PROPULSION SYSTEM DESIGN FOR THE INDONESIAN SEMI HIGH SPEED TRAIN

DESAIN SISTEM PROPULSI UNTUK KERETA API SEMI CEPAT INDONESIA

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Abstract

This paper describes a study on the development of methodology to select the most appropriate technology, and the most optimum design and configuration for the propulsion system of the semi-high speed intercity train that will be operated on the Jakarta-Surabaya corridor. It also describes the method to calculate resistance loads and tractive forces and hence the power required to propel the train along the specified route within targeted time. Among the output of this study is a recommendation for the most optimum propulsion system with basic/ main parameters for main components such as diesel engine, traction motor and the possibility of Diesel Electric Multiple Unit (DEMU) Hybrid battery system.

Keywords : Propulsion System; Semi High speed Train; DEMU; Hybrid Battery

Abstrak

Pada makalah ini diuraikan sebuah studi berisi metodologi untuk menentukan teknologi, desain dan konfigurasi yang paling sesuai untuk sistem penggerak kereta semi cepat yang akan dioperasikan pada jalur Jakarta-Surabaya. Makalah ini juga menjelaskan cara untuk menghitung gaya-gaya hambat (resistance forces) suatu kereta, gaya penggerak (tractive forces) yang diperlukan untuk mengatasi gaya hambat tersebut dan selanjutnya kebutuhan daya pada sistem penggerak kereta api. Output dari studi ini adalah saran untuk sistem propulsi, lengkap dengan spesifikasi dasar mesin diesel dan motor traksi, serta kemungkinan opsi Diesel Electric Multiple Unit (DEMU) Hybrid menggunakan baterai.

Kata kunci : Sistem propulsi; Kereta Api semi cepat; DEMU; Hybrid Baterai

Diterima (received) : 24 November 2019, Direvisi (revised) : 17 Desember 2019,
Disetujui (accepted) : 23 Desember 2019

INTRODUCTION

Ever since the first steam engine, transportation by rail has enhanced our way of life by reducing the time traditionally required to transport people and goods by land and sea. A low coefficient of friction between steel wheels and steel rails enabled a very efficient transportation system.

Railway propulsion technology has developed tremendously since the introduction of the first steam engine. The use of liquid fossil fuels in internal combustion engines enabled faster and more reliable operation. Very powerful trains that could haul hundreds of people and tonnes of goods were manufactured[1)].

In Indonesia, railway service was first opened in 1867 connecting Kemijen to Tanggung in Semarang area (26 km)[2)]. Nowadays, the Indonesian rail network has been developed mostly in Java and Sumatera with a total length of around 6,500 km. Only around 125 km of these tracks are electrified. The tracks are of the 1,067 mm narrow gauge track.

Passenger service is the main business of the Indonesian Railway company, known today as PT. KAI. Currently, diesel-electric locomotives are the main prime mover of both passenger and freight services.

Unlike diesel-hydraulic or diesel-mechanic locomotives that have a mechanical or hydraulic coupling between the diesel engine and the wheelsets, diesel-electric locomotives have an electromechanical coupling. While still having a diesel engine as the prime-mover, diesel-electric locomotives depended on electric motors for traction. Mechanical energy produced by the diesel engine is converted to electrical energy by an on-board generator (alternator), which is then converted to mechanical energy at the wheels by electric traction motors. This arrangement improved the overall reliability of trains, and drastically reduced the cost of maintenance[3)].

One of the most important PT.KAI's passenger services is the 725 km service connecting the two biggest cities in Indonesia, namely Jakarta and Surabaya.

The growth of population and economic activities, has generated heavy traffic between these two cities. Despite the fact that there are frequent air services and toll road which are now available, the demand for train service is still very high.

Meanwhile, the Indonesian government is targeting to increase the number of railway network 3 times longer than the existing network, and to increase the passenger capacity by 11-13%, as stated in the National Planning for Railways (RIPNAS)[4)].

To this regard, railway related industries in Indonesia will be driven to become priority industries. The main railway industry in Indonesia is the rolling stock industry, known as PT. INKA. The Indonesian government has been supporting the progress of PT INKA in the role of becoming the integrator for railway industries in Indonesia[5)]. In addition, the government is also supporting the advance of component industries as a strategy to increase the local content, especially the technological transfer of critical components in the railway system[6)].

