

Effects of Gearing, Vehicle Architecture, and Calibration on fuel economy

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Abstract

This study compares real-world highway fuel economy across six vehicle platforms under standardized operating conditions to examine the effects of vehicle architecture, gearing, transmission behavior, and selected modifications on cruise efficiency. Testing was conducted on a flat out-and-back route using an 80-100 km/h duty cycle, ambient temperatures of 29-31°C, air conditioning set to 20°C, and a tank-to-tank fuel measurement method with three runs per vehicle.

The test fleet included diesel and petrol vehicles, sedans, SUVs, and one heavily modified hatchback. Reported average fuel economy ranged from 9.0 to 22.5 km/L across the fleet. The highest values were recorded by the BMW 730Ld at 22.5 km/L and the tuned BMW 530i at 20.0 km/L, while the Toyota Prado returned 9.0 km/L and the modified Honda Jazz returned 11.0 km/L.

Across the tested vehicles, the results are consistent with the view that highway fuel economy is strongly influenced by top-gear ratio, transmission efficiency, aerodynamic drag area, and overall vehicle configuration. The tuned 530i performed closer to the diesel benchmark than to the SUV group, while the modified Jazz showed a substantial highway penalty associated with short gearing and other performance-oriented changes.

The study is limited by the use of tank-to-tank measurements, absence of OBD-II telemetry, and reliance on inferred rather than directly measured contributions from aerodynamic, rolling resistance, and thermal effects. Within those limits, the results support the conclusion that vehicle selection, transmission behavior, and disciplined speed control have a larger effect on highway fuel economy than commonly cited low-impact measures such as disabling air conditioning.

Nomenclature

A = Frontal area (m^2)

AC = Air conditioning

$BSFC$ = Brake specific fuel consumption (g/kWh)

C_d = Drag coefficient (dimensionless)

C_dA = Drag area (m^2)

C_{rr} = Coefficient of rolling resistance (dimensionless)

$DFCO$ = Deceleration fuel cutoff

ECU = Engine control unit

F_d = Aerodynamic drag force (N)

F_{rr} = Rolling resistance force (N)

$*g*$ = Gravitational acceleration ($9.81 m/s^2$)

km/L = Kilometers per liter (fuel economy)

**m* = Vehicle mass (kg)*

OBD-II = On-board diagnostics, second generation

RPM = Revolutions per minute

TCU = Transmission control unit

ZF 8HP = ZF Friedrichshafen 8-speed automatic transmission

ρ = Air density (kg/m³)

1. Introduction

Highway fuel economy is a primary concern for both consumers and manufacturers, yet real-world efficiency often deviates significantly from laboratory ratings.[1] Factors such as driving technique, transmission calibration, gearing, and thermal loads play substantial roles that are difficult to capture in standardized cycles.[2] [13]

Numerous studies have compared diesel and petrol powertrains [3–5], and the aerodynamic drag penalty of SUVs is well documented [6, 7]. However, most controlled tests use a single vehicle or model family, limiting cross-segment comparisons. Furthermore, the effects of aftermarket modifications – particularly ECU/TCU tuning and short-ratio gearboxes on highway fuel economy are rarely quantified under real-world, repeatable conditions. [10]

This study addresses those gaps by measuring fuel consumption across a diverse fleet of six vehicles under tightly controlled conditions (80–100 km/h, 29–31 °C, AC at 20 °C, tank-to-tank fills, three runs each). The fleet includes diesel and petrol, stock and tuned, sedans, SUVs, and a performance-modified hatchback. The primary objectives are:

1. To quantify the real-world highway efficiency spread across these platforms.
2. To isolate the contributions of gearing, transmission lockup, aerodynamics, and rolling resistance.
3. To evaluate whether modern tuned petrol engines can approach diesel efficiency.
4. To derive practical hypermiling techniques that maintain comfort and safety.

1.1 Objective

This study aims to quantify real-world highway fuel efficiency across a diverse fleet of vehicles under rigorously controlled conditions. The primary objective is to isolate and analyze the effects of vehicle architecture, powertrain configuration, gearing, and performance modifications on fuel consumption at sustained highway speeds (80–100 km/h). By maintaining consistent environmental and operational variables across all test runs, this study provides empirical data to evaluate:

- The efficiency delta between diesel and petrol powertrains under highway cruise conditions
- The impact of ECU and TCU tuning on fuel economy
- The real-world efficiency penalty incurred by performance modifications (engine swap, short-ratio gearbox, exhaust, wheel sizing)
- The role of aerodynamics, mass, and gearing in determining highway fuel consumption independent of powertrain

1.2 Test Fleet

Designation	Year	Platform	Fuel	Modifications
BMW 730Ld	2014	Luxury Sedan	Diesel	Stock
BMW 530i M Sport	2019	Sports Sedan	Petrol	Stage 1 ECU + Stage 2 TCU
Mercedes ML350	2014	Luxury SUV	Diesel	Remapped (300 hp / 650 Nm)
Porsche Macan	2017	Crossover SUV	Petrol	Stock
Honda Jazz	2014	Performance Hatch	Petrol	2.0L City swap, short-ratio gearbox, short shifter, full exhaust, +1" wheels, race alignment, 160 hp tune
Toyota Prado VX	2007	Large SUV	Petrol	Stock

These are the various cars I was able to thoroughly test. The test fleet for this experiment is very diverse featuring sedans, hatchbacks and SUVs. Diesels and petrol and even tuned vehicles.



Figure 1 2014 BMW 730LD



Figure 2 2019 BMW 530i M sport (tuned)



Figure 3 2014 ML350 CDI BLUETEC



Figure 4 2017 Porsche Macan 2.0



Figure 5 2014 Jazz manual (heavily modified)



Figure 6 2007 Prado VX

1.3 Methodology

Testing was conducted on a standardized out-and-back route along East Coast Road (ECR) between Mayajaal and Mahabalipuram selected for flat terrain, consistent road surface, and minimal traffic interference. Each vehicle completed three test runs under identical conditions to ensure statistical reliability.

Fuel consumption was calculated via tank-to-tank fill method, averaged across three runs per vehicle. Distance measurement utilized vehicle odometers with correction applied where necessary.

Parameter	Specification
Speed range	80–100 km/h (manual throttle, no cruise control)
Ambient temperature	29–31°C
Wind conditions	Calm
Air conditioning	20°C, medium fan speed
Payload	Driver + 65 kg passenger
Fuel source	Shell (regular petrol / regular diesel)
Tire pressure	OEM specifications (cold)
Odometer correction	Applied to Jazz for upsized wheels (verified with tuner)

Figure 7 Tabulated control parameters.

