AE234 Aircraft Propulsion - Quiz 4

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WHAT Price Speed?

Work Report

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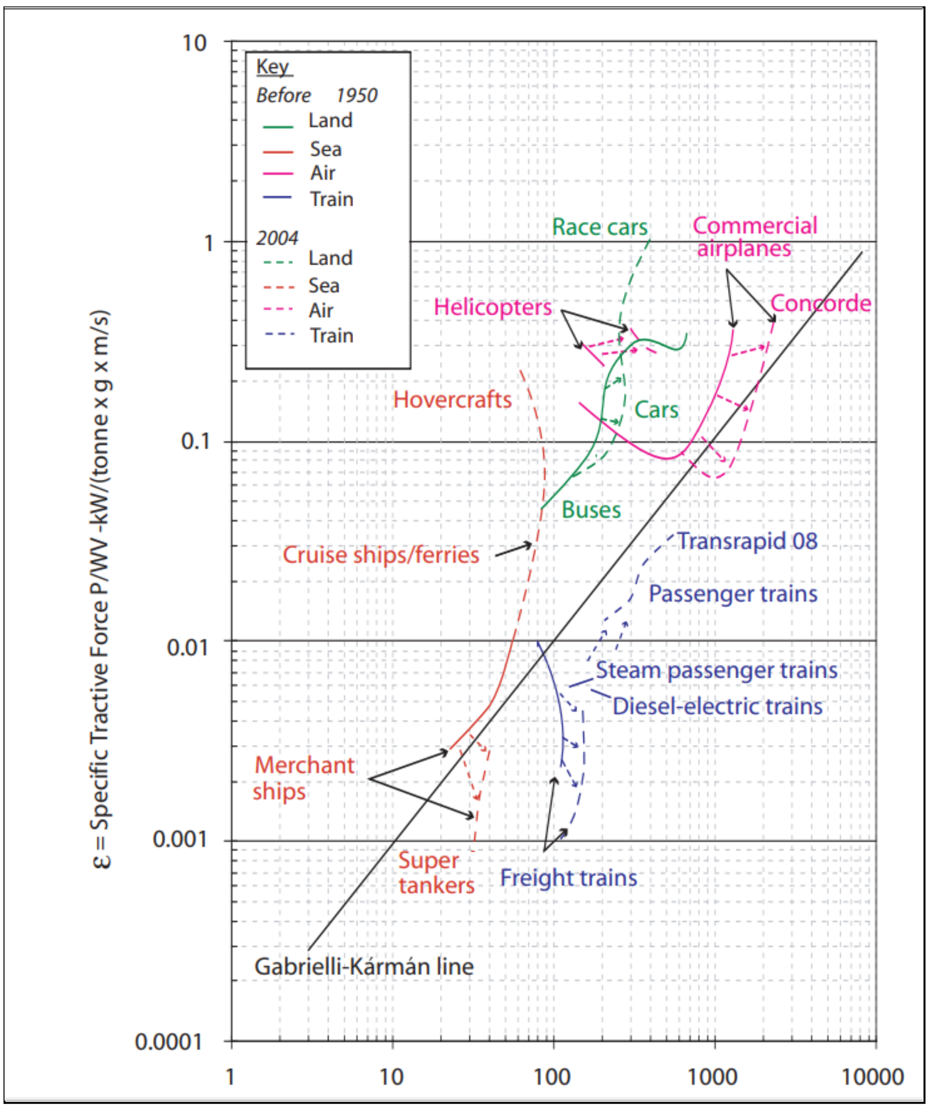
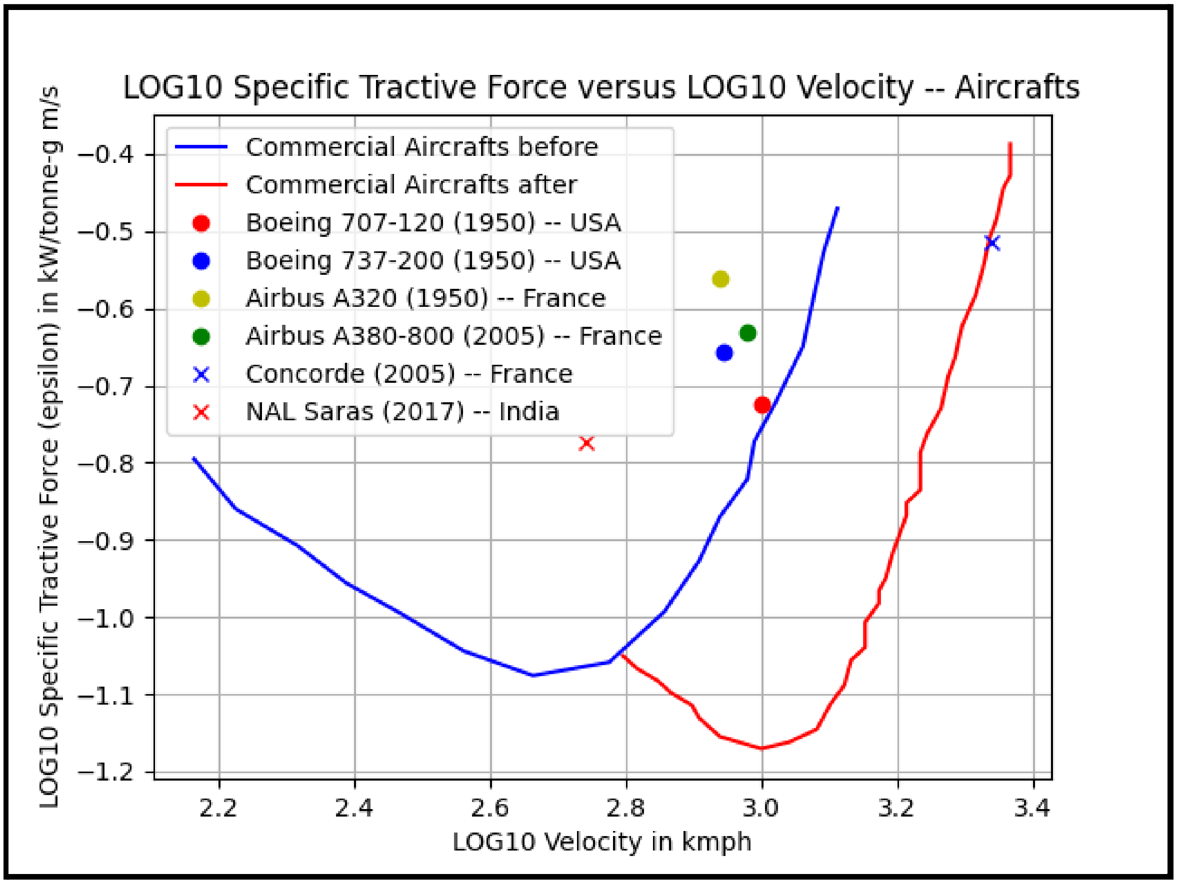
Abstract:
We have investigated Gabrielli-Karman curves for four classes of vehicles, namely planes, trains, cars, and ships. These curves depict the behaviour of specific tractive force and maximum velocity. Specific tractive force or $\epsilon$is the ratio of the Installed Power (P) per unit Gross Weight (W) multiplied by Maximum Speed (V_{max}). This analysis is essential to gauge the overall price of travelling at certain speeds for various vehicles and gives a good idea of the general energy usage.

