Engine Maps, Customers and Markets

2

2.1 Engine Mapping

In Chap. 1 the relationship between work, power, and engine speed was defined. It is this combination of work, power, and speed that is critical to an engine's performance, the way it responds to changing demands, the way it "feels" to the driver. This subject will now be taken up in further detail. The work measured at the crankshaft of an engine is referred to as the ***brake work.*** The product of the brake work and engine speed (with the appropriate unit conversions) is the brake power. These terms reflect the history of engine testing, since early dynamometers typically consisted of friction brakes clamped around a spinning disk bolted to the engine's crankshaft. While dynamometers have changed a great deal the fundamental principles remain the same. The measurement principles of the dynamometer are shown in Fig. 2.1. The dynamometer allows an engine to be loaded under controlled test conditions, and the twisting force, or torque, produced by the engine to be measured. Regardless of dynamometer type, the engine spins the input shaft, and the outer casing contains elements that resist the spinning of the shaft. The engine must produce work (torque) to overcome the resistance. If the dynamometer casing is placed on low friction bearings, and is then kept from spinning by a force exerted at some radius from the spinning shaft the product of the force and radial distance is equal and opposite to the torque produced by the engine.

The dynamometer just described can be used to determine the work output of the engine over its range of operating speeds. As depicted in Fig. 2.2, a speed can be selected, and the throttle setting can be increased to increment the engine speed upward from idle to the selected speed. The figure depicts the throttle position required to overcome mechanical friction and operate the engine at the selected speed at zero load. If the dynamometer load is now increased the engine again slows down. Incrementally opening the throttle

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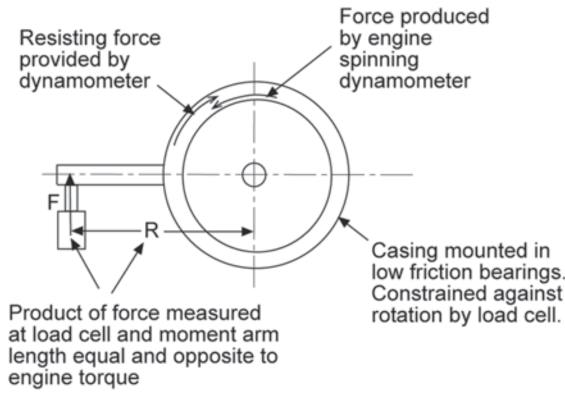

Fig. 2.1 Dynamometer operating principles

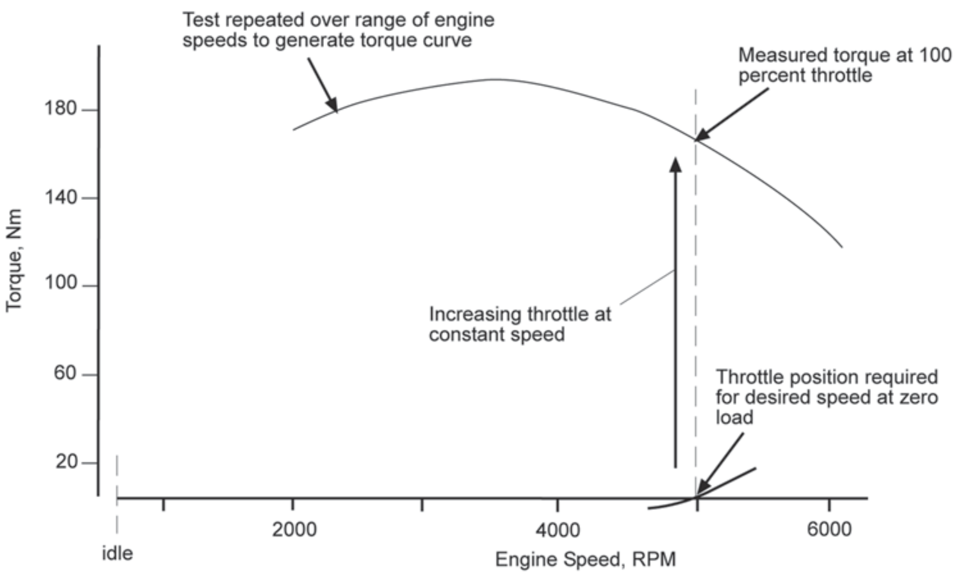

Fig. 2.2 Generating an engine operating map through dynamometer testing

further as the load is increased allows the selected engine speed to be maintained until the maximum, or ***full load*** work output at that speed is reached.

Repeating the test sequence just described over the range of speeds for which the engine can be operated generates the full load torque curve, thus defining the engine operating map. Example operating maps are shown in Figs. 2.3 and 2.4, for spark-ignition and diesel engines respectively. The operating maps as shown plot brake torque output versus engine speed—the two quantities directly measured during the dynamometer test. Recognizing that power is the product of torque and engine speed, the plots could alternatively be plotted as power output versus engine speed.

