European comparison. The coefficient  $K$  used is: 0.07 for US-t-1 and EU-t-1 (conventional equipment), 0.0935 for EU-t-2 and 0.11 for US-t-2 (double stack).

The train resistance for each train is proposed in the Fig. 3. We can observe that the running resistance is largest for US than European trains (Fig. 3, left). This is explained by the fact that the U.S. trains are much longer and heavier. If we compare the running resistance divided by transported mass, it can be seen with Fig. 3, right than the US-t-1 is more efficient. Moreover, we can observe that rock trains (US-t-1 and EU-t-1) are in the both case more efficient than the containers train. Due to high aerodynamic drag, the efficiency of US-t-2 (double stack) greatly decreases with the speed.

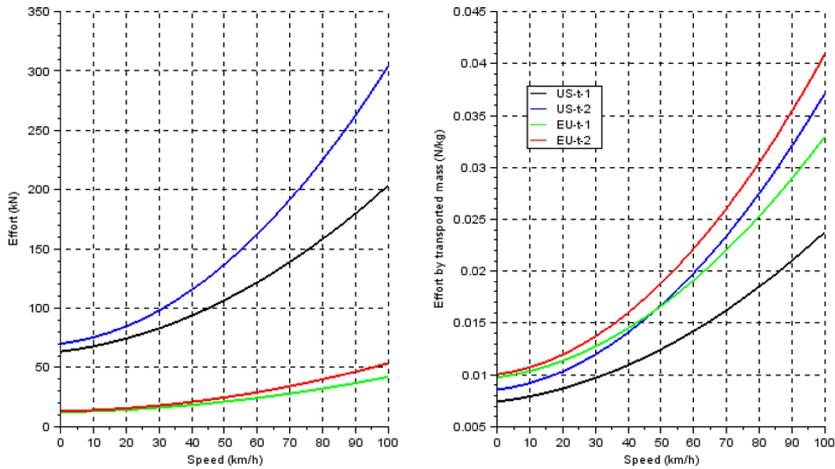


Figure 3 Train resistance (left) and train resistance by ton transported (right)

## 4 Speed profile simulation

A virtual line of 80 km was created to simulate a representative track and a speed profile. On this path, speed limits are introduced to comply with the regulations and practices in the US and Europe. A dynamic model of a train is used and subsequently presented.

### 4.1 Track profile

We compare the 4 trains on a track shown in Fig. 4. This 80 km itinerary is characterized by: 3 hill at a gradient of 8, 5 and 4 mm/m and one down at 10 mm/m.

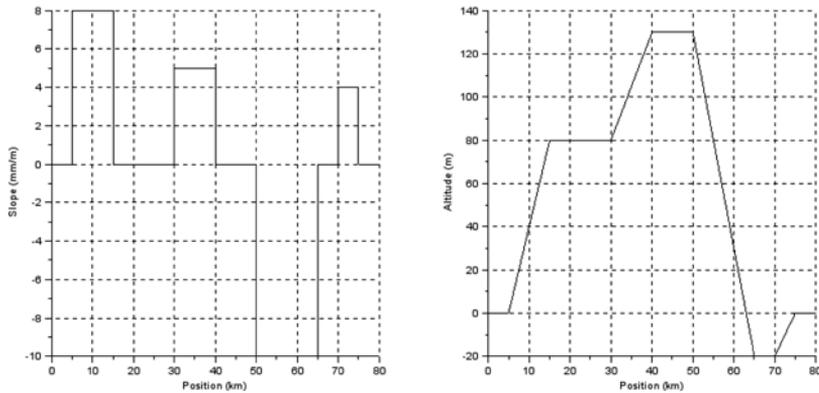


Figure 4 Slope (left) and profile (right) of the line

### 4.2 Dynamic model

As proposed by Lukaszewicz [2] or Rochard [3], a simplified dynamic model train is used. The train is considered as a point with a mass  $M$ . Newton's second law is applied on this point to calculate the total force to the drive wheels ( $F$ ) provided by the electric motor. The formula is:

$$F = m \cdot k \cdot \gamma - M \cdot g \cdot \sin(\alpha) - F_r \quad (2)$$

where:

- k conventional coefficient which represent inertia of rotating masses;
- m the mass of the train;
- $\gamma$  the longitudinal acceleration;
- $F_r$  the resistance force calculated by Davis equation;
- g the gravity acceleration and is local gradient of the line.

The rules of driving are as follows: two limit speeds are introduced. The first one is the set point speed ( $S_{sp}$ ). If the speed of the train is lower than the set point speed then F is positive. It is the case 1 (traction). The second one is the limit speed (S). If the speed of the train is between the set point and the limit speed then F is zero (case 2, coasting). If the speed of the train is above the limit speed then F is negative (case 3, braking).