Amidst the issue of increasing the passenger service capacity and the national industry capability, the Indonesian government is planning to build a higher speed rail service between Jakarta and Surabaya. A feasibility study has been carried out and it has suggested the development of a semi-high speed rail service that will be able to cut the current 10 hours travel time to the target of 5-6 hours.

Other than a new rail track, one of the components that should be developed for this new rail service is a new semi-high speed rolling stock or semi-high speed train (SHST).

Within the new rolling stock, the propulsion system is among the most critical one since it is the motive to drive all the train car body system. This includes the engine, control system, transmission and traction motors. And yet this propulsion system represents the weakest capability of the local railway industries in Indonesia[7)]. While the diesel engine is still categorized as a "red component", which means that is "*responsibility by overseas partners*", the other propulsion components such as traction motor, power converter and traction control unit are expected to be part of the process of technological transfer to local industries.

Motivated by the Jakarta-Surabaya SHST Feasibility Study[8)], this paper is focused on the application of SHST for Intercity service. Options for Diesel Electric Multiple Unit (DEMU) configurations and power calculation including engine and motor specification are further assessed in this paper.

In this paper we are developing a methodology for decision making in selecting the most appropriate propulsion system technology, its basic design and main parameters.

THEORY

Resistance Loads

Trains resistance is defined in terms of force required to encounter resistance arising due to vehicle, track, grade, curve, acceleration, wind at different time and place etc. It is measured in unit of either *kN* or *kg/ tonne*.

Primarily, train resistance is divided into internal and external resistance. The internal resistance is internal to the train and prevailing track geometry over the entire train run. External resistance is situational in nature.

The internal resistance plays different role during start and running and further subdivided into: starting resistance and running resistance.

The external resistances are those which are not fixed and depend on varying terrain (gradient and curve), prevailing conditions of air (speed and humidity), self-generation for lighting and air conditioning, brake binding etc. It is subdivided into: grade, curve, and acceleration resistances.

Starting resistance is to overcome the inertia and low temperature of the bearing, tightening of couplers. Resistance drops rapidly as the train speed increases. There is no derived formula for starting resistance. Based on the different measurements, empirically Train and Loco starting resistance are taken as 4 and 6 *kg/tonne,* respectively.

The running train resistance F_{rr} (in kg/ tonne) is given by an empirical formula[9]):

$$F_{rr} = a + bV + c\,V^2 \qquad \text{(Eq. 1)}$$

where the dependency of constants *a*, *b* & *c* are constants, *V* is speed in km/h. The constant factors accounts for the entire possible variable which has its role in the running resistance having bearing on weight alone or both weight and speed.

The constant factor *a* is independent of speed and multiplied solely with load to get the resistance. It primarily consists of Rolling, track, and journal bearing resistances. The rolling resistance results due to the resistance between the wheels tread and head of the rail.

The track resistance is due to loading, track is depressed in proportion to the loading and stiffness of the track structure. The journal bearing resistance is higher at the start and tapers down considerably up to a speed of 20 km/h and then slowly drop.

The constant factor *b* is directly proportional to the speed of the vehicle. Even on tangent track, the flange of the wheel touches the inner face of the rail in a sinusoidal motion thus creating a retarding force due to sliding friction. Track irregularities and load distribution influence the hunting causing frequency of sinusoidal motion and affecting resistance to the motion. This frictional resistance goes up on curved track and with increasing speed. So it is the lateral displacement of the wheel during the run and energy loss due to sliding friction results into this cause.

The constant factor *c* is directly proportional to the square of the speed and directly with the cross-sectional area of the vehicle. Therefore; its contribution is more visible under high speed. The factor accounts for the resistance of quite air which the vehicle envelope has to displace continuously during the run. The envelope, thus, is not only the frontal cross-section but also the space in-between vehicle, fittings under the vehicle, skin resistance of the sides, turbulence and draft created at the rear end. The effect of these additional cross-sections is generally not mentioned separately but included in c when worked out for a specific design of locomotive and trailing stock.