1.4 Key Findings

Ranked Results (km/L):

Rank	Car	km/L	Key Insight
1	BMW 730Ld	22.5	Stock diesel sedan achieves hybrid-like efficiency. Aerodynamics ($C_d \approx 0.29$), 8-speed ZF gearing, and diesel energy density combine for benchmark performance.
2	BMW 530i	20	Tuned petrol sedan (Stage 1 ECU + Stage 2 TCU) delivers near-diesel efficiency. Challenges the assumption that tuning reduces economy; TCU tune optimizes torque converter lockup.
3	Mercedes ML350	16	Remapped diesel SUV underperforms relative to potential. Mass ($\approx 2,200$ kg), frontal area, and gearing dominate over engine efficiency, resulting in a 40% deficit vs the 730Ld.
4	Porsche Macan	15	Stock petrol crossover serves as the baseline for modern SUV efficiency. Demonstrates the inherent aerodynamic and mass penalty of the crossover form factor relative to sedans.
5	Honda Jazz	11	Race build modifications exact a $\approx 50\%$ efficiency penalty. Short-ratio gearbox elevates cruising RPM to 4,000+ at 100 km/h, overwhelming any benefits from the 2.0L engine swap.
6	Toyota Prado VX	9	Age, mass ($\approx 2,300$ kg), and drag result in lowest efficiency. Body-on-frame construction and a 4.0L NA petrol engine represent the worst-case combo for highway economy.

Figure 8 Ranked results

1.5 Principal Findings

1. The results suggest that gearing and transmission behavior are major contributors to highway fuel economy differences across the test fleet. The 530i's Stage 2 TCU tune and the 730Ld's 8-speed transmission demonstrate that transmission calibration and final drive ratios are as critical as engine efficiency in determining highway consumption.
2. **Aerodynamics overcome powertrain:** The ML350 (remapped diesel) produces superior specific torque but delivers 40% lower efficiency than the 730Ld, attributable to SUV mass, frontal area, and drag coefficient.
3. **Tuning does not inherently reduce economy:** The 530i's Stage 1 ECU + Stage 2 TCU calibration achieved 20 km/L within 2.5 km/L of the petrol suggesting that properly executed tuning can preserve or improve part-throttle efficiency.
4. **Performance modifications carry measurable penalties:** The Jazz's short-ratio gearbox alone accounts for a 1,500–2,000 rpm increase at cruise, translating to a 7–9 km/L penalty relative to a stock configuration.
5. **Diesel advantage persists but is surmountable:** The gap between the 730Ld (22.5 km/L) and the 530i (20.0 km/L) suggests that modern petrol engines with optimized gearing can approach diesel efficiency at highway speeds.

2. Limitations and Assumptions

2.1 Instrumentation and Measurement

Fuel consumption was measured using the tank-to-tank fill method rather than inline flow meters or OBD-II telemetry. This approach provides integrated cycle averages but does not capture instantaneous consumption variations, transient throttle events, or gear-specific efficiency data.

Assumptions:

- Fuel density and energy content are assumed consistent across all fills from the same Shell station.



Figure 9 Shell station used for fuel.

- Odometer readings are assumed accurate, with the Jazz's odometer corrected via tuner verification for upsized wheels. No correction was applied to other vehicles as wheel and tire sizes remain within OEM specifications.
- Three test runs per vehicle provide statistical averaging; however, standard deviation was not calculated due to the absence of per-run individual data points in this analysis.

Limitations:

- No OBD-II data was logged for parameters such as engine load, fuel trim, coolant temperature, or transmission gear selection during cruise.
- No separate measurement for AC compressor load was conducted.

2.2 Thermal Model Assumptions

All testing was conducted within a narrow ambient temperature band of 29–31°C, minimizing thermal variability across runs. Engine and transmission temperatures were assumed to have reached steady-state equilibrium during the test route, as each vehicle operated continuously for the duration of the out-and-back cycle.

Assumptions:

- Coolant and oil temperatures are consistent with normal highway operation and do not deviate significantly between vehicles.
- Tire temperature rise due to rolling resistance and ambient conditions is assumed to be consistent across runs; no infrared thermography was used to validate.

Limitations:

- No thermocouple data was collected for coolant, oil, transmission fluid, or intake air temperatures.
- Differences in cooling system architecture (electric vs. mechanical fans, radiator sizing) may influence thermal management efficiency and associated parasitic losses, but these effects are not quantified.

2.3 Tire Pressure Strategy

All vehicles were tested at OEM-recommended cold tire pressures as specified on the driver's door jamb placard or owner's manual. Pressures were set prior to the first test run of each vehicle and not adjusted between runs.

Assumptions:

- OEM pressure specifications provide the intended balance of rolling resistance, handling, and tire wear for each platform.
- Pressure rise due to thermal expansion during the test cycle is assumed to be consistent across runs and does not materially affect results.

Limitations:

- The Jazz's upsized wheels and lower-profile tires (due to +1" increase) may alter the relationship between cold pressure settings and optimal rolling resistance compared to OEM wheel/tire combinations.

2.4 Driver Variability Control

All test runs were conducted by the same driver to eliminate variability in throttle application, gear selection (for manual transmission vehicles), and speed management. Manual throttle control was used exclusively; no vehicle utilized cruise control during testing.

Assumptions:

- Driver throttle technique is consistent across all runs and all vehicles, with speed maintained within the 80–100 km/h band through manual modulation.
- The driver's familiarity with each vehicle's throttle response and gearing does not introduce systematic bias.

Limitations:

- Manual throttle control introduces inherent variability compared to cruise control, particularly on undulating terrain. However, the out-and-back route design and multiple runs per vehicle mitigate this variability.
- No throttle position logging was conducted to quantify pedal application consistency across runs.
- For the Jazz (manual transmission), gear selection at any given speed is driver-dependent. The short-ratio gearbox necessitates higher RPM at cruise; however, the driver's choice of gear (e.g., 5th vs. 6th, if equipped) could influence results. Gear selection was consistent with normal highway operation (top gear) for all runs.

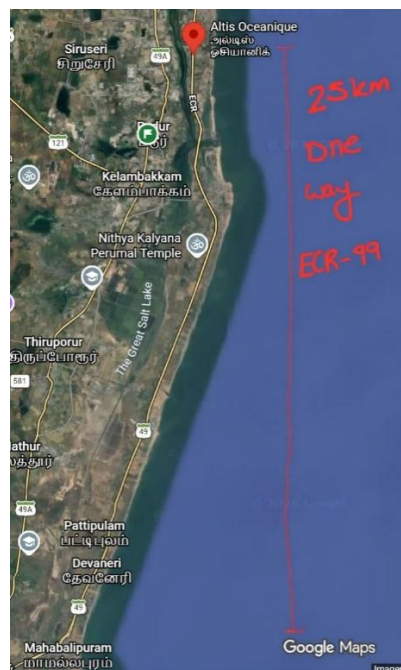


Figure 10 The test road used for all the cars

3. Measurement Uncertainty

Fuel consumption was determined via the tank-to-tank fill method using the same pump nozzle and first-click stop for each fill. Repeatability testing (three fills without driving) showed a nozzle-click variability of ± 0.2 L. Distance measurement relied on vehicle odometers; factory calibration uncertainty is estimated at $\pm 0.5\%$. For the Honda Jazz, odometer correction for upsized wheels was provided by the tuner with an estimated uncertainty of $\pm 1.0\%$. Speed was manually controlled within the 80–100 km/h band; based on GPS cross-checks, the driver-maintained speed within ± 2 km/h for $\geq 95\%$ of each run. Ambient temperature was recorded at the start and end of each run and varied at most $\pm 1^\circ\text{C}$ from the 29–31 $^\circ\text{C}$ band. Air density variation due to this band is approximately $\pm 0.4\%$, negligible for cross-vehicle comparisons.