Generally, low$\epsilon$is considered to be very efficient. The line corresponding to this on the plot is the Gabrielli-Karman Line which is a line with gradient 1, on the LOG10 Specific Tractive Force versus LO10 Maximum Velocity in kmph plot.

Gabrielli Karman Plot -- [Ingenia Article [1]] : What PRICE Speed?



Class I Airplanes:
The data about the aeroplanes can be found [here](), and the codes written for this section can be found [here]().
We have considered commercial aeroplanes in the narrow-body - Boeing 707-10, Boeing 737-200 and Airbus A320, wide-body - Airbus A380 and regional aircraft - NAL Saras, segments. We have indigenous as well as foreign-manufactured aircraft. Using *webplotdigitizer* (find it [here]() in a compressed format in a private Google Drive Link), we have extracted data from the ingenia article and obtained data for selected vehicles, and plotted the following graph:



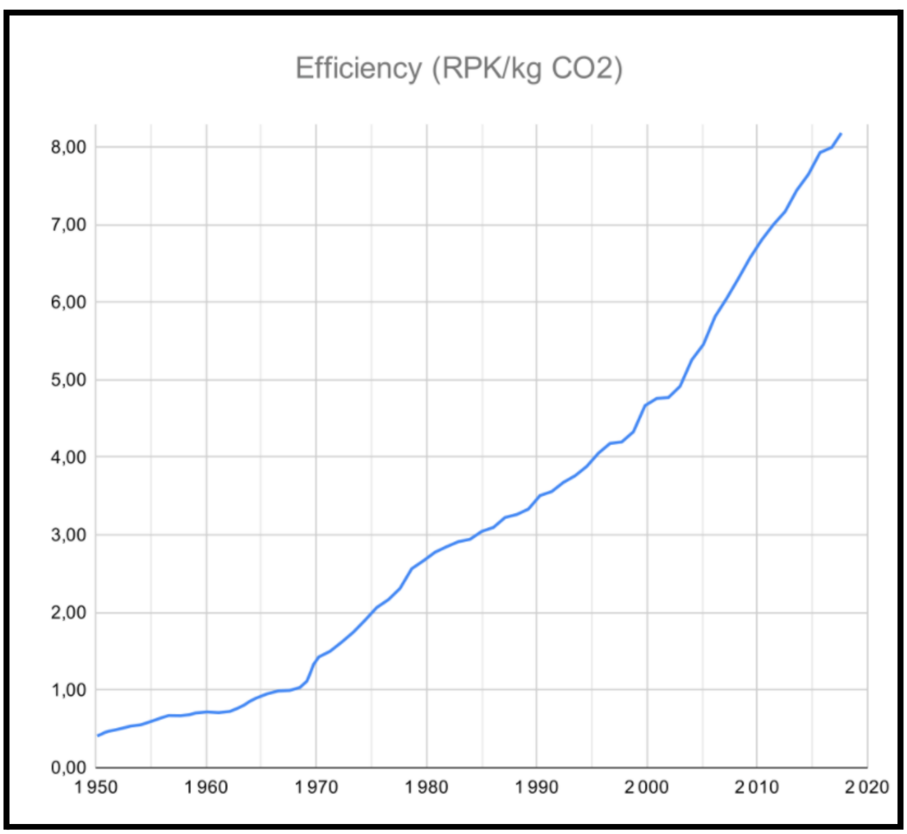
Here, we can see that all aircraft do not precisely match the given lines in the Ingenia plots. This is because of the difference in data obtained from various sources. However, some aircraft have been exactly matched, for instance - Concorde and Boeing 707-120, from different time ranges. Generally, we can see for achieving the same velocity; we have a considerable decrease in ϵ- which represents progress in technology. There also exists a certain maximum velocity for which ϵ is minimum. This is the optimum speed for the operation -- this will ensure efficient operation. Also, for the same ϵ we have higher maximum velocity due to technological progress ranging from improved aerodynamic shapes of aircraft, higher specific thrust producing engines, lighter structures due to the advent of composite materials etc.