Looking further at Figs. 2.3 and 2.4 there is a range of speeds in each figure over which the full-load work output decreases as engine speed increases. Remembering again the

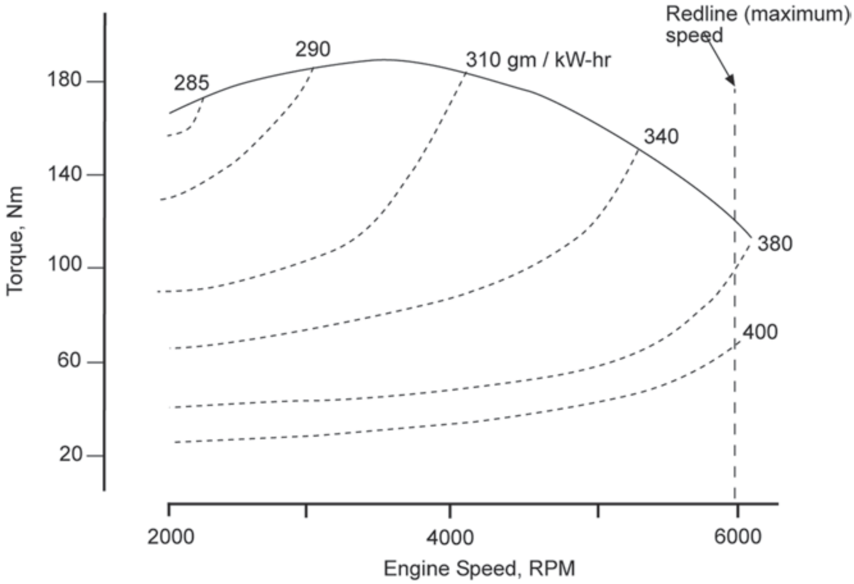

Fig. 2.3 Typical spark-ignition engine operating map, showing lines of constant specific fuel consumption, and maximum engine speed

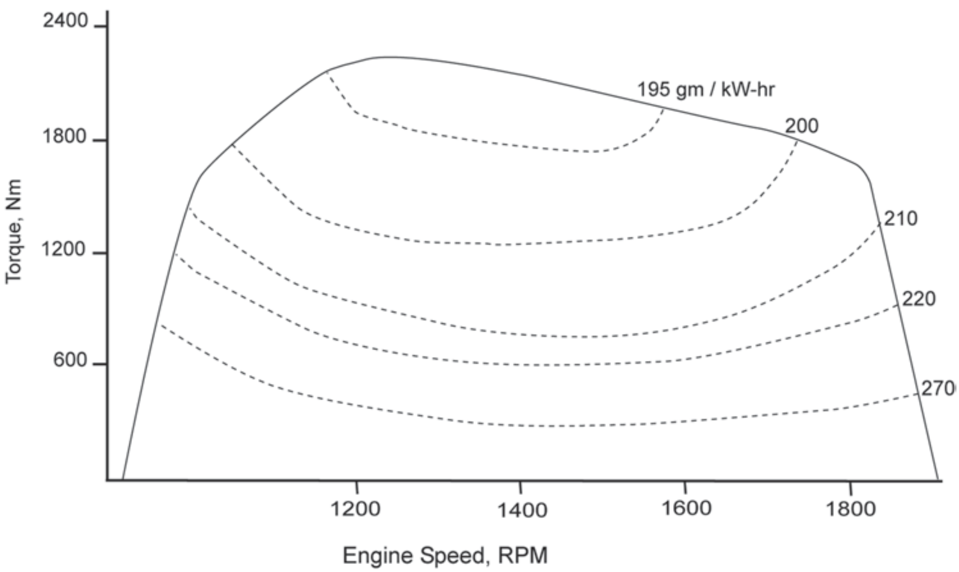

Fig. 2.4 Typical diesel engine operating map, showing lines of constant specific fuel consumption

relationship between power, work, and shaft speed it should be recognized that the slope of the full-load torque curve will determine whether the power is increasing or decreasing as speed is increased. As speed is increased from that of maximum torque the power will typically initially increase. The rate of speed increase is greater than the rate of torque decrease. At some engine speed the torque begins dropping more rapidly, and the power drops with any further speed increase. The speed at which the power reaches its maximum is referred to as ***rated speed,*** and the maximum power is referred to as ***rated power***. The speed range between peak torque and rated power is especially important in applications where the engine is intended to operate for extended periods of time at full load. The negative slope of the torque curve over this range of speed allows the engine to stably respond to changes in load. While operating at full load at any speed between rated power and torque peak if the engine suddenly experiences a further load increase it will slow down, but its work output will increase to address the increased load. If however the engine is operating at a lower speed, where the torque falls with falling speed, a sudden load increase will stall the engine. The engine cannot produce additional work, and therefore cannot address the increased load. The engine can be operated very nicely at part throttle at these lower speeds, but would be quite unstable at full load.