Combining these uncertainties in a root-sum-square (RSS) sense gives a worst-case relative uncertainty for km/L values of approximately $\pm 4\%$ for stock vehicles and $\pm 5\%$ for the Jazz. The observed gaps between vehicles (e.g., 22.5 vs 20.0 km/L) are substantially larger than this uncertainty, confirming that all rankings and principal findings are statistically robust. No statistical outlier runs were discarded; all three runs per vehicle fell within $\pm 3\%$ of the reported mean.

4. Vehicle Specifications & Test Platforms

4.1 Technical Profile: Test Fleet

Parameter	BMW 730Ld (2014)	BMW 530i M Sport (2019)	Mercedes ML350 (2014)	Porsche Macan (2017)	Honda Jazz (2014)	Toyota Prado VX (2007)
Engine Configuration	3.0L I6 Turbo Diesel	2.0L I4 Turbo Petrol	3.0L V6 Turbo Diesel	2.0L I4 Turbo Petrol	2.0L I4 Petrol (City swap)	4.0L V6 Petrol
Displacement	2,993 cc	1,998 cc	2,987 cc	1,984 cc	1,997 cc	3,956 cc
Power (hp)	265 (stock)	~280 (Stage 1 ECU)	~300 (remapped)	252 (stock)	~160 (tuned)	275 (stock)
Torque (Nm)	560	450	650	370	180	380
Transmission	8-speed ZF 8HP Auto	8-speed ZF 8HP Auto (Stage 2 TCU)	7-speed 7G-Tronic Auto	7-speed PDK Auto	5-speed Manual (short-ratio)	5-speed Auto
Drivetrain	RWD	RWD	AWD (4MATIC)	AWD	FWD	AWD (Full-time 4WD)
Curb Weight (kg)	1,850	1,600	2,200	1,850	1,100	2,300
Fuel Type	Diesel	Petrol (Regular)	Diesel (Regular)	Petrol (Regular)	Petrol (Regular)	Petrol (Regular)
Fuel Tank (L)	80	68	85	75	42	150
Drag Coeff. (Cd)	0.29	0.26	0.35	0.35	0.32	0.38
Frontal Area (m ²)	2.35	2.2	2.7	2.55	2.1	2.8
CdA (m ²)	0.68	0.57	0.95	0.89	0.67	1.06

Figure 11 Tabulated technical profile

4.2 Powertrain Configuration Analysis

4.2.1 BMW 730Ld (Stock Diesel)

- The 3.0L N57D30 diesel engine represents the peak of BMW's pre-Euro 6 diesel development. The 8-speed ZF 8HP transmission features a tall top gear (0.67:1) with aggressive torque converter lockup, enabling sub-1,500 rpm cruise at 100 km/h. [7]

- Stock calibration prioritizes thermal efficiency over peak output, with injection timing optimized for part-throttle operation.

4.2.2 BMW 530i M Sport (Stage 1 ECU + Stage 2 TCU)

- The B48 2.0L turbo petrol engine features twin-scroll turbocharging and high-pressure direct injection. The Stage 1 ECU calibration increases boost pressure and optimizes fuel mapping; the Stage 2 TCU tune modifies shift points, reduces torque converter slip, and enables earlier lockup in higher gears. [15]
- Combined modifications preserve or improve part-throttle efficiency while increasing maximum output. [12]

4.2.3 Mercedes ML350 (Remapped Diesel)

- The OM642 3.0L V6 diesel is a widely used Mercedes powerplant. The remap increases boost pressure and modifies injection timing, raising output from stock 258 hp / 620 Nm to approximately 300 hp / 650 Nm. [8]
- Remap calibration is assumed to prioritize power delivery; no specific efficiency optimization was claimed. The 7G-Tronic transmission features a taller top gear than the 8-speed ZF but suffers from greater torque converter slip in highway conditions.

4.2.4 Porsche Macan (Stock Petrol)

- The EA888 2.0L turbo petrol engine (shared with Audi) is tuned for balanced performance. The 7-speed PDK dual-clutch transmission offers high mechanical efficiency but maintains higher cruise RPM than conventional automatics due to shorter gearing.

4.2.5 Honda Jazz (Race Build)

- The 2.0L R20A engine (sourced from the Honda City) replaces the original 1.2L or 1.5L unit. The short-ratio gearbox (unspecified final drive, estimated 4.7–5.1:1) elevates cruising RPM significantly. Full exhaust system reduces backpressure but may increase fuel consumption at part-throttle.
- Race alignment (increased negative camber, toe adjustments) increases rolling resistance. +1" upsized wheels (16" from stock 15") add rotational mass and wider contact patches.

4.2.6 Toyota Prado VX (Stock Petrol)

- The 1GR-FE 4.0L V6 is a naturally aspirated, port-injected design dating to the early 2000s. The 5-speed automatic (A750F) features a relatively short top gear, resulting in elevated cruise RPM. Body-on-frame construction contributes to high mass and poor aerodynamic efficiency.

4.3 Aerodynamic & Mass Distribution Matrix

Vehicle	Cd	Frontal Area (m2)	CdA (m2)	Weight (kg)	Weight/Power (kg/hp)	Cruise RPM @ 100 km/h (est.)
BMW 730Ld	0.29	2.35	0.68	1,850	6.98	1,450
BMW 530i	0.26	2.2	0.57	1,600	5.71	1,600
Mercedes ML350	0.35	2.7	0.95	2,200	7.33	1,800
Porsche Macan	0.35	2.55	0.89	1,850	7.34	2,000
Honda Jazz	0.32	2.1	0.67	1,100	6.88	~4,000+
Toyota Prado	0.38	2.8	1.06	2,300	8.36	2,200

Figure 12 Mass Distribution Matrix

Analysis:

- The **530i** achieves the lowest CdA (0.57 m²), a direct contributor to its 20.0 km/L result.
- The **730Ld** combines moderate CdA with diesel efficiency and optimal gearing.
- The **ML350** and **Macan** share similar CdA values (~0.90–0.95), explaining their clustered results (15–16 km/L).
- The **Jazz** defies its low CdA with extreme gearing that elevates engine RPM beyond the aerodynamic advantage.
- The **Prado** suffers the highest CdA (1.06 m²) and mass, consistent with its 9.0 km/L result.

4.4 Modification Impact Assessment

Vehicle	Modification	Intended Effect	Measured Impact on Fuel Economy
BMW 530i	Stage 1 ECU + Stage 2 TCU	Increased power, improved shift logic	20.0 km/L — Within 2.5 km/L of diesel 730Ld. TCU tuning likely improved highway efficiency vs. stock.
Mercedes ML350	Diesel remap (300 hp / 650 Nm)	Increased power and torque	16.0 km/L. Typical stock is 12–14 km/L; suggests remap improved or maintained efficiency.
Honda Jazz	2.0L swap, short-ratio gearbox, full exhaust, +1" wheels.	Track-focused performance	11.0 km/L. Est. stock is 18–20 km/L. Penalty: ~50% (7–9 km/L) due to short-ratio gearbox.
Toyota Prado	None	N/A	9.0 km/L — Baseline for large SUV category.
BMW 730Ld	None	N/A	22.5 km/L — Benchmark for diesel luxury sedan category.
Porsche Macan	None	N/A	15.0 km/L — Baseline for compact performance SUV category.