CO_2 emissions study - Aircrafts

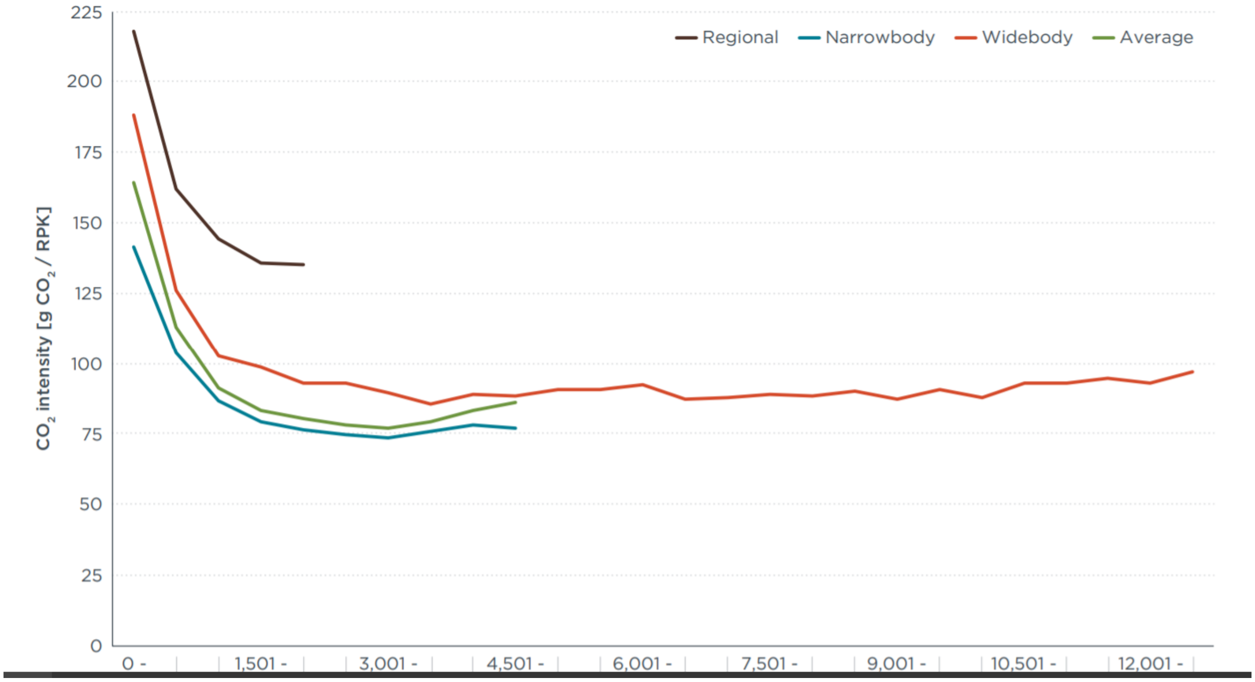
Sr No	Name of Aircraft	Range (in km)	Class	CO2 emissions (gm of CO2 per RPK[1])	References
1	Boeing 707-120	5,600	Narrow Body	92.69509982	https://drive.google.com/file/d/1Jzm4qaW9lODHKPOAoW6e8wSEQZjlxATX/view?usp=sharing
2	Boeing 737-200	4,800	Narrow Body	91.06170599	
3	Airbus A320	6,112	Narrow Body	89.42831216	
4	Airbus A380-800	14800	Wide Body	97.59528131	
5	Concorde	7222	Narrow Body	89.42831216	
6	NAL - Saras	1627	Regional	135.5716878	

[1] RPK - Revenue passenger kilometre -- one revenue passenger-kilometre means that one passenger is carried on one kilometre. [4] -- Reference : CO_2 from commercial Aviation - International Clean Transportation organization

Name of Aircraft	CO2 emissions (gms of CO2 per revenue passenger kilometer)	Heating Value of Aviation Gasoline -- Stationary Combustion (in mmBTU per gallon)	Specific Fuel Emissions Factor (in kg CO2 per mmBTU)	Specific Fuel Emissions Factor (in kg CO2 per gallon)	Specific Fuel Emissions Factor (in kg CO2 per litre)	Specific Fuel Consumption (in litres per passenger per km)	Specific Cost Factor (in rupees per passenger km)	References
Boeing 707-120	92.69	0.12	69.25	8.31	2.195	0.0422	0.9711	https://drive.google.com/file/d/1o-rl5MUIHHKCpFhrpPmHxPMpt3LJuonX/view?usp=sharing
Boeing 737-200	91.06	0.12	69.25	8.31	2.195	0.0414	0.9540	
Airbus A320	89.42	0.12	69.25	8.31	2.195	0.0407	0.9369	
Airbus A380-800	97.59	0.12	69.25	8.31	2.195	0.0444	1.0225	
Concorde	89.42	0.12	69.25	8.31	2.195	0.0407	0.9369	
NAL - Saras	135.57	0.12	69.25	8.31	2.195	0.0617	1.4203	