Empirical values of *a*, *b* and *c* forming the formula of Eq. 1 for different types of rolling stock are as given in Table 1, and further modification has been developed to take weight into account[10]; some example is given by Table 2:

Table 1
Empirical constant values for various Trains; Ref:[11]

	Name of Train	A	B	C
1	SNCF CC 6500 + 10 standard coaches	7.70	0	0.00090
2	JNR 8 unit Sanyo Shinkansen	5.46	0.0705	0.000666
3	SNCF TGV 001	1.04	0.0180	0.000258
4	BR British Passenger train with 10 Mk II cars	6.60	0.0111	0.001424

Table 2
Modified equation for Resistance Loads for several type of Trains[12, 9]

	Type of Train	Equation for Resistance Loads
1	Locomotive	$0.647+ (13.17/W) +0.00933V+ (0.057/W_n)^2$
2	Locomotive (WAP5)	$1.34819+.02153V +0.00008358V^2$ (*)
3	Motor Coach	$2.35 + (0.02933-.00049w)V+(0.03722/w)V^2$
4	Trailer Coach	$1.347 + 0.00385V + 0.000165V^2$
5	MEMU Trailer	$0.6855 + 0.02112V + 0.000082V^2$

The resistance load equation used in this study is the one which consider the weight of the motorized cars, W_m, the total weight, W_t, and the number of cars, *n*, as shown by (Eq.5):.

$$F_{rr} = (1{,}65 + 0{,}0247\,V)\,W_m + (0{,}78 + 0{,}0028\,V)\,W_t + (0{,}028 + 0{,}0078\,(n-1)\,V^2 \qquad \text{(Eq. 2)}$$

This equation, applied to the study of Indonesian SHST in this paper, is shown in the bold curve in Figure 1, and it is comparable to other trains listed in Table 1 and 2, except for TGV, a high speed train, which is of higher class, and hence better in aerodynamic performance and lower friction.

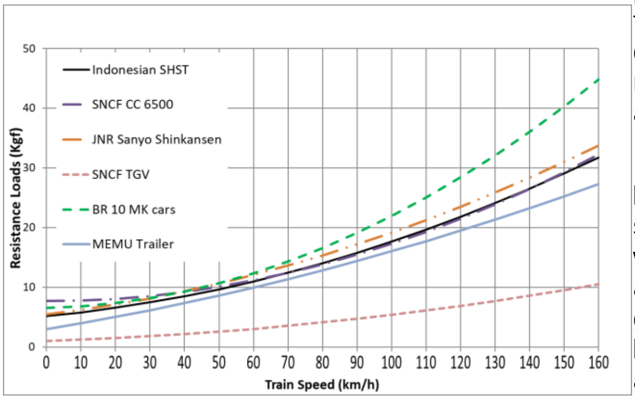

Figure 1
Comparison of Resistance Loads for various Trains

Grade resistance arises due to effort made work against gravitational force. While climbing on a grade, The resistive force of:

$F_{grade} = W. \sin\theta$ (Eq. 3)

Where θ is the angle of the grade, and W is the train total weight. Contribution of grade resistance plays an important role in limiting the hauling capacity in a section.

Curve resistance is caused due to: (1) The flange of the outer wheel of the leading axle rubs against the inner face of the outer rail causing resistance due to sliding friction; (2) The outer wheel rotates faster than the inner wheel causing transverse slip thus adding to sliding friction; and (3) Less super elevation causes increased pressure on outer rail whereas higher super-elevation results in increased pressure on the inner rail thus increasing curve resistance.

Resistance due to acceleration is the force exerted by the locomotive to accelerate the rolling stock and calculated as per Newton Second Law of Motion, F_a (in Newton) is

$F_a = m.a$ (Eq. 4)

Where m is the mass of train and locomotive in kg and a is acceleration in m/sec^2.

Tractive Forces

The propulsion force is the tractive effort that is dependent on the power of the prime mover, the speed of the train, and the efficiency of the system. The retardation force is the sum of the rolling resistance, air resistance and compensated grade.