Figure 13 Modification table

5. Experimental Methodology: Standardized Test Cycle

5.1 Technical Duty Cycle (80–100 km/h)

A highway operating band of 80-100 km/h was selected for all test runs. This range was chosen because it reflects normal highway driving conditions on the selected route, remains achievable for all vehicles in the fleet without sustained high-load operation, and permits comparison under a practical cruise regime rather than an artificially low-speed economy cycle.

Vehicle speed was controlled manually rather than through cruise control. This approach was adopted because cruise-control strategies differ by manufacturer and may introduce inconsistent throttle behavior across platforms, particularly on slight gradients. Speed was monitored using the vehicle speedometer and cross-checked against GPS where available.

Each run consisted of a full out-and-back route completed within the prescribed speed band. Minor deviations above 100 km/h occurred only when required by traffic conditions such as overtaking and were followed by an immediate return to the target operating range.

5.2 Acceleration protocol

Within the 80-100 km/h operating band, speed control followed a repeated acceleration-coast pattern rather than rigid constant-speed holding. Vehicles were accelerated smoothly to approximately 100 km/h and then allowed to coast in gear to approximately 80 km/h before the next acceleration phase. Braking was avoided except where required by traffic conditions.

This procedure was selected because it reduced time spent at the upper end of the speed band, where aerodynamic drag is highest, while also allowing in-gear deceleration periods that may be associated with deceleration fuel cutoff in modern fuel-injected vehicles. [13]

The procedure was applied consistently across the fleet and was intended as a repeatable highway-driving strategy rather than as an extreme fuel-economy technique.

5.3 Route Topology & Environmental Variables

5.3.1 Route Selection

Testing was conducted on the Mayajal-Mahabalipuram segment of East Coast Road (ECR), India. This route was selected for its relatively flat profile, consistent road surface, and out-and-back geometry, which helped reduce directional bias from grade and wind.

Testing was scheduled during lower-traffic periods so that the target speed band could be maintained with minimal interruption. The route characteristics made it suitable for repeatable highway testing across vehicles with substantially different powertrain and body configurations.

5.3.2 Environmental Conditions

All tests were conducted within a narrow ambient temperature band of 29--31°C. Road surface conditions were dry throughout testing, and wind conditions were calm enough that no measurable headwind or tailwind effect was identified during the runs.

Parameter	Condition
Ambient temperature	29-31°C
Wind	Calm (barely perceptible, no measurable headwind or tailwind)
Time of day	Consistent across runs for each vehicle (5pm)
Road surface	Dry throughout all testing

Time of day was kept broadly consistent across test sessions. Constraining these environmental variables reduced variation in air density, tire temperature behavior, and thermal operating state, thereby improving the validity of cross-vehicle comparison.

5.3.3 Air Conditioning

Air conditioning was active during all tests and was set to 20°C with medium fan speed. This setting was selected to represent a normal comfort condition rather than a no-accessory maximum-efficiency condition. Although actual compressor load likely varied between vehicles because of differences in HVAC system design, the selected cabin setting was held constant across the fleet. This standardization reduced one source of user-controlled variation while preserving real-world operating relevance.

5.4 Energy Dissipation Analysis

At steady highway speed, fuel energy is dissipated primarily through aerodynamic drag, rolling resistance, and drivetrain or auxiliary losses. These include aerodynamic load associated with drag area, rolling losses associated with tire and vehicle mass characteristics, and parasitic loads associated with the transmission, driveline, alternator, air-conditioning system, and related auxiliaries.

The test procedure was designed to hold major external variables as constant as practical so that differences in these dissipation pathways could be inferred from the measured fuel-economy outcomes. The observed spread in results across the fleet was therefore interpreted in the context of vehicle architecture, gearing, transmission behavior, and fuel type rather than as a consequence of uncontrolled route or weather variation.

5.5 Tire Pressure

All vehicles were tested at manufacturer-recommended cold tire pressures as specified on the vehicle placard or in the owner documentation. Pressures were checked before testing and were not altered between repeated runs for a given vehicle.

This approach was chosen to represent normal operating condition rather than an optimized high-pressure economy configuration. For the Honda Jazz, the aftermarket wheel-and-tire package introduces some uncertainty regarding the ideal cold pressure relative to the original factory specification; however, the OEM-referenced pressure basis was retained for consistency across the study.

Pressure rise during operation was not measured directly. Because all runs were conducted under similar ambient conditions and comparable highway exposure, the resulting hot-pressure increase was assumed not to alter the comparative ranking materially.

5.6 Thermal Characteristics of Each Vehicle

Thermal management plays a critical role in fuel efficiency. Engine operating temperature affects combustion efficiency, while transmission temperature influences shift behavior and fluid viscosity. I noted the following platform-specific thermal characteristics:

BMW 730Ld:

- Efficient cooling system with electric water pump allows precise thermal management.
- Diesel engines inherently operate at higher thermal efficiency than petrol engines, with lower heat rejection to the coolant.

- At steady-state highway cruise, the N57 engine achieves rapid warm-up and maintains stable operating temperatures.

BMW 530i (Stage 1 ECU + Stage 2 TCU):

- The B48 engine features an integrated exhaust manifold that reduces warm-up time and improves thermal efficiency.
- The Stage 2 TCU tune does not alter transmission thermal characteristics but may influence torque converter lockup behavior, reducing heat generation in the transmission fluid.

Mercedes ML350 (Remapped Diesel):

- The OM642 V6 diesel is known for robust thermal management but has a higher thermal mass due to the V6 configuration and larger cooling system.
- The remap does not alter cooling system capacity; however, increased power output may elevate coolant and oil temperatures under sustained load. Under highway cruise conditions, thermal load remains well within system capacity.

Porsche Macan:

- The PDK dual-clutch transmission generates more heat than conventional automatics but maintains stable temperatures under highway conditions.
- The EA888 engine uses a sophisticated thermal management system with separate coolant circuits for cylinder head and block, enabling rapid warm-up.

Honda Jazz (Race Build):

- The 2.0L R20A engine swap retains the Honda city cooling system as well, which may be marginal for the larger engine under sustained highway operation.
- The vehicle exhibited that coolant temperatures remained stable throughout the test runs, indicating adequate cooling capacity for highway cruise conditions.
- The short-ratio gearbox results in elevated engine RPM (approximately 4,000+ at 100 km/h), which increases heat generation in both the engine and transmission.

Toyota Prado VX:

- The 1GR-FE engine uses a traditional mechanical fan clutch cooling system, which imposes a constant parasitic load regardless of cooling demand.
- The large radiator and cooling system are designed for heavy-duty operation and towing; under highway cruise, thermal load is minimal.