Reference : https://en.wikipedia.org/wiki/Fuel_economy_in_aircraft



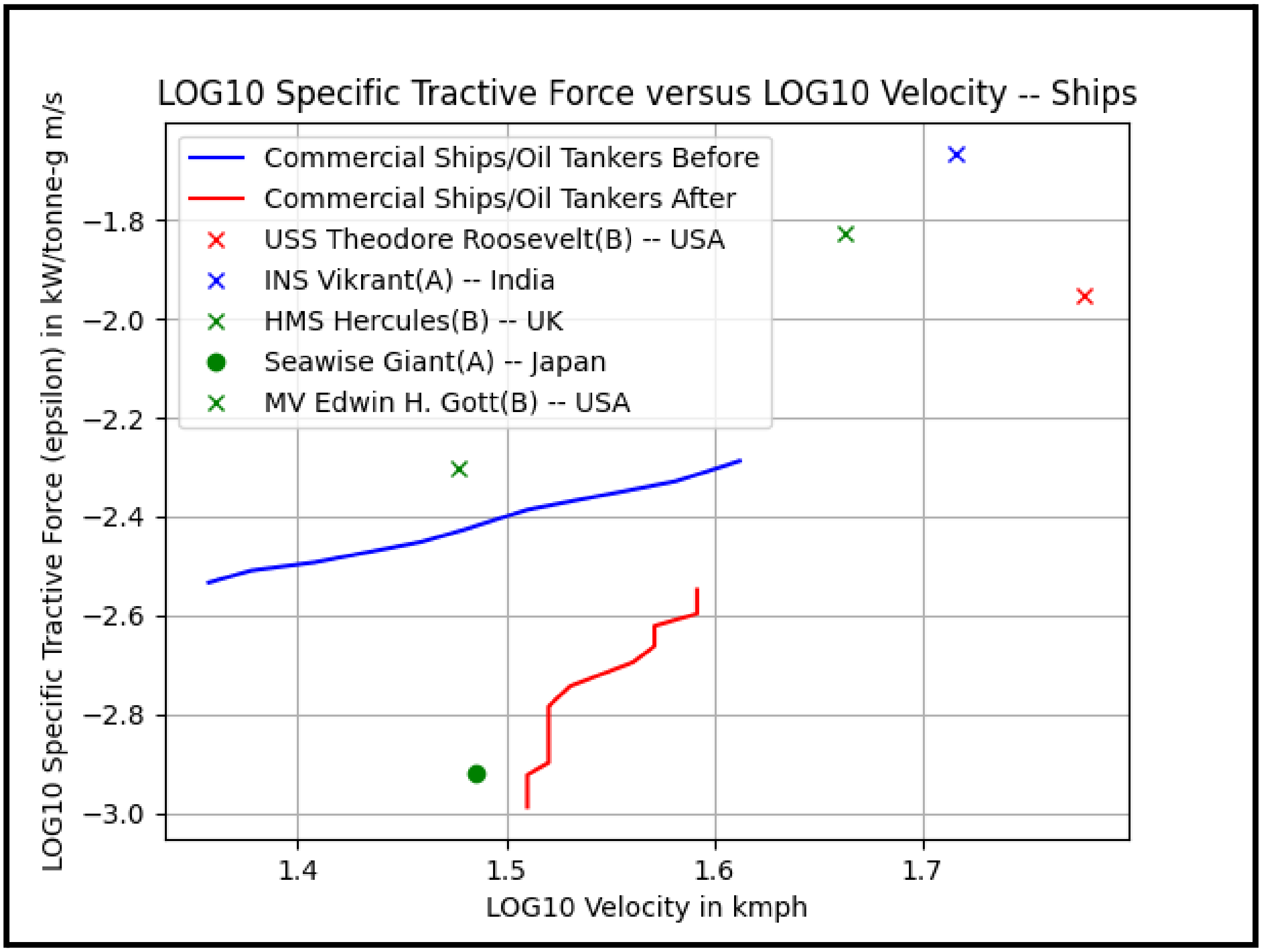
Range v/s CO_2 Intensity Plots for Aircrafts

https://drive.google.com/file/d/1Jzm4qaW9lODHKPOAoW6e8wSEQZjlxATX/view?usp=sharing

Class II Commercial Ships and Oil Tankers:

The data about Commercial Ships are documented here, and the codes written for this can be found here.

Here, we have considered commercial ships *Seawise Giant*, built by Sumitomo Heavy Industries - which is the longest ship built ever and MV *Edwin Gott*. Due to the lack of exact and complete details for commercial vessels, we have included some military vessels also. We have USS *Roosevelt*, which is a Nimitz class aircraft carrier and HMS *Hercules* - an old aircraft carrier of the Royal Navy and the recent aircraft carrier being developed for the Indian Navy, which is INS *Vikrant* by the Cochin Shipbuilders Ltd. Similar to aircraft, we have plotted the variation of **Log**ϵ v/s **Log** $\mathbf{V_{max}}$ below.



On observation, we can see a clear contrast between commercial and military vessels. Commercial vessels need to focus on the maximum amount of cargo with minimum possible fuel consumption and maintaining high-efficiency levels. They hence can be seen in close alignment with the curves plotted from Ingenia. However, military vessels have enhanced capabilities and features which focus on manoeuvrability, range covered, highest velocity, low response time etc., where efficiency is considered secondary and is reflected from the trends seen in the graph. As time passes, we have technological upgrades and have lower ϵ for the same maximum velocity as plotted in the graph. However, the graph also seems to shift toward the right, due to high obtainable speeds.

