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The problems of the presence of passenger and freight trains on the same track

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Abstract

Many features of the freight wagons/trains differ substantially from those of the passenger coaches/trains. As a result, sharing the same track affects directly or indirectly the design, construction, operation and maintenance of a railway system. In this context, this paper evaluates qualitatively and quantitatively the effect of some of the above features on the components and elements of the railway system and provides cost elements for the construction of a railway infrastructure considering different scenarios of operation. The main findings of this paper have shown that: for freight trains the track maintenance cost is much greater than that for passenger trains, the alignment is determined by the design speed defined for passenger trains, the construction cost of infrastructure for a typical mixed traffic corridor is generally higher than that of a passenger dedicated corridor.

Keywords: passenger dedicated corridor, freight dedicated corridor, mixed traffic, infrastructure cost

1. Introduction

Worldwide, the vast majority of railway networks is based on mixed train operation (routing of passenger and freight trains on the same track) (Batisse F., 1994, UIC, 2007).

On one hand, this practice seems to achieve economies of scale as more trains make use of the same railway infrastructure, on the other hand creates problems to the management of the railway system as trains with different technical and operational characteristics circulate in the same track. In the recent

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years, most mixed operation networks show an important decline of their transport volume. On the contrary, networks dedicated only for passenger or only for freight train operation are profitable (Pyrgidis and Georgakopoulou, 2007, Pyrgidis and Christogiannis, 2011)

Many features of the freight wagons/trains differ substantially from those of the passenger coaches/trains. This fact has an impact on the design, construction, operation and maintenance of a railway system.

In this context, this paper:

- records the features of the freight wagons/trains that differ significantly from those of the passenger coaches/trains and identifies among them the ones that affect directly or indirectly the construction, operation and maintenance of a railway system, depending on whether it is intended for dedicated or mixed train operation,
- evaluates qualitatively and quantitatively the effect of some of the above features on the components and elements of the railway system,
- provides cost elements for the construction of a railway infrastructure considering different scenarios of operation.

This paper constitutes a first approach of an overall research currently under way in the Transportation Department of Aristotle University of Thessaloniki. This research aims at investigating the effects of mixed train traffic in the efficiency of a railway system and at creating mathematical models, which could serve as decision support tools for the railway infrastructure managers, concerning the operational scheme to be adopted for a given rail corridor (dedicated or mixed operation).

2. Notations

a : parameter depending on traffic load

B_σ : rail weight per running meter (kg)

B : train total weight (t)

b : parameter depending on sleeper type

c : parameter depending on volume of track maintenance works

C : maintenance cost

C_{13} : infrastructure cost per km of track (meuro/km),

d : parameter depending on value of the axle load

E : parameter depending on subgrade quality

E_{max} : maximum permitted cant excess (mm)

e : total thickness of ballast layers (m)

e_b : ballast layer thickness (m)

e_{sb} : sub ballast layer thickness (m)

$2e_0$: track gauge (=1500mm)

f : parameter depending on train speed

g : gravitational acceleration ($= 10 m/sec^2$)

i : track gradient (‰)

i_{max} : maximum gradient (‰)

I_{max} : maximum permitted cant deficiency (mm)

I_z : rail moment of inertia in m^4

L_z : train length (m)

n_l : number of tracks of the line

Q : train axle load (t)

Q_0^{tr} : load of powered axles (t)

R_{cmin} : minimum curve radius in horizontal alignment (m)

T_f : daily traffic load (t)

T_1, T_2 : daily traffic load for $Q_1 = 16$ t and $Q_2 = 22.5$ t respectively

U_{max} : maximum permitted cant (mm)

V : train speed (km/h)

V_{max}, V_{min} : maximum and minimum train speed respectively (km/h)

V_1, V_2 : train speed for $Q_1 = 16$ t and $Q_2 = 22.5$ t

W_{zf} : static moment of inertia relative to rail foot in m^3.