The maximum speed of any engine will be determined by mechanical limitations. Such limitations may be defined by centrifugal or reciprocating forces, or by the rapidly increasing mechanical friction. In some engines a "redline" speed may define the maximum engine speed. The engine could be operated at higher speeds, but the operator risks damaging or destroying the engine. Sound design practice requires that the engine be capable of operating at speeds some margin above that at which maximum power is produced. For example, if an engine produces maximum power at 6600 rpm, a redline speed of 7000 rpm would be acceptable but a redline speed of 5800 rpm would not. The operator would regularly exceed the redline speed based on the "feel" of the engine. As an engine is tuned for higher speed in high performance or racing applications the need to simultaneously address structural considerations to increase redline speed becomes quickly apparent.

In many other applications a high-speed governor is included as part of the fuel metering system. The governor is designed to monitor engine speed and rapidly reduce fueling as the speed increases. The torque curve for such an engine will include a steeply dropping torque from speeds at or slightly above rated speed, to a zero-load, high idle speed. This is shown on the diesel engine operating map in Fig. 2.4. High-speed governors are almost universally used on diesel engines, and are included on spark-ignition engines in many industrial and non-automotive applications.

Also shown on these maps are lines of constant specific fuel consumption. Minimum specific fuel consumption will typically be seen at high loads, and at relatively low engine speeds. As engine speed increases the engine becomes less efficient due to the rapid rate of friction increase. At low speeds the specific fuel consumption will again increase because of increased heat transfer losses. This phenomenon is more pronounced in diesel engines where the air-fuel ratio drops with the increased torque. This results in increased flame temperatures during combustion, and minimum specific fuel consumption typically occurring between rated and peak torque speeds. As load is reduced at any speed the specific fuel consumption again increases. This is due to a combination of increased pumping work and the fact that friction losses stay nearly constant while the brake output is dropping.

Note that the specific fuel consumption increases more rapidly as load is reduced with the spark-ignition engine than with the diesel. This is due to the increased pumping work associated with the throttled intake on the spark-ignition engine.

At this point it is instructive to briefly review and compare the fundamental combustion characteristics of diesel and spark-ignition engines. The reader is referred to texts on combustion in engines for a more detailed treatment—the information presented here is merely an overview needed for engine design considerations. Figure 2.5 provides a general comparative look at automotive diesel versus spark-ignition engine operating maps for the same vehicle. Two important points should be emphasized. First, the spark-ignition engine inherently operates at higher speeds, and over a wider speed range. In part this is due to the necessarily heavier construction of the diesel engine. Faced with peak cylinder pressures two to three times those seen in spark-ignition engines, the diesel combustion chamber and power transfer components must be more robust. Higher rotating and reciprocating forces associated with these heavier components limits their maximum speed. However, a more importan speed limitation results directly from the combustion process of the diesel engine. While the flame speed in a spark-ignition engine scales very well with engine speed, diesel combustion does not scale well with speed. Diesel combustion

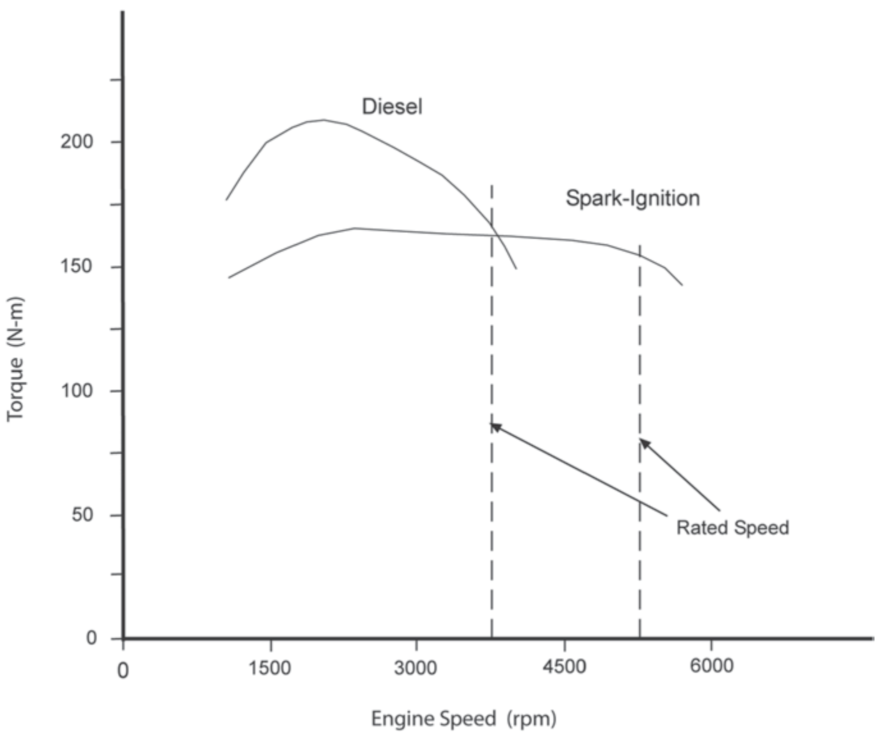

Fig. 2.5 Comparative engine maps for spark-ignition engine and turbocharged diesel engine of similar displacement