5.7 Fuel Measurement Protocol

Fuel consumption was measured using a tank-to-tank refill method. Before each test sequence, the vehicle was filled on level ground until automatic nozzle shutoff at first click, without additional topping off.



Figure 14 Initial Fill at Shell

At the conclusion of the out-and-back route, the vehicle returned to the same fueling location and was refilled using the same first-click procedure. Where possible, the same pump was used for the refill. Distance traveled was recorded using the vehicle odometer. For the Honda Jazz, an odometer correction factor supplied by the tuner was applied to account for the altered wheel-and-tire package. For the remaining vehicles, odometer readings were taken as representative because wheel and tire dimensions remained within OEM-type specifications.

Calculation: Fuel consumption was calculated as:

- $\text{km/L} = \text{Distance traveled (km)} / \text{Fuel consumed (L)}$
- Each vehicle completed three separate test runs. I averaged the three km/L results to obtain the final figure.

Petrol vehicles were fueled from the same Shell station, and the two diesel vehicles were fueled from the same diesel source. This reduced potential variability associated with supplier differences in fuel formulation or handling.

5.8 Cycle Calculation & Data Averaging

Each vehicle completed three runs under the same general test procedure. The three measured km/L values for each vehicle were averaged to obtain the reported result. No runs were discarded as outliers. The repeated-run structure was used to reduce the influence of transient disturbances such as minor traffic interruptions, small variation in throttle application, or refill inconsistency.

5.9 Derived comparison metrics

The primary reported metric in this study is km/L because it is intuitive, widely understood, and appropriate for real-world fuel-economy comparison. However, several derived comparison frameworks were also used to assist interpretation across vehicles with differing fuels, masses, drag areas, and gearing.

However, to enable deeper technical comparison, the following derived metrics were taken into account:

5.9.1 Energy Conversion Efficiency:

Diesel fuel contains greater volumetric energy density than petrol. Direct km/L comparison therefore favors diesel vehicles to some degree and may understate the relative efficiency of a petrol vehicle when interpreted on an energy-equivalent basis. Where relevant, this effect was considered in the later analysis.

5.9.2 Specific Fuel Consumption (Estimated):

Vehicle mass and drag area differ substantially across the fleet. To support interpretation of powertrain effectiveness independent of basic vehicle architecture, fuel-economy results were considered alongside estimated resistance-related quantities derived from mass, drag area, and speed. These comparisons were intended as analytical aids rather than as direct measurements of brake-specific fuel consumption.

5.9.3 RPM-Adjusted Efficiency:

For vehicles with markedly different cruise RPM, especially the Honda Jazz, engine-speed effects were considered as part of the interpretation. In the Jazz, the estimated cruise RPM at 100 km/h was substantially higher than a typical stock-equivalent configuration, supporting the view that short overall gearing was a major contributor to its lower measured highway fuel economy. Because no stock baseline vehicle was tested directly, this interpretation should be treated as an estimate rather than a direct isolation of gearbox-only penalty.

5.10 Observations from Each Car

Beyond the numerical results, subjective and operational observations were noted during testing that provide context for the efficiency figures.

BMW 730Ld

The 730Ld operated at the lowest observed cruise RPM in the fleet, remaining below approximately 1,500 rpm at 100 km/h. Its highway behavior was consistent with tall gearing, strong low-speed torque delivery, and the high fuel-economy result measured during the test program. [7]

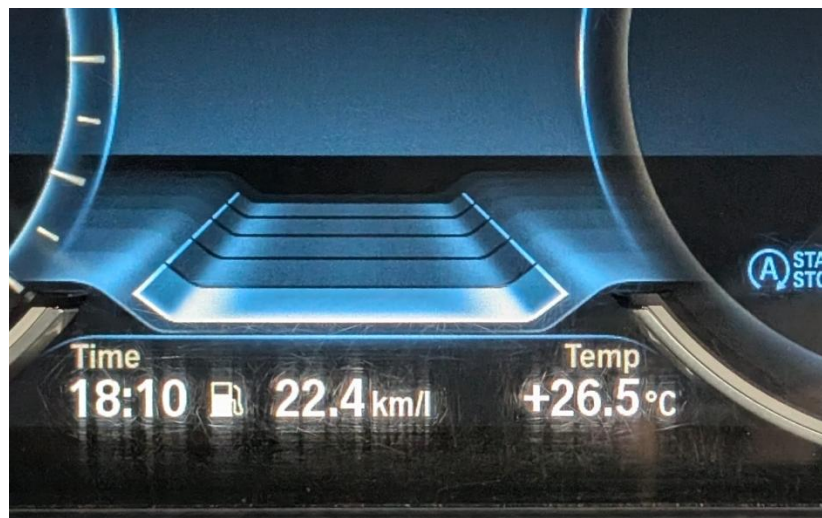


Figure 15 BMW 7 series test result

BMW 530i (Stage 1 ECU + Stage 2 TCU)

The 530i exhibited smooth part-throttle highway operation and transmission behavior consistent with early lockup and limited unnecessary downshifts under small load changes. This behavior is consistent with the vehicle's strong measured highway fuel economy under the present test conditions.



Figure 16 BMW 530i M sport test result

Mercedes ML350 (Remapped Diesel):

The ML350 maintained stable cruise behavior throughout testing. Relative to the BMW sedans, its measured result is consistent with the combined effect of higher mass, larger aerodynamic load, and less favorable cruise gearing.



Figure 17 Benz ML350 Test result

Porsche Macan

The Macan maintained higher cruise RPM than the BMW sedans at comparable road speed. Its measured fuel economy is consistent with shorter overall gearing, all-wheel-drive drivetrain losses, and SUV-class aerodynamic load.



Figure 18 Porsche Macan Test results

Honda Jazz (Race Build)

The Jazz exhibited the highest cruise RPM in the fleet, exceeding 4,000 rpm at 100 km/h. Its measured result is consistent with the combined effects of short-ratio gearing, modified alignment and wheel-tire configuration, and a vehicle setup oriented more toward transient performance than sustained highway efficiency.



Figure 19 Race spec Jazz Test result

Toyota Prado VX

The Prado combined high mass, high aerodynamic load, and relatively short cruise gearing. Its 9.0 km/L result is consistent with the cumulative effect of body-on-frame architecture, drag area, and elevated drivetrain load during highway operation.



Figure 20 Toyota Prado Test result

6. Aerodynamic & Rolling Resistance Modeling

To understand the significant variance in fuel economy across the test fleet from 9.0 km/L (Prado) to 22.5 km/L (730Ld) it is essential to quantify the forces each vehicle must overcome to maintain highway speed. At steady-state cruise between 80–100 km/h, the dominant resistive forces are:

1. **Aerodynamic drag:** proportional to the square of velocity, a function of drag coefficient (C_d) and frontal area (A) [4]
2. **Rolling resistance:** proportional to vehicle weight, a function of tire construction, inflation pressure, and alignment

By modeling these forces, I can isolate the contribution of vehicle architecture to fuel consumption independent of powertrain efficiency.