### 4.3 Results

We can see in Fig. 5 the simulated speed profiles of the 4 trains. The black line is the speed of the train, the blue dotted line is the set point speed and the red dashed line is the limit speed. The set point speed is 60 km/h for US-t-1, 80 km/h for US-t-2 train and 100km/h for European train. Moreover, to respect the rules of traffic in the country, the set speed is reduced to 25 km/h in the US and 100 km/h in Europe in the slope. To represent a real driving, coasting is introduced for U.S. trains before the speed reduction for slope. It can be seen that the speed profiles are very different between the U.S. and Europe trains. US train speed is more sensitive to the track profile.

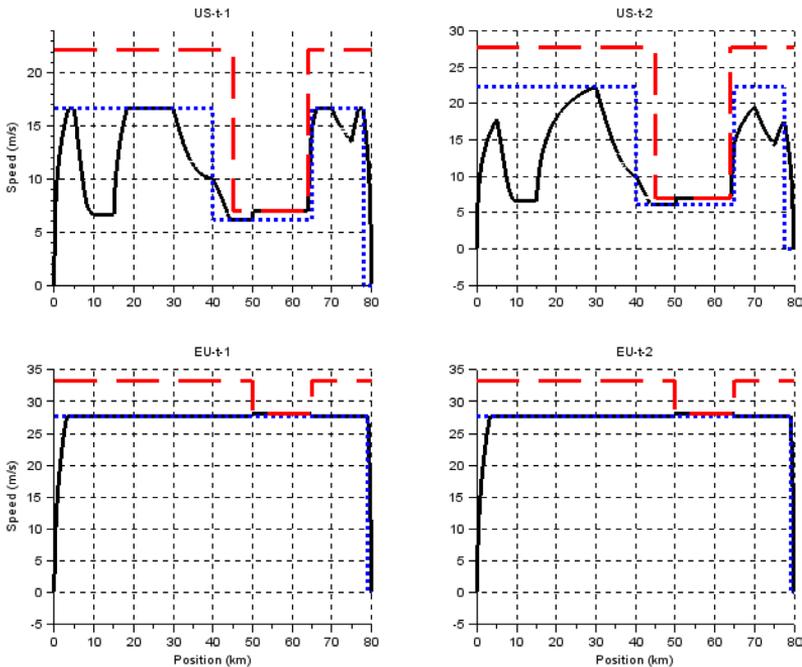


Figure 5 Speed profile of the 4 trains

## 5 Energy consumption

For all trains, the power transmitted to the wheel  $P_w$  is calculated (product of velocity  $v$  and force  $F$ ). Furthermore, a constant  $P_a$  is added to take into account the consumption of auxiliary (cooling engine, compressed air system, etc.). Then, the energy consumed by the train  $E_{train}$  is calculated using the equation 3:

$$E_{train} = \int \frac{P_w + P_a}{\eta} dt \quad (3)$$

where:

$\eta$  efficiency of the traction system.

For electric traction (European train),  $\eta$  equals 80% (Jeunesse [6] give a ratio of 87% for the French high speed train) and for diesel train (US-t-1 and US-t-2),  $\eta$  equals 45% (according to [7]). Finally, to calculate the primary energy, losses to extract and process oil and to produce electricity are taken into account. The well-to-tank ratio is taken at 1.3 (according to [8]) and the production electricity ratio is taken at 3.1 (according to [8] or [9]).

In addition, the GHG emission indicator is calculated. According to [8], we considered 530 g of GHG rejected for 1 kWh of electricity consumed (emission power generation in Europe) and 92 g of GHG rejected for 1 MJ of diesel burned.

## 6 Results

The results of our 4 simulations are shown in Tab. 2. European trains consumption is upper than 2 times US trains consumption per transported mass in energy. Moreover, GHG emissions are significantly higher.

**Table 2** Primary energy (MJ/tkm) and greenhouse gas emissions (g/tkm) comparison

	US-t-1i	US-t-2	EU-t-1	EU-t-2
MJ/tkm	0.097	0.11	0.25	0.27
g/tkm	7	9	12	13

These results are consistent with data from [9]. According to this reference, the consumption in primary energy is about 0.25 MJ/tkm in Europe. Obviously, the travel time of 4 trains are different. It is approximately 130 minutes for US trains and 50 minutes for European trains.

## 7 Conclusion

We show in this paper that rail freight is more interesting from an energy and GHG emissions point of view in the United States. Despite the low efficiency of thermal engines, US trains are more efficient for several reasons: technological choices (couplers, electric/diesel traction, etc.) and different operating methods (speed, priority, etc.). In the perspective of this works, other simulations can be performed with different engine efficiency or well-to-tank ratio for instance if more accurate data are available. It would be interesting to work on the Ofoten line in Norway for example. Indeed, this line combines the advantages of two systems: heavy trains with resistant couplers, electric traction and high performance energy mix (electricity production in Norway is mainly generated by hydropower).

We note that the rail freight remains more interesting than road transport from an energy point of view. Indeed, according to [9], road transport consumption is 0,7MJ)/tkm (between 3 and 7 times more than rail).

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