requires a sequence of processes—atomization of liquid fuel injected into the combustion chamber; vaporization of the fuel droplets; mixing of the vaporized fuel with the surrounding air; and finally combustion. Clearly these processes do not all scale with engine speed. The maximum speed of a diesel engine is thus limited by the time required to complete the combustion process before efficiency is penalized by extending combustion too far into the expansion stroke. A practical limit for a direct-injection diesel engine will be on the order of 3500–4500 rpm.

The second point to note from Fig. 2.5 is the significantly higher torque rise of the diesel engine. In the case of the spark-ignition engine, the mass ratio of air to fuel must remain approximately constant over the full-load speed range from peak torque to rated speed. With a constant air-to-fuel ratio the torque output can change only with changes in thermal efficiency (brake specific fuel consumption) or volumetric efficiency. The specific fuel consumption drop with reduced speed, seen previously in Fig. 2.3 provides a natural but relatively small increase in torque output. To a greater extent, the shape of the torque curve is dependent on how the volumetric efficiency changes with engine speed. The resulting change in torque with engine speed is significantly less than that which can be achieved in the diesel engine. In the case of the diesel engine a full charge of air is drawn into the cylinder under all conditions. The torque output at any given speed is governed by the amount of fuel injected, and again by the thermal efficiency that can be achieved at that speed. The result is generally a significantly higher rate of torque rise, as shown in Fig. 2.5.

Two final notes should be made about this comparison. First, the diesel may not always demonstrate this much higher rate of torque rise. Because the engine may be set up to operate in the same installation as a spark-ignition engine one may choose to inject more fuel at higher engine speeds to increase peak power. Also the capability of the drivetrain may preclude high torque rise and limit the fueling at low speed. Finally, if the spark-ignition engine is turbocharged boost control versus speed provides another parameter allowing the torque curve shape to be adjusted—in some cases this may allow the torque curve to approach the torque rise of a diesel engine.

2.2 Automobile, Motorcycle, and Light Truck Applications

Automobiles, motorcycles, and light trucks clearly encompass a wide range of vehicles. While detailed coverage of each of these markets cannot be provided in this book several general observations can be made to provide perspective for the designer. In each of these cases, with the exception only of racing engines, the duty cycles seen by the engines will be extremely low. That is, the vast majority of time is spent at very light loads and low engine speeds. While the steady-state loads are increasing as smaller displacement, boosted engines are adopted to increase efficiency, the duty cycles continue to be relatively low. Excursions to higher speeds and loads continue to be limited to brief transients, with many drivers never operating their engines at full load. This observation is of vital importance in two regards. First, it has a great impact on mechanical development of the engine for durability; it creates the difficulty of developing the engine for an expected duty cycle, but recognizing that there may be a wide range of driver operating practices, resulting in significant variation in expected engine life. Second, while the engine achieves its best thermal efficiency much nearer to full load, it spends very little operational time there. Conventional drivetrains are not well suited to providing maximum fuel efficiency, and a great deal of attention is now being given to alternatives such as hybrid electric drive.

Of primary importance to most customers is the drivability of the vehicle. While drivability is a term having many meanings, for these customers its primary meanings are those associated with rapid acceleration, smooth transitions between operating conditions, and minimal noise and vibration.

Most of these markets are quite cost sensitive, and any design features that add cost must be carefully studied for market acceptance. Is the resulting improvement something the customer will appreciate and be willing to pay for?

Fuel economy varies in importance, correlating most closely with fuel costs in the region or country in which the vehicle is to be operated. Weight is a criterion most customers would not identify as having importance, but its impact on package size, cost, and fuel economy make it an important consideration for the engine designer.

Reliability and durability will be more carefully defined in Chap. 3. For now it is important to say that most segments of these applications have expectations of surpassing some threshold engine life, or durability—some number of miles that can be expected before the engine would need to be replaced or rebuilt. Since most customers of these vehicles are not thinking about life to overhaul at the time of initial purchase design improvements that improve durability beyond the customers' threshold expectations can seldom be justified—especially if they add cost to the engine. Reliability refers also to minimizing or eliminating unexpected problems that force repairs over the useful life of the engine. As with virtually every engine application this aspect of reliability expectations are high.