α, β, γ : empirically determined coefficients (Esveld,1989), which vary with the infrastructure element fault.

γ_{ncmax} : maximum permitted residual centrifugal acceleration

κ : W^4_{zf}/I_z

μ : friction coefficient (wheel – rail)

3. Trains’ characteristics and their impact to the railway system – Qualitative approach

Table 1 (attached at the end of the paper) shows typical values for the basic features of the passenger coaches/trains that differ from those of the freight wagons/trains such as train speed, axle load, train weight e.t.c. Furthermore it is shown the qualitative impact of feature values increase on the components and elements of a railway system. Finally in the last column it is shown the requirements considered in design, construction and maintenance of the railway system.

4. Trains’ characteristics and their impact to the railway system – Quantitative approach

4.1. Impact of the axle load

Axle load – rail profile

Based on formula (1) (Esveld, 1989), it is deduced that axle loads of 20, 25 and 30 t require rails of minimum weight 50, 60 and 70 kg/m respectively. A 25% increase in the axle load requires a 20% increase in the rail weight. The choice of rail weight is also greatly conditioned by the track design speed and the daily traffic load

$$\mathrm{B}_{\sigma} = 2.25 \cdot Q + 3 \qquad (1)$$

Axle load – track inclination

Formula (2) expresses the relation that ensures the motion of a train after a stop in a slope with a gradient i.

$$\sum Q_0^{tr} \cdot \mu \ \geq B \cdot i \qquad (2)$$

Considering a passenger train and a freight train with the features of table 2 and based on formula (2), for $\mu = 0.3$ it is derived a 35‰ and a 20‰ maximum track inclination for the passenger and freight train respectively.

Table 2: Features of typical passenger and freight trains

Train features	**Passenger train**	**Freight train**
Total weight	680 t	2400 t

Number of power vehicles	1	2
Number of powered axles	4	4
Load per axle (powered axles)	20 t	20 t

Axle load – maintenance requirements

Considering two railway tracks with axle load values of Q_1 = 16 t and Q_2 = 22.5 t respectively. Assuming that speed is equal in both cases, it deduced (Esveld and all, 1989, Lichtberger, 2005):

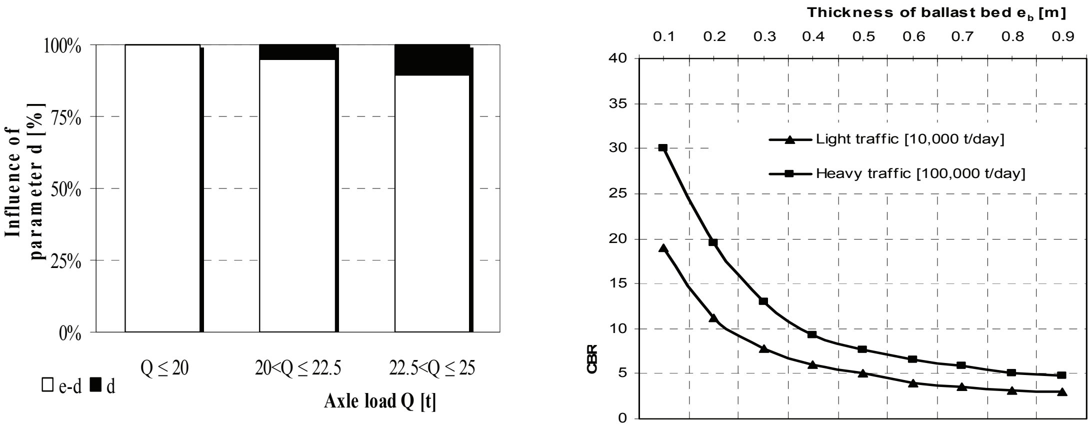
$$\frac{C_2}{C_1} = 1.406^{\frac{\beta}{\alpha}} \quad (3)$$

The ratio C_2/C_1 is calculated between 1.41 and 2.78 (the ratio β/α is calculated between 1 and 3.5). i.e. the maintenance cost in the case of a track with Q_2 = 22.5 t is between 41% and 178% greater than that for a track with Q_1 = 16 t.