Specific CO_2 Emissions -- Ships

Name of Ships	Power Produced (in MW)	Fuel economy (in kmpl)	Specific Emissions (in kg CO2 per km)	Specific Emissions (in kg CO2 per tonne per km)
USS Theodore Roosevelt	1000	-	-	-
INS Vikrant	25	0.015	146.351386	-
HMS Hercules	30	0.003622047244	606.0856311	-
SeaWise Giant	37.284994	12.35820896	0.177636646	0.0000003145330803
HMAS Choules	11.5	18	0.1219594883	0.000000215948085
MV Edwin Gott	14.5	12.35820896	0.177636646	0.00003552732921

There is some lack of data, since most of them are military vehicles. We couldn't exactly find the data corresponding to specific vehicles. But we try to present a general approach which can be used to determine specific emissions in waterways:

Reference : *GREENHOUSE GAS EMISSIONS FROM GLOBAL SHIPPING, 2013–2015*
NAYA OLMER, BRYAN COMER, BISWAJOY ROY, XIAOLI MAO, AND DAN RUTHERFORD

First we can employ the general technique of,

$$\text{Emissions} = \text{Energy Use} * \text{Emission Factor}$$

Then we estimate energy usage with the help of fuel consumption. Various types of fuels are used in the shipping industry, which are tabulated below:

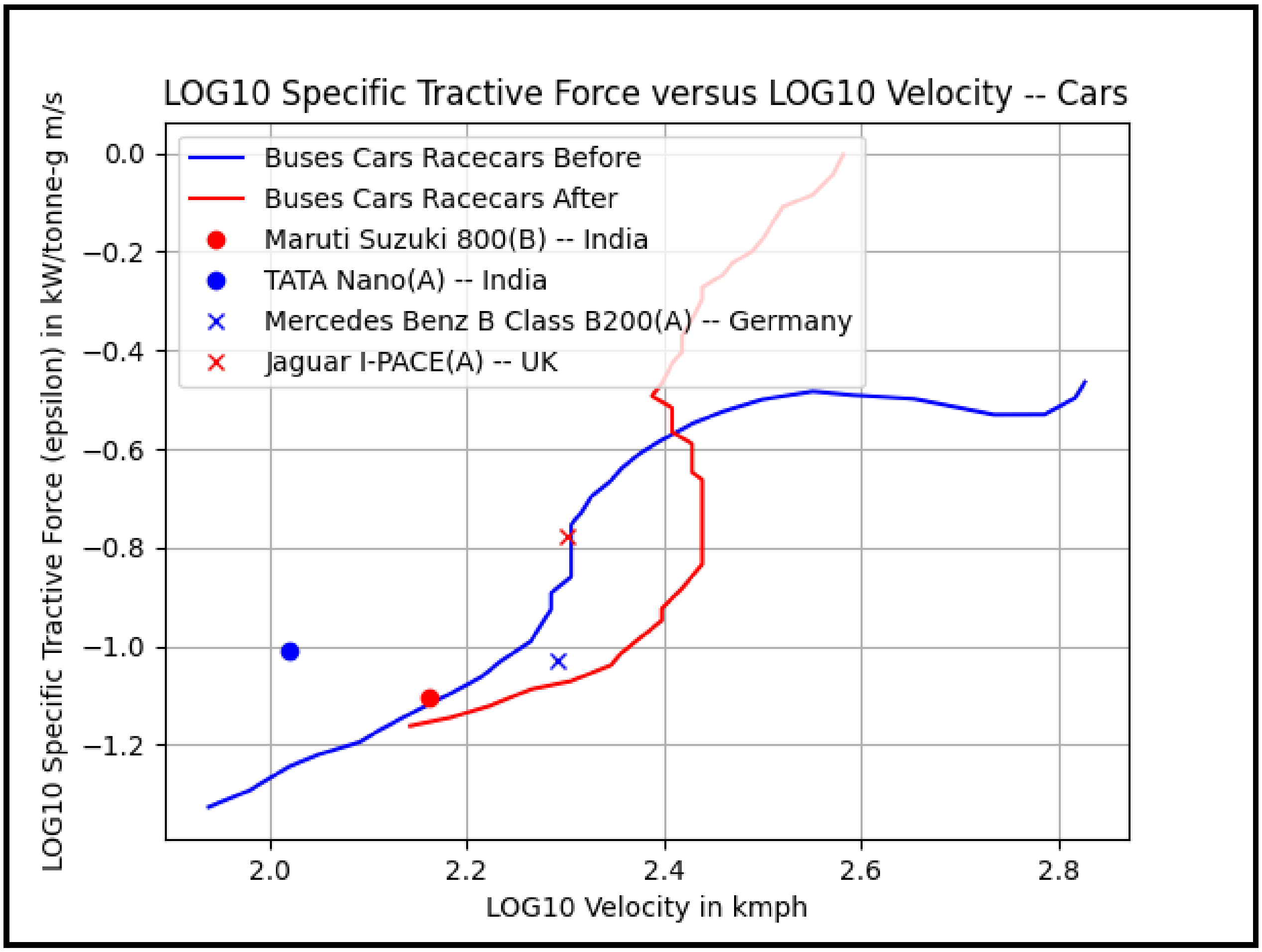
Fuel type	CO2 intensity of fuel (g CO2/g fuel)
Residual	3.114
Distillate	3.206
LNG	2.75

Then we can calculate the fuel economy of the vehicle in terms of kilometres per litre. Further we can calculate the Specific Emissions Factor (in kg CO_2 per passenger/ per tonne km) and Specific Cost Factor (in rupees per passenger / per tonne km).

Class III Cars:

The data about Buses, Cars, RaceCars has been documented here, and the codes written for this can be found here.