An installed engine operating map for these applications is typically presented as shown in Fig. 2.6. The figure shows tractive force at the drive wheels versus vehicle speed. The individual curves each show the steady-state full-load engine torque curve with a different drive ratio between the engine and drive axle. The dashed lines show each of the five transmission ratios with a particular axle ratio, and the solid lines show the same five transmission ratios with another axle ratio. The right end of each curve is at the engine's redline speed in the particular gear, and thus the maximum vehicle speed in that gear. Also shown on the figure is the force required to move the vehicle on a level road at any given speed. The top speed of the vehicle is determined by either the intersection of this curve with the engine's torque curve corresponding to the highest transmission gear, or by the redline speed of the engine if the torque curve is above the vehicle load curve. A final limit on this diagram is the maximum tractive force or wheel spin limit. If the engine torque as multiplied through the transmission and drive axle gears exceeds this limiting force the tire will break free from the pavement. The force at which this occurs is dependent on the gripping force between the tire and the particular road surface.

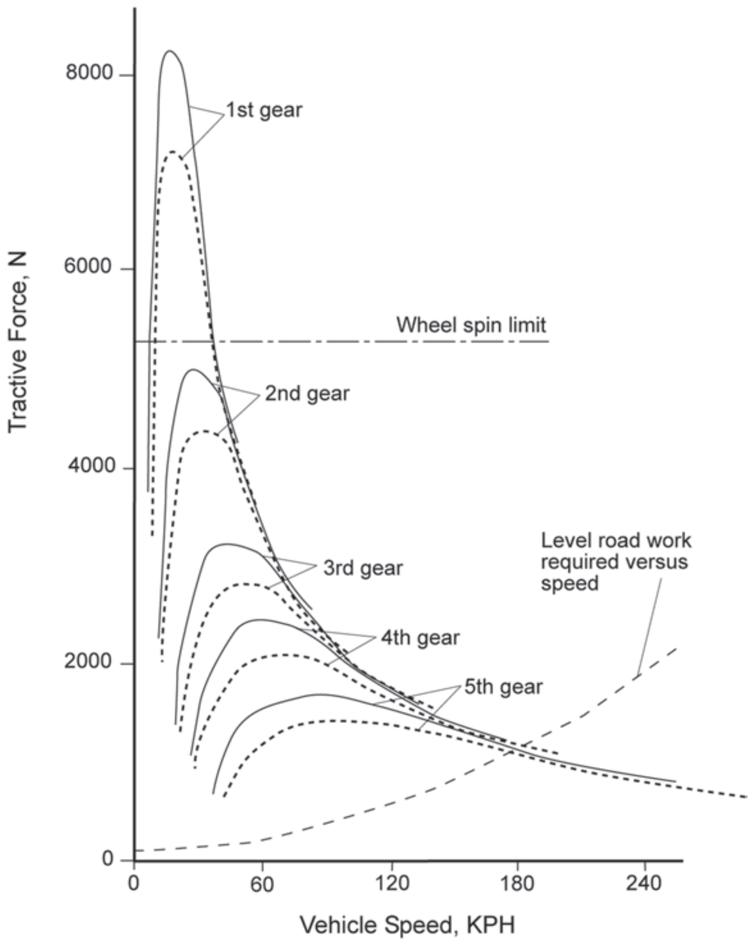

Fig. 2.6 Tractive force in each transmission gear, with two different axle ratios, and level road vehicle load versus engine speed

The plots presented in Fig. 2.6 cover steady-state operation. Also important in automobile applications is transient performance—specifically acceleration rate. The acceleration rate for the same vehicle, at the lower (numerically higher) axle ratio, is shown in Fig. 2.7. Also shown in the figure are the shift points for maximum acceleration. The lower axle ratio of Fig. 2.6 provides more rapid acceleration, and is thus favored in many high performance applications. The higher ratio (numerically lower) results in higher maximum vehicle speed, and of more importance in most applications, it results in lower engine speeds at any given vehicle speed. Because of the strong impact of friction on fuel economy the lower engine speeds provide better fuel economy while the engine will feel less responsive (lower acceleration rates) in the vehicle.

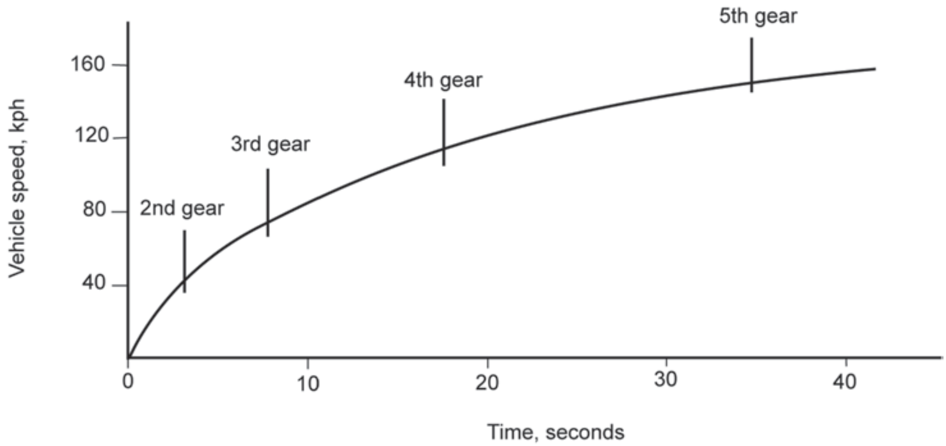

Fig. 2.7 Vehicle speed versus time under conditions of maximum acceleration, indicating points at which each gear shift takes place