Axle load – ballast layers thickness

Based on formula (4) (UIC, 2006, Esveld and all, 1989), it can be calculated the influence of the axle load to the thickness of the ballast and sub ballast layer respectively.

$$e=e_b+e_{sb}=E+a+b+c+d+f \quad (4)$$



(a) **(b)**

Figure 1: (a) Influence of the axle load on the thickness of the ballast layers, (b) Required ballast layer thickness as a function of substructure CBR index and daily traffic load

From figure 1a is concluded by the authors that for passenger trains (*Q ≤ 20 t*) the influence of the axle load on the total ballast layers thickness is negligible, while for freight trains (*22.5<Q ≤ 20 t*) the total thickness could be increased up to 21%.

4.2. Impact of the daily traffic load

Daily traffic load – track bed thickness

Based on the diagram of figure 1b (Alias, 1984), for a track substructure with a CBR index of 15 and heavy daily traffic load, a 30 cm thick ballast layer is required. If traffic is light, a 15 cm thick ballast layer is adequate.

Daily traffic load – maintenance requirements

Considering two railway tracks where trains are routing with equal axle load and speed. Based on formula (5) (Esveld and all, 1989, Lichtberger, 2005) it can be derived the influence of daily traffic load on the volume of maintenance works and on relevant cost respectively

$$C_2 = \left(\frac{T_2}{T_1}\right)^{\alpha} \cdot C_1 \qquad (5)$$

i.e. an 100% increase of daily traffic load results in an increase greater than 100% of the maintenance cost.

4.3. Impact of the train length

Train length – track capacity

In figure 2 is depicted the track capacity of a track of one way traffic operation with an intermediate block signal as a function of train length. (UIC, 1983, Pyrgidis and Stergidou, 2011). From this diagram it can be deduced that track capacity decreases as train length increases. This is due to the fact that longer trains require greater time to release a block section, leading to longer minimum train follow-up intervals. For example, an increase in train length from 500 to 1500m leads to a decrease of track capacity from 88 to 81 trains per day.

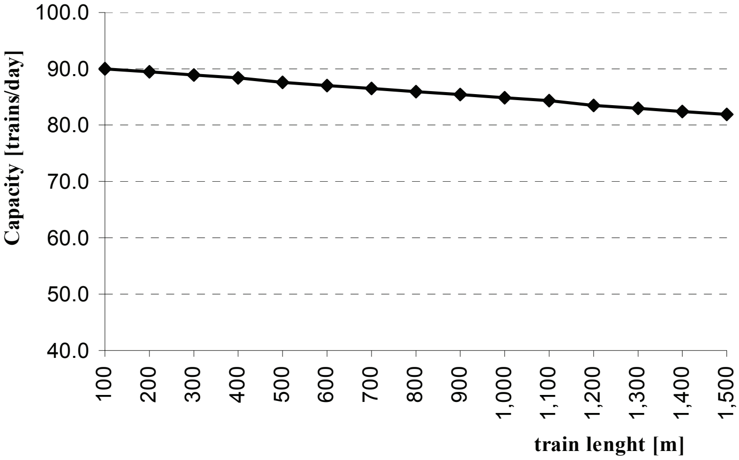


Figure 2: Track capacity – train length variation diagram (track with one way traffic operation)

4.4. Impact of the passenger dynamic comfort requirements

Lateral dynamic passenger comfort – horizontal curvature radius

Based on formula (6) (Alias, 1984) it can be derived the minimum permitted horizontal curvature radius R_{cmin} :

$$R_{c\min} = \max\left\{\frac{11.8 \cdot V_{\max}^2}{U_{\max} + I_{\max}}, \frac{11.8 \cdot (V_{\max}^2 - V_{\min}^2)}{E_{\max} + I_{\max}}\right\} \qquad (6)$$

In figure 3 is depicted by the authors the minimum permitted horizontal curvature radius R_{cmin} as a function of the maximum permitted lateral residual centrifugal acceleration γ_{ncmax}, for maximum allowed track cant U_{max} = *160 mm*, and for two values of V_{max} = *200 km/h* and *120 km/h*.