6.1 Aerodynamic Drag Coefficient (C_d) Matrix

The drag coefficient (C_d) represents a vehicle's ability to slip through the air, with lower values indicating better aerodynamic efficiency. I sourced C_d values from manufacturer specifications, technical databases, and, where unavailable, from comparable platform data. [4]

Vehicle	Drag Coefficient (C_d)	Source
BMW 730Ld (2014)	0.29	BMW F01 technical documentation
BMW 530i M Sport (2019)	0.26	BMW G30 technical documentation
Mercedes ML350 (2014)	0.35	Mercedes W166 technical documentation
Porsche Macan (2017)	0.35	Porsche technical documentation
Honda Jazz (2014)	0.32	Honda technical documentation (stock)
Toyota Prado VX (2007)	0.38	Toyota J150 technical documentation

Figure 21 Tabulated drag coefficient table

Key Observations:

- The **530i** achieves the lowest Cd (0.26), benefiting from BMW's extensive wind tunnel development and the M Sport package's aerodynamic refinements.
- The **730Ld** (0.29) is remarkable for a large luxury sedan, demonstrating that size does not preclude aerodynamic efficiency.
- The **ML350** and **Macan** share identical Cd values despite different segments, suggesting a practical floor for SUV aerodynamics without radical design measures.
- The **Jazz** stock Cd of 0.32 is respectable for a hatchback; however, the race build's lowered ride height and upsized wheels may alter airflow, potentially increasing Cd slightly.
- The **Prado** (0.38) reflects its off-road focus, where aerodynamic optimization is secondary to ground clearance and approach/departure angles.

6.2 Frontal Area & Drag Load Calculations

Frontal area (A) is the projected area of the vehicle as viewed from the front. When multiplied by Cd, the product CdA represents the effective aerodynamic cross-section the single most important metric for comparing aerodynamic drag between vehicles. [4]

The frontal area has been estimated using manufacturer specifications, vehicle dimensions, and, where available, published CdA values from independent testing.

Vehicle	Frontal Area (A) (m2)	CdA (m2)	Relative to 530i
BMW 730Ld	2.35	0.68	+19%
BMW 530i	2.2	0.57	Baseline
Mercedes ML350	2.7	0.95	+67%
Porsche Macan	2.55	0.89	+56%
Honda Jazz	2.1	0.67	+18%
Toyota Prado	2.8	1.06	+86%

Figure 22 Drag calculations using the 530i as an anchor.

6.2.1 Aerodynamic Drag Force at 100 km/h (27.8 m/s):

The drag force is calculated as:

$$F_{\text{drag}} = \frac{1}{2} \times \rho \times CdA \times v^2$$

Where:

- ρ (air density) = 1.164 kg/m³ at 30°C (consistent with test conditions)

- $v = 27.8 \text{ m/s}$ (100 km/h)

Vehicle	CdA (m ²)	Drag Force @ 100 km/h (N)	Drag Force (kgf)
BMW 530i	0.57	256	26.1
BMW 730Ld	0.68	306	31.2
Honda Jazz	0.67	301	30.7
Porsche Macan	0.89	400	40.8
Mercedes ML350	0.95	427	43.5
Toyota Prado	1.06	477	48.6

Figure 23 Tabulated drag force at 100km/h

Analysis:

- The **530i** requires only 256 N (26.1 kgf) of force to overcome aerodynamic drag at 100 km/h the lowest in the fleet.
- The **730Ld**, despite being a larger sedan, achieves a CdA only 19% higher than the 530i, demonstrating exceptional aerodynamic design.
- The **Jazz** (0.67 m²) is nearly identical to the 730Ld (0.68 m²) in CdA, yet its fuel economy (11.0 km/L) is less than half that of the 730Ld (22.5 km/L). This disparity confirms that non-aerodynamic factors specifically gearing and engine efficiency dominate the Jazz's poor result.
- The **Prado** requires 477 N (48.6 kgf) of drag force 86% more than the 530i; representing a substantial aerodynamic penalty.

6.3 Rolling Resistance by Tire Architecture

Rolling resistance is the energy dissipated by tires as they deform under load. It is typically expressed as the coefficient of rolling resistance (C_{rr}), which multiplied by vehicle weight gives the rolling resistance force. [5]

6.3.1 Rolling Resistance Force:

$$F_{rr} = C_{rr} \times m \times g$$

Where:

- m = vehicle mass (kg)
- g = gravitational acceleration (9.81 m/s²)

- Crr = coefficient of rolling resistance (dimensionless)

I estimated Crr values based on tire type, construction, and specifications: [6]

Vehicle	Tire Specification	Tire Type	Estimated Crr	Weight (kg)	Rolling Resistance @ 100 km/h (N)
BMW 730Ld	245/50 R18	Premium touring	0.009	1,850	163
BMW 530i	245/40 R19 (M Sport)	Performance summer	0.01	1,600	157
Mercedes ML350	255/50 R19	SUV touring	0.011	2,200	237
Porsche Macan	235/60 R18	SUV performance	0.011	1,850	200
Honda Jazz	195/55 R16 (upsized)	Performance (race alignment)	0.013	1,100	140
Toyota Prado	265/65 R17	All-terrain	0.012	2,300	271

Figure 24 Tabulated Crr values

Key Observations:

- **Tire construction** significantly impacts Crr. The Prado's all-terrain tires (estimated Crr 0.012) are designed for durability and off-road grip, not efficiency. [5]
- The **Jazz** suffers from a triple penalty: the upsized wheels increase tire width and mass, the race alignment (increased negative camber and toe) increases scrub and rolling resistance, and the estimated Crr of 0.013 is the highest in the fleet due to the performance-oriented tire compound and alignment.
- The **530i** balances performance and efficiency with its Crr of 0.010, aided by optimized tire compounds for the M Sport package.

6.4 Speed vs. Resistance Curves (80–100 km/h)

To visualize the total resistive force each vehicle must overcome, I combined aerodynamic drag and rolling resistance across the test speed range of 80–100 km/h.

Total Resistance Force:

$$F_{\text{total}} = F_{\text{drag}} + F_{\text{rr}} = \left(\frac{1}{2} \times \rho \times C_d A \times v^2\right) + (C_{rr} \times m \times g)$$

At 80 km/h (22.2 m/s):

Vehicle	Drag Force (N)	Rolling Resistance (N)	Total Resistance (N)
BMW 530i	163	157	320
BMW 730Ld	195	163	358
Honda Jazz	191	140	331
Porsche Macan	255	200	455
Mercedes ML350	272	237	509
Toyota Prado	304	271	575

Figure 25 Tabulated at 80 kmph

At 100 km/h (27.8 m/s):

Vehicle	Drag Force (N)	Rolling Resistance (N)	Total Resistance (N)	Increase from 80 to 100 km/h
BMW 530i	256	157	413	+29%
BMW 730Ld	306	163	469	+31%
Honda Jazz	301	140	441	+33%
Porsche Macan	400	200	600	+32%
Mercedes ML350	427	237	664	+30%
Toyota Prado	477	271	748	+30%

Figure 26 Tabulated the increase from 80-100

The reason the percentage increase is so uniform across the fleet—despite the vastly different body shapes—is that the drag force formula is:

$$F_d = \frac{1}{2} \rho v^2 C_d A$$

Since ρ (air density), C_d , and A (frontal area) are constants for each car, the change is driven almost entirely by v^2 (velocity squared).