2.3 Heavy Truck Applications

Whereas automobile and light truck duty cycles are almost invariably quite low those seen in heavy truck applications are very high, with significant percentages of operating time spent along the full-load torque curve. Combining this with the fact that mileage accumulation rates are quite high (200,000 km per year is typical), results in great emphasis on engine durability or useful life to overhaul. Fuel economy often receives great emphasis as the combination of high usage and high loads makes fuel costs significant. One important distinction within the heavy truck market is between weight-limited and volume-limited hauling. In weight-limited markets, where the maximum allowable vehicle weight is attained before the cargo volume is filled, engine weight is an important criterion—any reduction in engine weight translates directly into increased payload. Economics figures strongly in purchase decisions, and the cost of design improvements must be tied closely to resulting fuel economy, weight, reliability or durability improvements.

Figure 2.8 shows the engine operating map for a diesel engine used in a heavy truck. Overlaid on the engine map is the operating sequence seen when climbing a hill. While the exact power requirements will depend on the aerodynamic drag and rolling resistance of the particular vehicle, it will typically require a power of approximately 150 kW to propel a 36,300 kg truck along a level road at 100 km per hour. The mass chosen is the maximum gross vehicle weight allowed for an 18-wheeled tractor-trailer traveling the interstate highways in the United States (80,000 lbm GVW = 36,287 kg). If the particular engine has a rated power of 300 kW the engine will be operating at approximately half-load when traveling at freeway speed on a level road. This is depicted as point ‘1’ in Fig. 2.8. The engine speed at point ‘1’ will depend on the final drive ratio (the product of the transmission gear ratio in the highest gear and the differential gear ratio). Selecting a numerically higher ratio will increase the engine rpm, and a lower ratio will decrease rpm. The trade-off is pri-

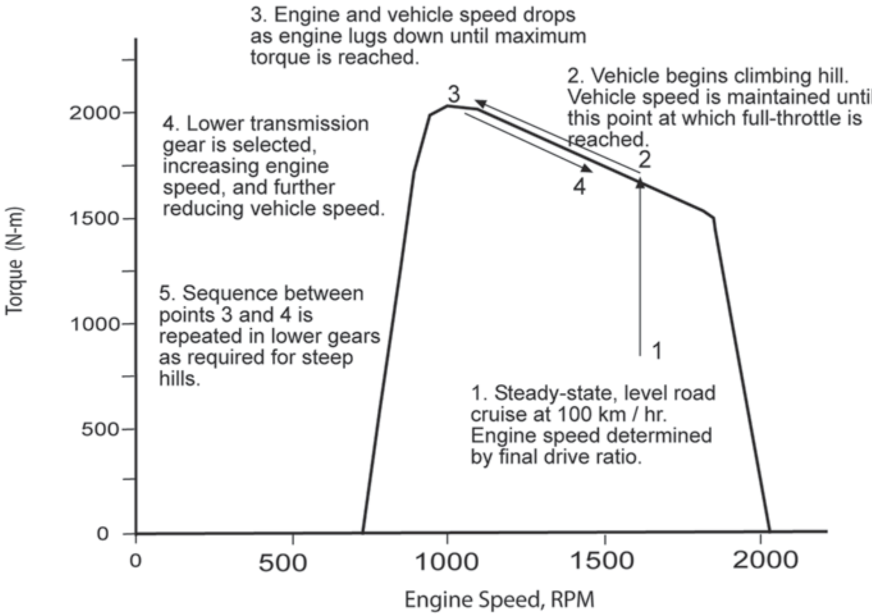

Fig. 2.8 Operating sequence for a heavy truck encountering an uphill grade

marily one between fuel economy and drivability. Increasing the engine speed will allow the operator a greater rpm range and require fewer gear shifts, but fuel economy rapidly deteriorates at high engine speed due to increased friction losses.

Returning now to the sequence of events in Fig. 2.8, if the operator encounters a hill she or he will depress the accelerator pedal further in order to maintain vehicle speed. At point '2' the engine reaches wide-open throttle. Vehicle speed has been maintained to this point, as engine speed has remained constant, and no gear shifts have occurred. Once point '2' has been reached the engine and vehicle will begin slowing down. The engine's torque rise allows increased work to be done to lift the vehicle up the hill, but it is now done with a steadily dropping speed. As point '3' is approached the operating conditions must be changed to avoid stalling the engine. Assuming the truck is still climbing the hill, the operator must select a lower gear (downshift). This brings the engine speed back up (as indicated by point '4') while vehicle speed continues to drop.