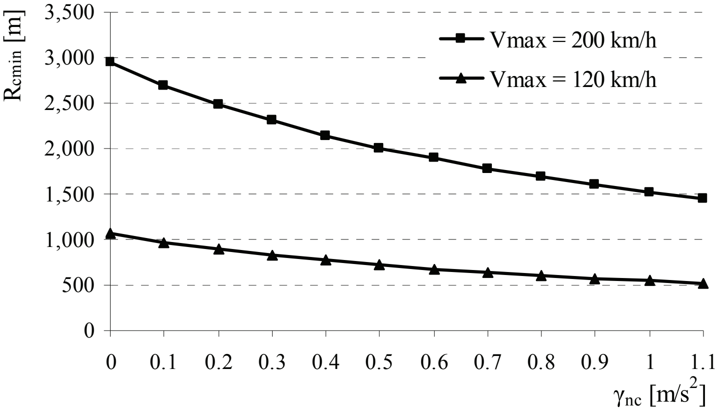


Figure 3: Minimum horizontal curvature radius R_{cmin} as a function of maximum permitted residual centrifugal acceleration γ_{ncmax}

Assuming three operation schemes:

1. Dedicated passenger train service with uniform speed $V_{max} = 200$ *km/h*, $U_{max} = 160$ *mm*, $\gamma_{ncmax} = 0.6$ m/s^2 (typical value for passenger trains), maximum permitted cant deficiency I_{max} = 90 mm (deriving from formula (7)) (Alias ,1984)

$$I_{max} = \frac{2e_0}{g} \cdot \gamma_{nc\max} \tag{7}$$

2. Dedicated freight train service with uniform speed $V_{max} = 120$ *km/h*, $U_{max} = 160$ *mm*, $\gamma_{ncmax} = 1.0$ m/s^2 (no dynamic lateral comfort issue in freight trains), I_{max} = 150mm (deriving from formula (7))
3. Mixed train operation with $V_{max} = 200$ *km/h* ,V_{min} = 120 km/h, U_{max} = 160 mm, γ_{ncmax} = 0.6 m/s^2, I_{max} = *90 mm*, maximum allowed cant excess E_{max} = *100 mm*

The following minimum horizontal curvature radii are derived , respectively: R_{cmin} = *1888 m*, R_{cmin} = *548 m*, R_{cmin} = *1589 m*. It is noted that the fastest (passenger) trains determine the horizontal curvature radius.

4.5. Impact of the train speed

Train speed – rail profile

The diagram in figure 4 is derived by the authors applying the Eisenmann method and presents the rail profile requirements for axle loads of 16 and 22.5 t, as a function of train speed. As can be seen from the diagram, a speed increase leads to a rail profile weight increase, for the same axle load. The same rail weight is required for freight trains with 22.5 t axle load and V=80 km/h and for passenger trains with 16 t axle load and V=200 km/h.

It must be stressed in this point that achieving high speeds relies heavily on ensuring retaining track geometry. To this end, high speed networks (V > 200 km/h) are using only heavy rails (UIC 60 (60.3 kg/m)) as these limit track vertical displacement to acceptable levels.

Train speed – maintenance requirements

Considering two railway tracks with the same daily traffic load, where trains are routing with equal axle load. Based on formula (8) (Lichtberger, 2005) it can be derived the influence of train speed on the volume of maintenance works and on relevant cost respectively.

$$C_2 = \left(\frac{V_2}{V_1}\right)^{\gamma} \cdot C_1 \tag{8}$$

i.e. an 100% increase of speed results in an increase greater than 100% of the maintenance cost.