The longitudinal force reaching the wheel-rail contact that is generated by the prime mover on-board the train is known as the tractive effort. To move in a given direction, the tractive effort must exceed any retardation forces such as wheel-rail friction, air resistance and elevation.

The maximum tractive effort F_{TE} a locomotive can produce to propel a stationary train is the starting tractive effort, which is a function of the locomotive's weight and the wheel-rail adhesion factor (μ) as given by Eq. 8, and it is independent of the locomotive's power and speed. The factor of adhesion depends on the material from which the wheels and the rail are made, which is typically 30% for steel wheels on steel rail. In this mode of operation, the locomotive's power increases as it gains speed.

$F_{TE} = \mu W_{motor}$ (Eq. 5)

The power of the locomotive will keep on increasing as the train picks up speed, until it levels at the rated horsepower as presented in Figure 2.

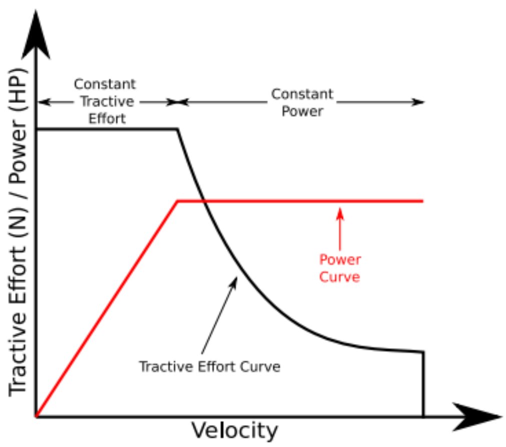

Figure 2
The relationship between a trains's applied power, resultant tractive effort and its velocity

This region of operation is termed the *constant power* region, and in it the tractive effort drops as the train picks up speed. The relationship is defined by Eq. 9:

$F_{TE} = \frac{P\eta}{v}$ (Eq. 6),

where P stands for the power of the prime mover in watts, η stands for the efficiency of the system, V stands for velocity in m/s, F_{TE} stands for the tractive force in J, respectively.

METHODOLOGY

The methodology used to determine the propulsion system of the train is as follows, as shown by Figure 3:

1) Determining the design requirements,
2) Screening propulsion technologies
3) Choosing propulsion technology.
4) Calculation of resistance force & tractive force
5) Selecting type and specification of diesel engine and traction motor
6) Screening other possible improvement

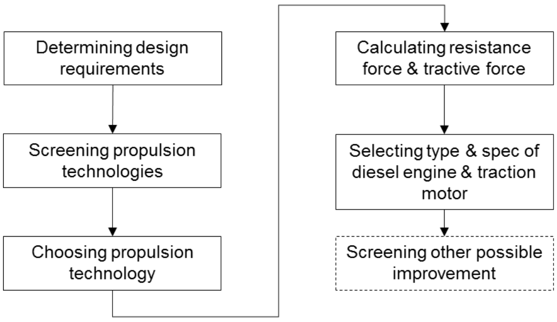

Figure 3
Flow Chart of Methodology to Calculate the Propulsion System

(1) Determining of the design requirements

The design requirements of this study follows the parameters determined in previous work[8], as tabulated in Table 3.

Table 3
Design Requirements

Item	Specification	Remarks
Route	Jakarta-Surabaya	Manggarai St for Jakarta, Pasar Turi st for Surabaya
Distance	713 km	Current alignment adjusted for higher speed
Inter-stop	Cirebon, Semarang	
Track width (Gauge)	1067 mm (narrow)	Decided by the Ministry after FS
Maximum Speed	160 km/h	Empirical maximum commercial speed
Maximum axle load	18 ton	Lower is better
Electrification	(none)	Possible in the long future
Propulsion	Diesel Engine	
Travel time	5,5-6-5 hours	Depends on the assumption of speed profile, stop durations and train crossing
Seat Capacity	500 pax	All classes mixed
Number of Cars	10	

The following are the considerations for the choice of propulsion technology:

- The SHST system should obey/ consider the RAMS (reliability, availability, maintainability, safety) aspects, i.e. safe, reliable, and easy to maintain, energy efficient and environmentally friendly
- The SHST system should boost the capability of local railway industries
- The trip frequency is targeted for at least 5 trips for each directions. The additional track will be built as a *single track*, so that apart from Cirebon and Semarang stations, it will require several *siding rail* at a number of stations for train crossing.
- The maximum load for the track is 18 tonnes per axle, which means that for four axles, the maximum car weight is 4 x 18 = 72 tonnes.