An alternative portrayal of heavy truck operation is given in Fig. 2.9. This figure is similar to that given earlier for the automobile application. Power required at the wheels is plotted versus vehicle speed for a level road, and 1 and 2 % upgrades and downgrades. Also shown is the full throttle engine curve in high gear. The steeply downward sloped portion of this curve represents the high speed governor, and the transition point to the flatter portion occurs at rated power. Note that for this very typical vehicle the engine will reach full load when encountering a 1 % uphill grade, and will be required to downshift if the grade reaches 2 %. Similarly, at somewhere between a 1 and 2 % downhill grade the throttle will be closed and the engine will be motored by the vehicle.

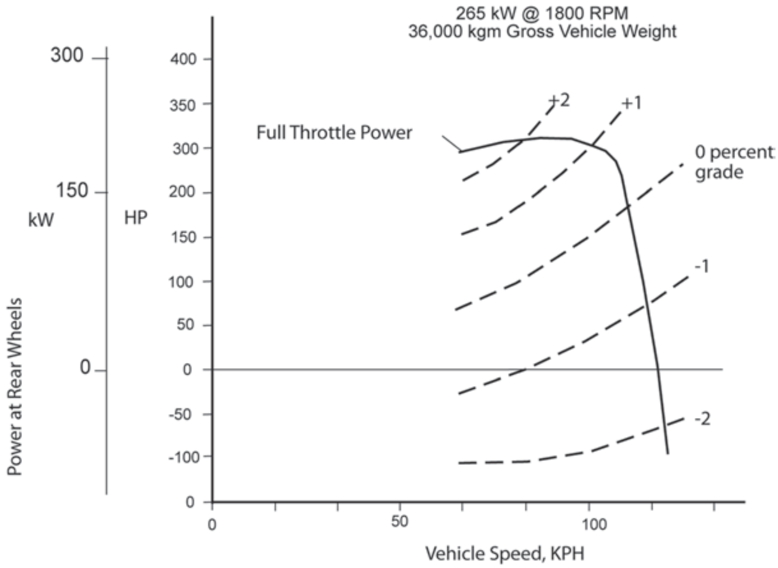

Fig. 2.9 Heavy truck power requirements versus vehicle speed under uphill, downhill, and level road conditions

Based on the discussion just presented it should be clear that engine speed range and torque rise will be critical design parameters for these customers. The more torque rise available to the operator the less rapidly the engine will slow down with increasing grade. The combination of torque rise, gearing, and speed range will dictate how often the operator must shift gears—an important consideration for cross-country driving.

2.4 Off-Highway Applications

Because of the high torque rise and durability requirements diesel engines are used in the vast majority of agricultural and construction applications. In almost all of these applications the operator sets but does not continuously adjust the throttle position. While the engine map requirements are generally very similar to those for heavy trucks, the fueling control strategy is quite different. This is depicted in Fig. 2.10. The two sets of parallel lines overlaid on the diesel engine map represent lines of constant throttle position for on-highway and off-highway applications. In the case of a heavy truck for example, the operator is controlling vehicle speed through continuous adjustment of accelerator pedal position. The desire is to maintain a constant vehicle speed over variable terrain. In any chosen gear constant vehicle speed translates directly to constant engine speed (assuming the manual transmission used in nearly 90 % of these applications). The shallow slope of the lines of constant throttle position results in the operator having full use of accelerator pedal position (0–100 % throttle) at any given speed.

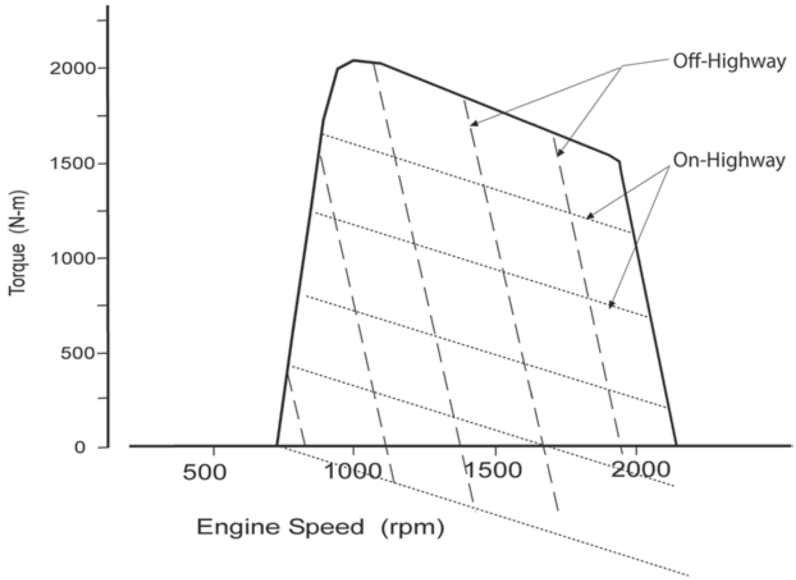

Fig. 2.10 Desired throttle control characteristics for on- and off-highway applications of diesel engines