We have considered Maruti Suzuki 800, TATA Nano, Mercedes Benz B Class 200 in the conventional category and Jaguar I Pace in the electric vehicle category. We can see that we have a close match of the cars with respect to the Gabrielli Karman curves in What PRICE Speed ? -- Railway Research Institute, ICL, Ingenia Article. [1]



Specific CO_2 Emissions -- Cars

Name of Cars	Fuel Economy in Miles per Gallon on Highway	Fuel Economy in Miles per Gallon on city	Average Fuel Economy in Miles per Gallon	Fuel Economy in miles per litres	Fuel Economy in kmpl	Fuel Economy in miles per kWh
Maruti 800	35	35	35	9.24602619	14.8799	1.038575668
TATA Nano	60	60	60	15.85033	25.50857	1.78041543
Mercedes Benz B Class B200	39.2	39.2	39.2	10.3555493	16.6655997	1.163204748
Jaguar I-PACE	72	80	76	20.07708	32.3108566	2.255192878

Name of Cars	Fuel Economy in km per kWh	Fuel Used	Fuel Emissions Factor (in kg CO2 per gallon/per unit of electricity kWh)	Fuel Emissions Factor (in kg CO2 per litre/per unit of electricity)	Specific Emissions Factor (in kg CO2 per km)	Specific Emissions Factor (in kg CO2 per passenger km)[2]	Specific Cost Factor (in rupees per passenger km)
Maruti 800	1.6714	Diesel	10.21	2.6971	0.1812	0.0453	1.478
TATA Nano	2.8652	Diesel	10.21	2.6971	0.1057	0.0264	0.8624
Mercedes Benz B Class B200	1.8719	Diesel	10.21	2.6971	0.1618	0.0404	1.320
Jaguar I-PACE	3.6293	Electricity	0.6	0.6	0.0185	0.0046	0.0387

[2] Note: Jaguar IPACE is an electric car and CO2 emissions running to operating time is zero. But we are considering CO2 emission relating to electricity production which will be used for charging

It can be clearly seen that, in electric cars the fuel economy is very large as compared to conventional diesel powered vehicles. Also, the specific CO_2 emissions are very low in case of electric vehicles and the specific cost factor is very low. We can see that newer cars are much more efficient than their older counterparts in terms of fuel economy per passenger kms, which has become possible due to numerous advances in technology, such as more streamlined bodies, lighter materials for structure. More powerful and efficient engines etc.

Class IV Passenger and Freight Trains:
The data about trains and locomotives have been documented [here]() and the codes written for this can be found [here]().

Specific CO_2 emissions -- Trains:

Reference :
https://drive.google.com/file/d/1Arsj2nRAN3yBPZHKSazuYjOWpQz8vPlD/view?usp=sharing

The Indian Railway network is one of the busiest railway networks of the world. The railways emitted 6.84 million tons of CO_2 eq. in 2007, in which more than 90% of the emissions were in the form of CO_2 [3]. Based on [3], we have

1. Material Transport: 0.00996 kg CO_2/Tonne – km) (2014 - 2015)
2. Passenger Transport: (kg CO2 / Passenger – km)
    a. Non-Suburban - 0.007837 kg CO2 / Passenger – km
    b. Suburban – 0.007976 kg CO2 / Passenger – km

To calculate the values we can adopt the following methodology [3]:

1. Fuel consumption data for passenger transport
    a. Diesel Consumption (in litres) [A]
    b. Electricity Consumption (in kWh) [B]
2. Emission factor for fuels
    a. Diesel Emission Factor (in kg CO_2/lit) [A_1]
    b. Electricity Emission Factor (in kg CO_2/kWH) [B_1]
3. Total Emissions from Passenger Transport:
    a. Total CO_2 emissions (in kg CO_2) = $\{A * A_1\} + \{B * B_1\}$
4. Passenger kilometer data and Freight tonnage-km data:

a. Total Passenger kms
b. Suburban passenger kms
c. Non Suburban passenger kms
d. Tonnage-km for Freight transport

5. Specific Emissions Factor : Divide total emissions by passenger km or tonnage km
    a. Emission factor (in kg CO_2/passenger-km) Non-Suburban:
        i. Total Emissions Non-Suburban (in kg CO_2)/Non-Suburban Passenger-km
    b. Emission factor (in kg CO2/pax-km) Suburban :
        i. Total Emissions Suburban (in kg CO_2)/Suburban Passenger-km)
    c. Emission factor (in kg CO2/ton-km) :
        i. Emissions Material transport (in kg CO2)/ Tons-km

We can easily convert the Specific Emission Factor (in kg CO_2 per passenger/per tonne per km) to Specific Cost Factor (in rupees per passenger/ per tonne per km)
We already have,

1. Material Transport: 0.00996 kg CO_2/Tonne – km) (2014 - 2015)
2. Passenger Transport: (kg CO2 / Passenger – km)
    a. Non-Suburban - 0.007837 kg CO2 / Passenger – km
    b. Suburban – 0.007976 kg CO2 / Passenger – km
3. Fuel Emission Factor :
    a. Diesel (in kg CO_2 per litre) = 2.651
    b. Electricity (in kg CO_2 per kWh) = 0.82
4. Cost of Diesel (in rupees per litre) = ₹ 88
5. Cost of Electricity (in rupees per kWh) = ₹ 5
6. Specific Cost Factor (in rupees per passenger km) (for Diesel Operated):
    a. Suburban : ₹ 0.2647 per passenger per km
    b. Non-Suburban : ₹ 0.26014 per passenger per km
7. Specific Cost Factor (in rupees per tonne km) (for Diesel Operated) : ₹ 0.33 per tonne km
8. Specific Cost Factor (in rupees per passenger km) (for Electricity Operated):
    a. Suburban : ₹ 0.0486 per passenger per km
    b. Non-Suburban : ₹ 0.0477 per passenger per km
9. Specific Cost Factor (in rupees per tonne km) (for Electricity Operated) :
    a. ₹ 0.06 per tonne km

From this analysis, it can be concluded that passenger and goods transported through railways have very low specific cost factors as compared to aircraft based cargo and passenger transport. But due to quicker delivery, aircrafts may be preferred over trains.