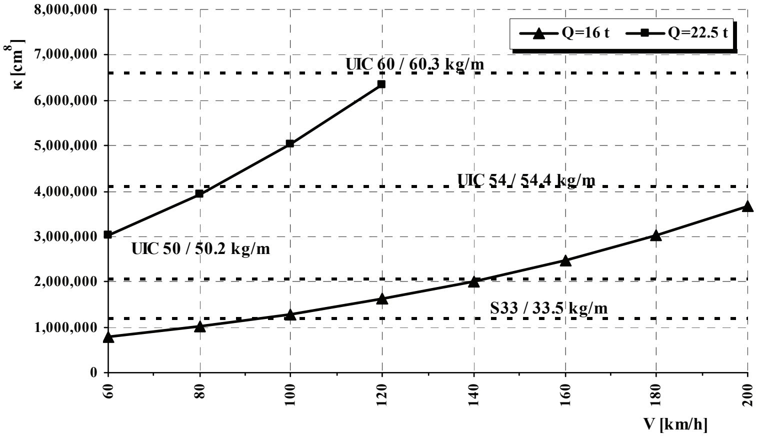


Figure 4: Rail profile as a function of train speed for axle loads Q =16 t and 22.5t

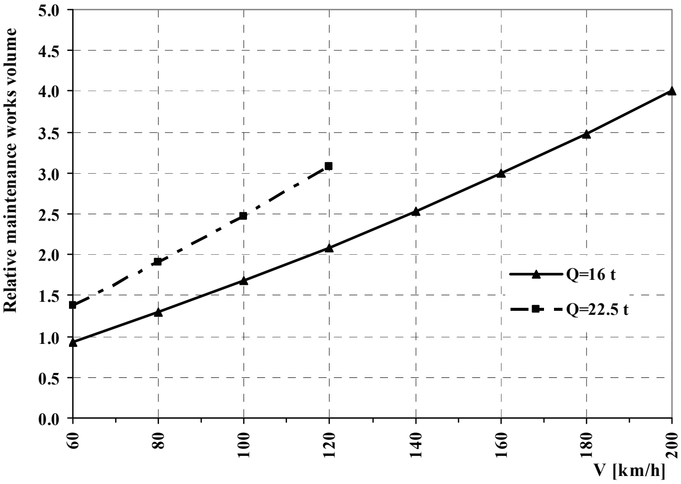


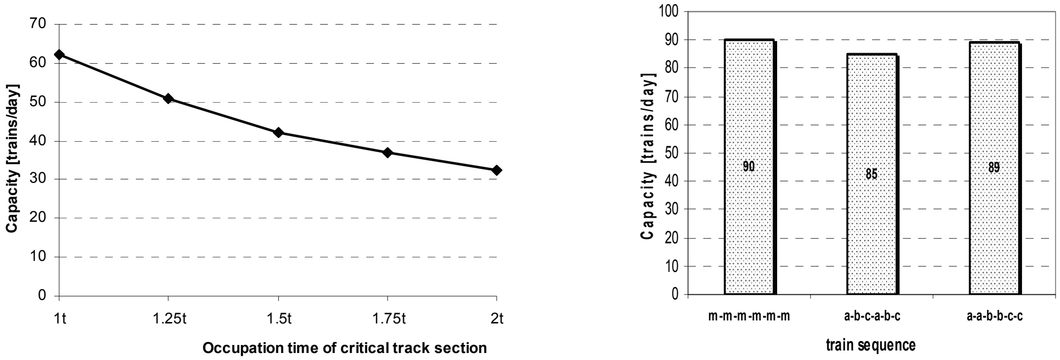
Figure 5: Influence of train speed to maintenance work volume – passenger and freight trains

From figure 5 it can be derived the influence of train speed on maintenance work volume for passengers and for freight trains.

i.e. the maintenance work volume for a passenger dedicated track (Q=16t and V=160km/h) it can be until 50% greater than the maintenance work volume for a freight dedicated track (Q=22.5t and V=80km/h) for the same daily traffic load.