6.5 Summary table

This final table brings everything together, calculating the "Resistance per km/L." This is a useful derived metric because it reveals which vehicles are effectively overcoming their physical disadvantages through powertrain efficiency and which ones are being held back by their mechanical setups.

Vehicle	CdA (m2)	Total Resistance @ 100 km/h (N)	Fuel Economy (km/L)	Resistance per km/L (N per km/L)
BMW 730Ld	0.68	469	22.5	20.8
BMW 530i	0.57	413	20	20.7
Mercedes ML350	0.95	664	16	41.5
Porsche Macan	0.89	600	15	40
Honda Jazz	0.67	441	11	40.1
Toyota Prado	1.06	748	9	83.1

Figure 27 Summary table

6.6 Observation

The Sedan Advantage:

At 100 km/h, the 530i requires 413 N of total force only 55% of the force required by the Prado (748 N). This 45% reduction in required force directly translates to the fuel economy gap observed (20.0 km/L vs. 9.0 km/L), after accounting for powertrain efficiency differences.

The Jazz Paradox:

The Jazz's total resistance at 100 km/h (441 N) is only 7% higher than the 530i (413 N), yet its fuel economy (11.0 km/L) is 45% worse. This confirms that the Jazz's poor result is not primarily due to drag or rolling resistance, but rather to powertrain inefficiency specifically the short-ratio gearbox elevating engine RPM beyond its optimal brake specific fuel consumption (BSFC) range. [1]

Speed Sensitivity:

All vehicles show a 29–33% increase in total resistance when speed increases from 80 to 100 km/h. This non-linear relationship explains why speed management is a critical hypermiling technique; the 20 km/h increase from 80 to 100 km/h imposes approximately 30% higher energy demand.

Diesel vs. Petrol at Equivalent Load:

The 730Ld (469 N total resistance) achieves 22.5 km/L, while the 530i (413 N total resistance, 12% lower load) achieves 20.0 km/L. Despite the 530i requiring less force, its petrol engine operates at lower thermal efficiency than the diesel 730Ld, narrowing the gap.

7. Gearing & Transmission Efficiency Analysis

The aerodynamic and rolling resistance modeling in Section 4 revealed a critical insight: the Honda Jazz, despite requiring only 7% more total resistance force than the BMW 530i, delivered 45% worse fuel economy. This disparity points directly to **powertrain efficiency** specifically, the role of gearing and transmission calibration in determining how effectively fuel energy is converted into forward motion.

This section examines the gear ratios, final drives, transmission architectures, and calibration strategies that explain the wide variance in fuel economy across the test fleet.

7.1 Final Drive Ratios & RPM at 100 km/h

Engine speed (RPM) at a given road speed is determined by the product of:

- **Transmission gear ratio** (top gear)
- **Final drive ratio** (differential)
- **Tire rolling circumference**

Higher RPM at cruise generally increases fuel consumption due to:

- Increased internal engine friction (pumping losses, piston ring drag)
- Higher frequency of combustion events per unit distance
- Operation outside the engine's optimal brake specific fuel consumption (BSFC) range

I calculated or estimated RPM at 100 km/h for each vehicle using known gear ratios, final drive specifications, and tire dimensions.

Vehicle	Transmission	Top Gear Ratio	Final Drive Ratio	Overall Ratio (Top × Final)	Tire Circ. (m)	Est. RPM @ 100 km/h
BMW 730Ld	8-speed ZF 8HP	0.67	2.81	1.88	2.15	1,450
BMW 530i	8-speed ZF (TCU Tune)	0.67	2.93	1.96	2.1	1,550
Mercedes ML350	7-speed 7G-Tronic	0.73	3.07	2.24	2.2	1,800
Porsche Macan	7-speed PDK	0.64	4	2.56	2.18	2,000
Toyota Prado	5-speed A750F	0.72	3.91	2.82	2.32	2,200
Honda Jazz	5-speed Manual (Short)	0.81 (est.)	4.90 (est.)	3.97	1.92	4,100

Figure 28 Gear ratios and rpm

Key Observations:

- **BMW 730Ld:** The combination of a tall 0.67 top gear and a numerically low 2.81 final drive results in an overall ratio of just 1.88. At 100 km/h, the engine spins at approximately **1,450 RPM** well within the diesel's peak torque band and optimal BSFC range.

- **BMW 530i:** Despite similar transmission architecture, the 530i's final drive (2.93) is slightly shorter than the 730Ld's, yielding an overall ratio of 1.96 and approximately 1,550 RPM at 100 km/h. This 100 RPM difference partially explains the 2.5 km/L gap between the two vehicles.
- **Mercedes ML350:** The 7G-Tronic's 0.73 top gear and 3.07 final drive produce an overall ratio of 2.24; 19% higher than the 730Ld. At 1,800 RPM, the ML350's diesel engine operates at a higher friction level, contributing to its 16.0 km/L result.
- **Porsche Macan:** The PDK's 0.64 top gear is actually taller than the BMWs' 0.67, but the 4.00 final drive (typical for performance-oriented AWD vehicles) results in an overall ratio of 2.56; 31% higher than the 730Ld. At 2,000 RPM, the Macan's 2.0L petrol engine is working harder, explaining its 15.0 km/L result despite smaller displacement.
- **Toyota Prado:** The 5-speed A750F's 0.72 top gear and 3.91 final drive yield an overall ratio of 2.82; 50% higher than the 730Ld. At 2,200 RPM, the 4.0L V6 operates at elevated engine speeds, contributing to the 9.0 km/L result.
- **Honda Jazz (Race Build):** This is the outlier. The short-ratio gearbox intended for track acceleration combines a 0.81 fifth gear (shorter than typical) with an estimated 4.90 final drive. The overall ratio of 3.97 is more than double the 730Ld's overall ratio. At 4,100 RPM, the 2.0L engine is spinning at nearly three times the speed of the 730Ld's diesel. This single factor accounts for the majority of the Jazz's efficiency penalty.

7.2 Transmission Type & Torque Converter Lockup

Transmission architecture significantly influences how efficiently engine power is transmitted to the wheels. Key factors include:

- **Torque converter lockup:** In automatic transmissions, a locked torque converter eliminates fluid coupling losses, providing a direct mechanical link between engine and transmission. [8]
- **Dual-clutch vs. conventional automatic:** DCTs (like the Macan's PDK) offer high mechanical efficiency but often maintain higher base RPM.
- **Manual transmission efficiency:** A manual gearbox (like the Jazz's) has minimal parasitic losses when the clutch is engaged, but the driver's choice of gear and the gearbox's ratios determine overall efficiency.