Difference in Single Locomotive and Railway Convoys and their effect on the behaviour of the curves in Specific Resistance v/s Maximum velocity plots [2]
[Reference -- What PRICE Speed ? - Gabrielli, Von Karman Original Research Paper, Proceedings of ASME]:

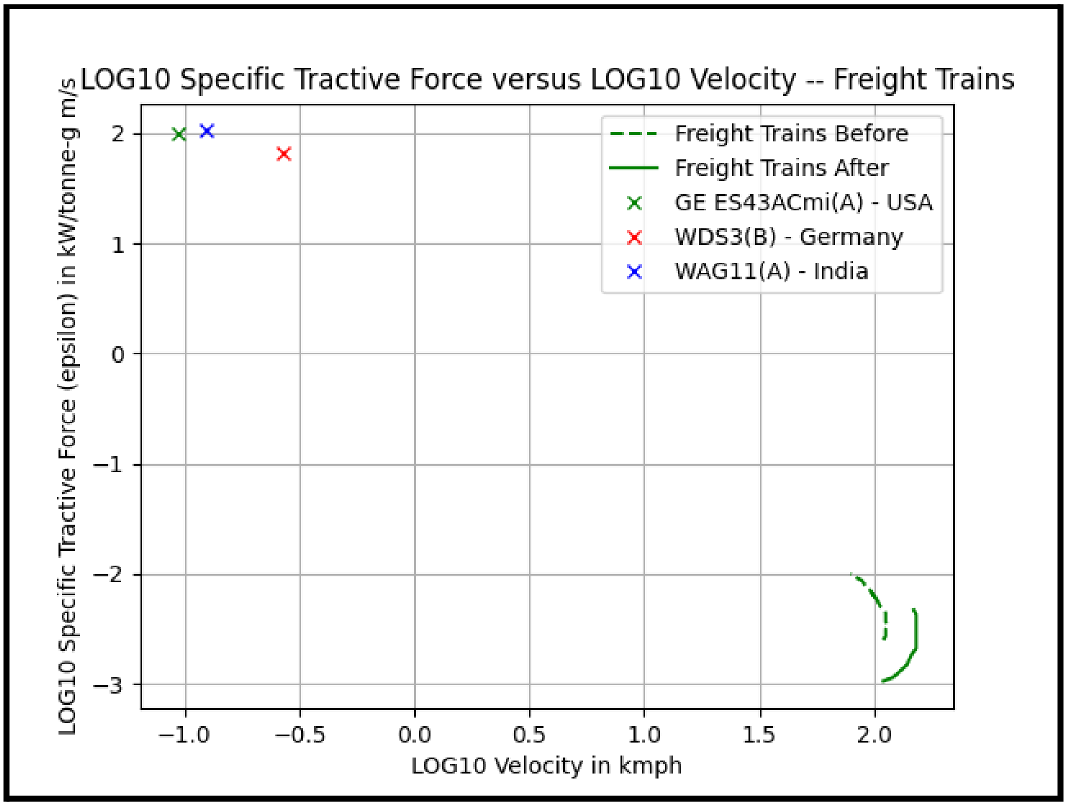
Why is that the data points are not very close enough to the data curves from Ingenia? This is because we have considered Locomotives but not entire train sets. Generally, we have multiple rakes connected in series to a Locomotive, which leads to reduction of power required per unit weight which happens due to the following reasons --

1. Especially for fast trains, the air resistance of the complete train is considerably less than the sum of single cars used separately.
2. The concentration of the propulsive power in the locomotive allows the employment of large power plant units with better efficiency and lower specific weight.

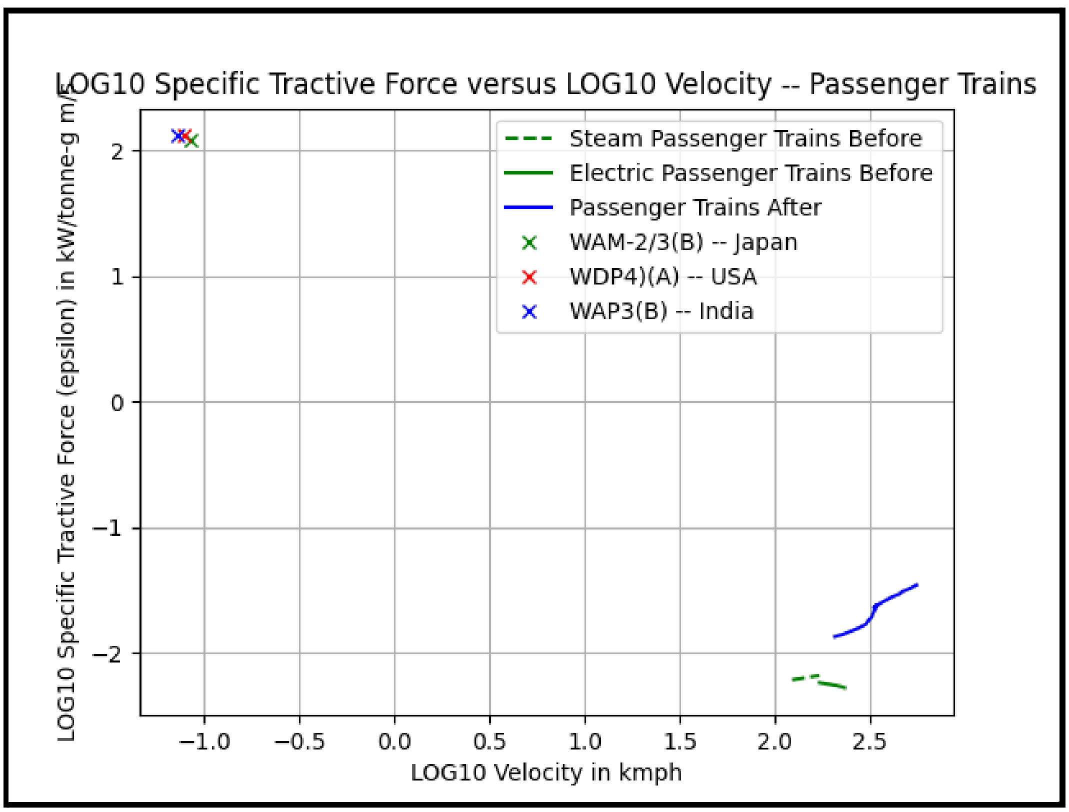
Si, as we have a reduction of power installed per unit weight, we can see the entire train curves in the lower section of the plots as opposed to locomotives which are in the upper left corner -- high specific resistance and low maximum speed.