Train speed – track capacity

In figure 6a is depicted the track capacity of a track of two directions of circulation as a function of the time required to travel the critical track section by the trains. It is noted that an increase in travel time for all trains (resulting from proportional decrease of their speed) leads to a capacity reduction. As an example, doubling the travel time (i.e. reducing speed by half) results to track capacity reduced to half (from 62 to 32 trains/day).(Pyrgidis and Stergidou, 2011)



(a) **(b)**

Figure 6: (a) Track capacity of a track with two directions of circulation – average travel time of critical track section, (b) Capacity of a track with one way traffic operation with intermediate block signal – traffic composition (homogeneity)

In figure 6b is depicted the capacity of a track of one way traffic operation as a function of traffic composition (homogeneity).The mark “a” denotes a train traveling the critical section in a short time (in this example this is a=8min), “c” denotes a train traveling the critical section in a long time (c=12min), “b” denotes a train traveling the critical section in an average time (b=10min), while “m” denotes a train type traveling the critical section in a time equal to the weighted average of travel times of all trains (here m=11min). From figure 6b it can be concluded that in the case of an intermediate block signal in the critical track section, track capacity is maximized when trains are homogenous in terms of critical section travel time, and, accordingly, speed (90 trains / day – sequence “m-m-m-m-m-m”). If there are three train types, namely a, b, c, the sequence “a-b-c-a-b-c” leads to a capacity decrease to 85 trains /day.

5. The influence of the traffic composition to the construction cost of a railway system

The construction cost of infrastructure includes the construction cost of bridges, tunnels, walls, water ducts, embankments, drainage, overpasses and underpasses, noise barriers, fences, service roads and other costs as initial maintenance, work management, rerouting of roads, interim financial charges e.t.c. The construction cost of infrastructure represents approximately the 50% of the total project. (Profillidis, 2006)

Based on data analysis for construction cost of railway infrastructure (Baumgartner, 2001) all over the world an analytical formula combining minimum longitudinal radius and maximum gradient of track has been be derived by the authors for topography of average difficulty:

$$C_{13} = \frac{\{1 + 0.4 \cdot (n_l - 1)\}}{1.4} \cdot \left\{(37.1 \cdot 10^{-3} \cdot R_{c\min} - 560) \cdot i_{\max} + 16.4 \cdot 10^{-4} \cdot R_{c\min} + 21.3\right\} \quad (9)$$

Based on formula (9) it can be derived an approach of infrastructure cost in preliminary study level. i.e. Assuming three operation scenarios and based on the calculations of paragraph 3.4 it derived :

- Passenger dedicated corridor (two tracks) with the following technical characteristics: $V_{max} = 300$ km/h, $R_{cmin} = 4248$ m, $i_{max} = 40‰$ (typical for passenger dedicated lines). Based on formulae (9) we derive a construction cost of railway infrastructure of approximately 12.2 meuros/km for a double track line. The construction cost of Frankfurt – Cologne (V=300 km/h) double track line was 27.4

million euro/km of line included the cost of track construction (rails, sleepers etc), electric traction system, signaling and railway stations, where the infrastructure cost was approximately 13.7 meuros/km of line (50% of the total project).