In contrast, the objective in off-highway applications is to set the throttle position, and minimize the amount of engine speed variation as the load changes. The much steeper lines of constant throttle position ensure that the engine speed varies over a narrow band, even with large changes in load. If the on-highway control scheme were used a large change in engine speed would be seen even with very small changes in load. Using the off-highway control scheme in an on-highway engine would result in a very touchy accelerator pedal, with almost the entire range of fueling occurring over a small percentage of pedal travel. Whether it is done with a fully mechanical fuel injection system or through the use of electronic control, it is necessary to provide these very different throttle control characteristics for different applications.

As was previously discussed, the remaining customer expectations for these markets will be very similar to those for heavy trucks. The fuel economy versus engine speed range trade-off often plays out differently. The number of hours of use per year tends to be lower, and thus fuel economy plays a smaller role in equipment purchases. On the other hand, the equipment sees more excursions toward peak torque operation, making a wider speed range attractive. Similar engine designs to those for heavy trucks will be used, but often with higher rated speeds and equal torque peak speeds.

In off-highway applications such as railroad locomotives and some mining vehicles the engine is used to drive an electric generator and electric motors then drive the wheels. This approach further separates the torque characteristics of the engine from those required at the wheels. While a mechanical drive system can increase the force available at the wheels by going to higher and higher gear ratios the electric motor has the characteristic of maximum torque at zero rpm. To approach this characteristic with a mechanical transmission would require a very large, complex, and expensive drivetrain. The required engine characteristics for an electric drive system are very similar to those for other heavy-duty off-highway applications, but the engine can be optimized over a narrower speed range. This may allow higher peak work or power output, and an opportunity to optimize the engine for greater efficiency.

A unique area of IC engine application is in the wide array of marine applications—everything from small spark-ignition outboard engines to extremely large, low-speed diesel engines in huge ships. The power demand seen by engines in marine applications is summarized in Fig. 2.11. The application is unique in that power output follows a propeller curve, where the power requirement increases at a cubic rate (theoretically) with speed. This ensures that while the engine will see rated power at wide-open-throttle it will not see peak torque conditions. The engine is generally loaded along the prop curve shown in Fig. 2.11. There are a few deviations from this general statement. First, in smaller, high performance boats, the boat's position in the water will shift as it accelerates—this is typically referred to as the boat coming up "on plane." This has the effect of shifting the prop curve to the right. If the prop curve at speed intersects with the peak power point on the engine map, then while the boat is accelerating it will see lower speed, full-load operation. In large boats there may be significant auxiliary loads (electric power, hydraulic winches, etc.) that draw load while the boat is being propelled at high throttle positions. These too will cause the engine to see high loads at speeds below rated power.

The significance of the marine operating characteristics for engine development is that the engine can be developed with very low rates of torque rise. If the designer does not have to simultaneously accommodate high power and high rates of torque-rise the rated power of the engine can often be significantly increased. In some markets—those where

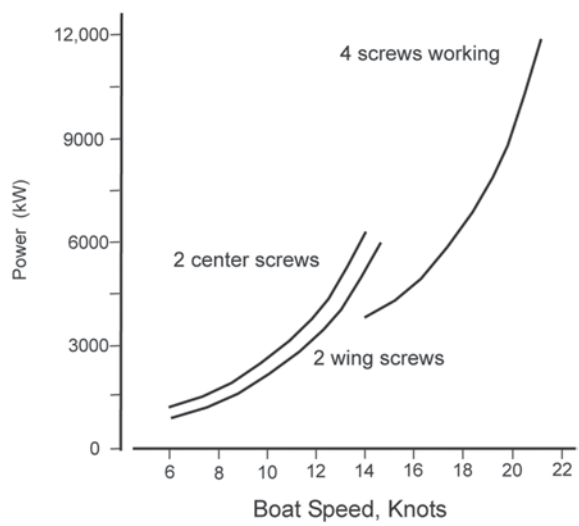

Fig. 2.11 Marine engine power requirements versus boat speed

fuel economy is not important, such as high performance pleasure craft—this can be furthered by increasing rated speed. The net result is that marine engines using the same carcass as those for other applications will often be rated at nearly double the peak power output. Different ratings will be available depending on the hours expected to be spent under high power output conditions.

2.5 Recommendations for Further Reading

Engine testing in a dynamometer test cell is discussed in detail in this book by Plint and Martyr (see Plint and Martyr 1995).

The following papers provide examples of experimental and analytical work in matching the engine to a transmission and vehicle. The final reference discusses heavy truck applications (see Thring 1981; Barker and Ivens 1982; Ren and Zong Ying 1993; Jones 1992).

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