Reference :
https://drive.google.com/file/d/1FMPaOlWiK-FFot1Lu9VBWmUmXpgABGEk/view?usp=sharing

Plots :



LOG10 Specific Tractive Force versus LOG10 Velocity -- Freight Trains
LOG10 Specific Tractive Force (epsilon) in kW/tonne-g m/s
LOG10 Velocity in kmph
Freight Trains Before
Freight Trains After
GE ES43ACmi(A) - USA
WDS3(B) - Germany
WAG11(A) - India
2
1
0
−1
−2
−3
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0



LOG10 Specific Tractive Force versus LOG10 Velocity -- Passenger Trains
LOG10 Specific Tractive Force (epsilon) in kW/tonne-g m/s
LOG10 Velocity in kmph
Steam Passenger Trains Before
Electric Passenger Trains Before
Passenger Trains After
WAM-2/3(B) -- Japan
WDP4)(A) -- USA
WAP3(B) -- India
2
1
0
−1
−2
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5

Some Final Comments:

1. **How have the curves changed over the last 15 years?**
    a. In the previous times, the vehicles were having higher specific resistance and lower maximum velocity, and hence in the upper left corner of the Gabrielli Karman plot. Only a few vehicles were able to come close to the Gabrielli Karman Line. Over time, due to advances in technology we have found that the curves have shifted downwards as well as rightwards, resulting in higher obtainable maximum velocity and lower specific resistance. Exceptions to this are very few which are modern race cars and military vehicles which heavily depend on maneuverability and have secondary importance to efficiency and other aspects. Some completely new vehicles have emerged like the high speed trains like Shinkansen, and some concepts like Air transport of goods which were not considered by Gabrielli and Karman. The vehicles now have improved streamline body which results in lower aerodynamic drag, highly efficient high thry=ust producing engines -- gas turbines, improved IC engines, newer advanced materials and composite structures which result in lighter deadweight structure of the vehicle, advanced sensor technology dnb controllers which lead to overlap in flight optimization to improve performance and efficiency.

2. **Comparison of Flights based on**
    a. **Specific CO_2 Emissions (in kg CO_2 per passenger km)-**
        i. NAL Saras > Airbus A380-800 > Boeing 707-120 > Boeing 737-200 > Airbus A320 == Concorde
    b. **Specific Cost Factor (in rupees per passenger km) -**
        i. NAL Saras > Airbus A380-800 > Boeing 707-120 > Boeing 737-200 > Airbus A320 == Concorde

Generally, the trend we observed here was, CO_2 intensity per revenue passenger kilometre decreases when we increase the aircraft range -- obviously this can be further related to the other parameters of the aircraft which affect or get affected by Range say for instance, total fuel carrying capacity, cruise altitude etc.

3. **Comparison of Cars based on**
    a. **Specific CO_2 Emissions (in kg CO_2 per passenger km) -**
        i. Maruti Suzuki 800 > Mercedes Benz B Class 200 > TATA Nano > Jaguar I-PACE
    b. **Specific Cost Factor (in rupees per passenger km) -**
        i. Maruti Suzuki 800 > Mercedes Benz B Class 200 > TATA Nano > Jaguar I-PACE

Here, it can be clearly seen that as the technology has progressed and the specific emission and cost factor have decreased to a considerable extent. ALso, the striking feature is that of the electrically powered car, which if we dont consider the emissions and costs related to electricity generation in power plants, comes out to be the best mode of road transport with a very low specific emission as well as costs. It also has a very low specific resistance.

References:

1. Ingenia Article -- What PRICE Speed? Revisited - ICL Railway Research Institute
2. What PRICE Speed? -- Gabrielli, Von Karman Original Research Paper
3. International Clean Transportation Organization Documents for Clean Aviation and Shipping -- relevant links provided
4. Wikipedia -- relevant links provided
5. Emission Factors Document -- US Department of Energy -- https://drive.google.com/file/d/1o-rl5MUIHHKCpFhrpPmHxPMpt3LJuonX/view?usp=sharing
6. AE234 Soham Phanse Webplotdigitizer -- Plot extraction project on Webplotdigitizer -- Link -- https://drive.google.com/file/d/1Cz5xDKFQJKnC3egbET7xRQYIVYbq-FAl/view?usp=sharing

Acknowledgement:

1. Meera Upasana 190010046, Aerospace Btech 2019 Student, for pointing out an article for referencing trains -- Link -- https://en.wikipedia.org/wiki/Locomotives_of_India#Electric
   (No data was shared -- Meera has only pointed out to this article on Wiki, we have gathered data individually and separately/)