- Freight dedicated corridor (two tracks) with the following technical characteristics: V_{max} = 120 km/h, R_{cmin} = 548 m, i_{max} = 15‰ (typical for freight dedicated lines). Based on formulae (9) we derive a construction cost of railway infrastructure of approximately 14.1 meuros/km for a double track line. The construction cost of Betuwe line in Netherlands (V=120 km/h) was 28.7 million euro/km of line included the cost of track construction (rails, sleepers etc), electric traction system, signaling and railway stations, where the civil the infrastructure cost was 14.4 meuros/km of line.
- Mixed corridor (two tracks) with the following technical characteristics : V_{max} = 200 km/h, V_{min} = 60 km/h, R_{cmin} = 2261 m, i_{max} = 20‰ (typical for mixed traffic). Based on formulae (9) we derive a construction cost of railway infrastructure of approximately 15.5 meuros/km for a double track line. The expected construction cost of infrastructure of Lianokladi - Domokos line in Greece (V=160 km/h, i_{max} = 20‰) is 14.6 million euro/km of line.
- Mixed corridor (two tracks) with the following technical characteristics : V_{max} = 200 km/h, V_{min} = 60 km/h, R_{cmin} = 2261 m, i_{max} = 15‰ (typical for mixed traffic). Based on formulae (9) we derive a construction cost of railway infrastructure of approximately 17.9 meuros/km for a double track line.

In figure 7 is depicted the infrastructure cost in million euros as a function of design speed for passenger dedicated, freight dedicated and mixed traffic composition corridors for several values of i_{max} and for average difficulty topography.

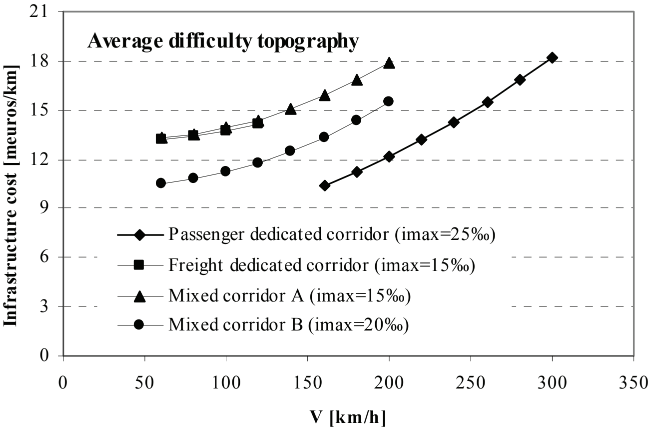


Figure 7: Influence of traffic composition on infrastructure cost of a double track corridor

From the figure 7 it can be deduced the following conclusions:

- The construction cost of infrastructure for a typical mixed traffic corridor is generally higher than of a passenger dedicated corridor for the same maximum train speed (approximately 10% to 20% higher).
- The construction cost of infrastructure for a mixed traffic corridor is slightly higher than of a freight dedicated corridor, for maximum gradient, i_{max}=15‰ and for the same maximum train speed.
- The construction cost of infrastructure for a typical freight dedicated corridor (i_{max}=10-15‰) is generally higher than of a mixed traffic corridor (i_{max}=20-25‰), (approximately 10% to 15% higher).

6. Conclusions

This paper is a first attempt to investigate the influence of traffic composition on the constituents of a railway system and on the construction cost of railway infrastructure. The motivation for this investigation was the fact that in recent years, most mixed operation networks show an important decline of their transport volume. On the contrary, dedicated freight networks are profitable, in constant growth and in no need of financial subsidy (Pyrgidis and Christogiannis, 2011).

The findings of this paper have shown that :

- Many features of the freight wagons/trains differ substantially from those of the passenger coaches/trains.
- The different features of passenger and freight trains have a significant influence on the design, construction, operation and maintenance of a railway system. In the case of constructing a single or double track for mixed train operation:
  - ✓ The alignment is determined by the design speed defined for passenger trains
  - ✓ Superstructure is built based on passenger train speed and freight train axle load
  - ✓ Track maintenance policy considers the daily traffic load made up of all trains.
  - ✓ Train traffic schedule diagram must include trains running at different speeds, with whichever consequence to the track capacity.
- The different features of passenger and freight trains have an significant impact to the construction cost of infrastructure of a railway system and generally it can be deduced that :
  - ✓ The construction cost of infrastructure for a typical mixed traffic corridor is generally higher than of a passenger dedicated corridor.
  - ✓ The construction cost of infrastructure for a mixed traffic corridor is slightly higher than of a freight dedicated corridor, for the same maximum gradient.
  - ✓ The construction cost of infrastructure for a typical freight dedicated corridor is generally higher than of a typical mixed traffic corridor.