(2) Screening propulsion technologies

Without electrification, the choice of propulsion technology would be three main options:

a. *Diesel Locomotive hauled train*, in which the train set is propelled by a diesel locomotive, as has been used by the existing service of Jakarta-Surabaya "Argo Bromo Anggrek".
b. *Diesel push-pull train*, in which the train set is propelled by two diesel locomotive, one each in either ends, as has been used by the existing service of Brisbane-Cairns in Australia.
c. *Diesel Multiple Unit train*, in which a number of diesel engines are distributedl in several cars, as has been used in the Sapporo-Kushiro service in Japan.

In order to reach the maximum speed of 160 km/h, the *locomotive hauled train* is not possible, and therefore this option is immediately eliminated for the following reasons.

A single diesel engine with the current power would not be capable to drive up to 160 km/h. It would require much larger engines which is prohibited due to overweight axle loads that exceeds 20 tonnes. This would require higher civil work, construction cost and maintenance cost.

The second option, the *push-pull train* as have been used in the UK and Australia, the locomotive weight might be kept to less than 18 tonnes each, however, it is still relatively heavy and would affect wearness on the track so that the maintenance cost is high.

The next option is the *diesel multiple unit train*, which is the most preferred option by the world railway industry nowadays such as: Alstom Coradia, Hitachi class 800, Siemens Desiros, CAF Civity, Bombardier Voyagers/Vlocity, Nippon Sharyo, dan Hyundai Rotem.

Among the strength and the weaknesses between the two technology options are listed in Table 4 below:

Table 4
Comparison between the Push-pull and the DEMU

Type	Positives	Negatives
Diesel Push-pull	• The locomotive units are interchangeable during maintenance; although the maintenance schedule for the passenger cars are not yet due. • Any bad passenger cars may be replaced individually without replacing the whole set • Changing the length of the train set is possible as required • No noise or vibration in the passenger cars due to diesel engines.	• Less passengers for a same length, e.g TGV sud-est 200 m for 350 pax, ICE 3 200 m for 460 pax. • The total weight might be similar to multiple unit, however the weight of the loco unit is still heavier, causing wearness to the track and hence higher, e.g TGV max axle load 17 tons, N700 max axle load 10 tons maintenance cost • The loco unit is the weakest point for failure; for if it fails then all of the service must stop.
Diesel Multiple Unit	• All the unit carry passengers • Less wearness to the track due to more distributed loads • More reliable since in the case of one unit failure, the total set still able to run • Fuel saving is possible by shutting down an engine in case of low power requirements • Adhesion power between wheel and rail track is better due to more traction from powered wheels.	• More vibration and noise from the diesel engines which are installed in the passenger cars • In case of requirement to change the length of the train set, the cars configuration must be considered • More components to maintain, e.g TGV 8 traction motors, N700 56 traction motors

(3) Choosing the propulsion technology

After considering the design requirement and screening the three possible technologies, the choice is the diesel-electric multiple unit (DEMU). The need to carry more passengers and the less wear and tear on the track are the main considerations. Also the operational requirements require better acceleration (due to frequent stop for siding and deceleration due to curves).

After the DEMU is chosen, the next options to decide is where to install the engine; on-floor, on-roof or under-floor. If the engines are mounted on-floor, then the advantage to carry more passenger will be lost.

Therefore, the choice is to mount the engines distributed underfloor. This option has advantage that although there will be more engines, each of them will be smaller. Moreover, there is a possibility to design a trainset with all-propelled cars. This will add a flexibility in the operation.

(4) Calculation of Resistance Force and tractive Force

From the calculation of resistance and tractive efforts (equations 5, 6 and 9), there are two extreme conditions when medium speed train is operated, at track gradient of 0 ‰ and 14 ‰. Figure 4 shows that with the calculated total power of 2700 kW (blue curve) on track gradient of 0 ‰ (red curve), the train can be operated at maximum speed of 160 km/h, although on gradient of 14 ‰, (green curve) the achievable speed is reduced to 100 km/h.

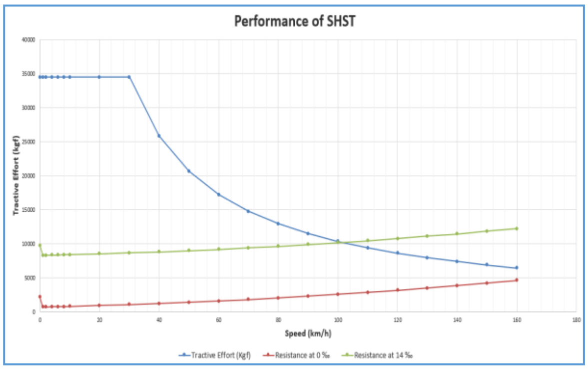

Figure 4

Tractive Force and Resistance Forces as function of Train speed

(5) Selecting engine and motor

From the calculation of tractive efforts, the total power required is in the order of 2700 kW. This represents 85% of the power needed in the train, due to the need for auxiliaries (air conditioning, lighting, entertainment, and others). Therefore the total power requirement would be around 3100 kW. Assuming that the motor efficiency will be around 85%, it is obtained that the total output engine power should be around 4000 kW. Dividing this total power by eight (the number of middle cars; which means there are two spare space under both end cars) then each diesel engine should be around 500 kW. Several candidate engines are listed below (Table 5).

Table 5
Specification of candidate engines

	Cummins	MTU power pack[13]	TAD Penta Volvo	MAN
Power (kW)	563	565	565	460
Bore (mm)	159	122	144	126
Stroke (mm)	159	150	165	166
Speed (rpm)	1800/ 2000	2100	1900	1800
Dimension L/W/H	168/ 193/ 86	390/ 21/ 85		163/ 97/ 103
Weight (kg)	2012	4500	1437	1125
Ref	QSK 19-R	MTU R70 P	TAD1643 VE-B	D2676

As for the traction motor, the power needed for each car will be 2700 kW divided by 16 (the total number motors) or 170 kW. Assuming that the total gear box and motor efficiency is 0.85, then the power of each motor car should be around 200 kW. Several candidate motors are listed in Table 6 below

Table 6
Candidate Traction Motor specification

	Toshiba	Toyodenki	Siemens
Power (kW)	220	207	220
Dimensions (Ø x W mm)	540 x 550		
Weight (kg)	580	393	500
Ref	TRA EMU800		

By using eight distributed motorised cars, there will be several advantages, i.e. lighter engines, better adhesion, better reliability, and flexibility. Further calculation must be performed to verify that the targeted travelled time of 5.5-6.5 hours (Table 3) is achieved. This is carried out by analysing the speed profile which consider the track alignments and scheduled operation[14)].

Moreover, fuel consumption can be calculated based on the engine performance (bsfc), and the speed profile which is specific for each operational route[15,16)]. This is reported in separate paper (ref; paper under preparation).

(6) Possible Improvement

A possible feature for improvement is to include battery to the train in order to get a hybrid trainset[17,18)]. The application of hybrid system in this semi- high speed train will require a further study[14)]. The advantage of a hybrid system on this semi-high speed train is increasing energy efficiency, and reducing noise.

CONCLUSIONS

Based on the methodology developed in this study, it is suggested that the semi-high speed train for Jakarta-Surabaya train service will use Diesel Electric Multiple Unit, with a total output power of 4000 kW. The engine and all other traction equipment (i.e. motors, traction inverter, auxiliary power unit, and transformer) will be installed under-floor. All middle cars will be powered, therefore there will be 8 diesel engines and 16 traction motors. The diesel engine power specification to meet the requirement is 500 kW each, whereas the traction motor is rated as 200 kW. Improvement on the energy efficiency is possible using the hybrid system.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Indonesian Ministry for Research and Technology for supporting this study through the INSINAS 2019 program.

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