Mixed networks satisfy primarily passenger transportation. So the features of passenger trains predominate on the constituents of a railway system and in extend on the construction cost of a railway project. On the other hand the increasing needs of cargo transportation leads the capabilities of mixed corridors in extreme conditions. This situation combined with the significant differences of passenger and freight trains seems to enforce the progressive segregation of networks for passenger and freight transportation.(Kopecky, 2003, OECD, 2002, Woodburn and all, 2008)

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Table 1: Qualitative impact of train features to the components and elements of a railway system – Requirements

Feature	Typical values of features		Effects of feature value increase on components and elements of a railway system	Impact of feature value increase on the requirements of the components and elements of a railway system
	Passenger trains	**Freight trains**		
Speed (V)	120-350km/h	60-120km/h	Increase of : track design dynamic load, train braking distance, centrifugal effort in curves, aerodynamic resistance, track capacity, consequences in case of accident	Larger axial distance between tracks, higher curvature radius in the longitudinal and vertical alignment , higher track cant, greater length of transition curve in the horizontal alignment , continuously welded and heavier rails, concrete sleepers, elastic fasteners, thicker track bed, track fencing, electric signaling, longer signal spacing, electrification (for V>160 km/h), specific rolling stock, slow train overtaking, increased safety measures along the track, bigger tunnel cross-section, higher maintenance needs
Axle load (Q)	12-18t	16-25t (heavy haul corridors up to 35 t)	Increase of : track design static load, train braking distance, track geometry defects deterioration rate, train running resistance	Less steep gradients, heavier rails, thicker track bed, longer signal spacing, greater traction power requirements, higher maintenance needs
Train weight (B)	200 – 800 t	1,500 – 3,000 t (heavy haul corridors up to 20,000 t)	Increase of : braking weight, train running resistance	Less steep gradients, longer signal spacing, greater traction power requirements
Train length (L_z)	100-300 m	400-800 m (heavy haul corridors up to 5,000 m)	Decrease of track capacity	Longer tracks and platforms in stations
Daily traffic load (T_f)	10,000 – 60,000 t	10,000 – 100,000t (heavy haul corridors up to 300,000t)	Increase of track geometry defects deterioration rate	Heavier rails, thicker track bed, higher maintenance needs
Dynamic passenger comfort	maximum permitted residual centrifugal acceleration $\gamma_{ncmax} \leq 0.7$ m/sec^2	maximum permitted residual centrifugal acceleration $\gamma_{ncmax} \leq 1.2$ m/sec^2	Decrease of passenger comfort	Greater curvature radius in the longitudinal and vertical alignment, higher track cant, greater length of transition curve in the horizontal alignment . In case of mixed traffic, adoption of track cant satisfying both train categories
Punctuality	10 sec – 3 min	30 min – 1 h	Increase of attractiveness of transportation	Priority for the passenger trains, timetables adapted on passenger trains requirements
Vehicle clearance gauge	Normal clearance gauge	Expanded clearance gauge		Differentiates depot and station dimensioning, axial distance between tracks, height clearance
Stations	Stops every 80 – 200 km	Stops every 300 – 1000 km		Totally different design and equipment in passenger and freight stations
Transported good	passengers	goods		Different safety measures required for the infrastructure and the rolling stock when transporting passengers compared to cargo. Special safety measures in tunnels when carrying passengers, special safety measures in the open track when carrying dangerous goods