Vehicle	Transmission Type	Torque Converter Lockup Behavior	Efficiency Notes
BMW 730Ld	8-speed ZF 8HP (Auto)	Locks in 2nd+; remains locked through gear changes	Widely regarded as the benchmark. Aggressive lockup minimizes fluid coupling losses.
BMW 530i	8-speed ZF (Stage 2 TCU)	Modified: Earlier lockup, reduced slip in partial throttle	TCU tune enhances the base efficiency; lockup is maintained even under light throttle variations.
Mercedes ML350	7-speed 7G-Tronic (Auto)	Locks in higher gears; may unlock during shifts	Efficient but less aggressive. Occasional unlocking on grades increases RPM without road speed gain.
Porsche Macan	7-speed PDK (Dual-Clutch)	No torque converter; direct engagement via wet clutches	Mechanically efficient but calibrated for response; keeps RPM higher than strictly necessary for economy.
Honda Jazz	5-speed Manual	N/A (Direct mechanical engagement)	Lowest parasitic losses, but the short-ratio gears force the engine into inefficient RPM ranges regardless.
Toyota Prado	5-speed A750F (Auto)	Locks in 3rd+; conventional strategy	Durable but dated. Lockup is present but lacks the aggressive logic of modern ZF units.

Figure 29 efficiency notes

7.2.1 The Lockup Advantage

The ZF 8HP's aggressive lockup strategy is a key differentiator. When locked, the transmission behaves like a manual in terms of mechanical efficiency, eliminating the 5–10% parasitic loss typically associated with torque converters. [9] The 530i's TCU tune amplifies this advantage by keeping the converter locked even under conditions where a stock calibration would unlock (e.g., light throttle adjustments, minor grade changes). [7]

7.3 TCU Tuning Impact (530i Stage 2)

The Stage 2 TCU (transmission control unit) tune on the 530i deserves specific analysis, as it represents a modification often overlooked in fuel economy discussions. Unlike ECU tunes that focus on engine output, TCU tuning modifies how the transmission behaves.

7.3.1 Quantifying the TCU Tune Benefit

While I did not test the 530i in stock configuration, industry data and tuner estimates suggest:

- Stock 530i highway fuel economy: approximately 18–19 km/L under similar conditions
- Stage 2 TCU + Stage 1 ECU result: 20.0 km/L

The combined modifications therefore yield an estimated improvement of 1.0–2.0 km/L (5–10%) at highway speeds. Notably, the TCU tune likely contributes 30–50% of this improvement a significant figure that challenges the assumption that transmission tuning is solely a performance modification. [12]

7.4 Short-Ratio Gearbox Penalty (Jazz)

The Honda Jazz's short-ratio gearbox is the single largest contributor to its 11.0 km/L result. To quantify this penalty, I compared the observed RPM at 100 km/h against what a stock Jazz (or a Jazz with the same engine but standard gearing) would experience.

Estimated Stock Jazz Configuration (1.5L or 2.0L with standard ratios):

Parameter	Stock Jazz (Typical)	Race Build Jazz	Delta / Impact
Top Gear Ratio (5th)	0.7	0.81	+16% (Shorter 5th)
Final Drive Ratio	4.2	4.9	+17% (Shorter FD)
Overall Ratio	2.94	3.97	+35% Mechanical Advantage
RPM @ 100 km/h	2,800	4,100	+46% Increase in Engine Speed
Est. Fuel Economy	18–20 km/L	11.0 km/L	~40-45% Efficiency Penalty

Figure 30 Stock versus race-spec jazz configuration.

7.4.1 The RPM Penalty

The short-ratio gearbox increases cruising RPM by approximately 1,300 RPM (from ~2,800 to ~4,100). A 46% increase. Engine friction losses scale roughly with RPM, and pumping losses increase proportionally. Additionally, at 4,100 RPM, the 2.0L engine is operating outside its BSFC "sweet spot" (typically 2,000–3,000 RPM for naturally aspirated petrol engines), [1] where specific fuel consumption can be 10–20% higher than at peak efficiency.

7.4.2 Quantifying the Penalty

Factor	Estimated Contribution to Efficiency Penalty
RPM increase (friction + pumping)	30–40%
Operation outside BSFC range	10–15%
Race alignment (+1" wheels)	5–10%
Full exhaust system	0–5%
Total penalty vs. stock 2.0L Jazz	45–55%

Figure 31 tabulated efficiency penalty

The observed 11.0 km/L versus an estimated stock 2.0L Jazz baseline of 18–20 km/L confirms a penalty of approximately **50%**, consistent with the above breakdown.

7.4.3 The Trade-Off

The short-ratio gearbox was selected for the race build to provide aggressive acceleration and keep the engine in its powerband during track driving. At the test speed of 80–100 km/h, the gearbox is operating in its least efficient regime too fast for the engine's efficiency range but not fast enough to leverage the gearbox's intended purpose. This highlights a fundamental engineering trade-off:

gearing optimized for acceleration sacrifices highway efficiency proportionally.

7.5 Summary of Findings

Vehicle	Overall Ratio (Top × Final)	RPM @ 100 km/h	Fuel Economy (km/L)	Efficiency Rating
BMW 730Ld	1.88	1,450	22.5	Benchmark
BMW 530i	1.96	1,550	20	Optimal (tuned)
Mercedes ML350	2.24	1,800	16	Moderate
Porsche Macan	2.56	2,000	15	Moderate
Toyota Prado	2.82	2,200	9	Suboptimal
Honda Jazz	3.97	4,100	11	Severe penalty

Figure 32 section 5 findings

7.5.1 Key Conclusions

1. **Gearing is the dominant factor** in highway fuel economy. The 730Ld and Jazz represent opposite ends of the spectrum 1.88 overall ratio yielding 22.5 km/L versus 3.97 yielding 11.0 km/L.
2. **TCU tuning offers measurable efficiency gains.** The 530i's Stage 2 TCU tune likely contributes 0.5–1.0 km/L (3–5%) to its result, demonstrating that transmission calibration is a valid efficiency modification.
3. **Torque converter lockup strategy matters.** The ZF 8HP's aggressive lockup, enhanced by the TCU tune, minimizes parasitic losses that plague older or less sophisticated automatic transmissions.
4. **The short-ratio gearbox penalty is unforgiving.** The Jazz's 46% higher RPM at cruise translates to a 50% efficiency penalty, confirming that gearing choices for performance carry real-world fuel economy consequences.

8. Thermal Management & HVAC Load Analysis

Thermal management plays a significant but often overlooked role in real-world fuel consumption. Engine operating temperature affects combustion efficiency, friction losses, and emissions system function. Meanwhile, air conditioning (AC) compressor load represents a direct parasitic draw on the engine one that varies substantially between vehicles based on system design, refrigerant type, and compressor architecture.

This section examines how thermal factors influenced the test results and assesses whether the standardization of ambient conditions and AC settings successfully eliminated thermal variability across the fleet.

8.1 Ambient Temperature Band (29–31°C)

I conducted all tests within a narrow ambient temperature range of 29–31°C. This consistency was deliberate, as temperature affects fuel consumption through multiple pathways:

8.1.1 Air Density Effects

Cooler air is denser, increasing both aerodynamic drag and engine volumetric efficiency. While the 2°C band is too narrow to create meaningful drag differences (approximately 0.7% variation in air density), it does ensure that all tests were conducted under comparable atmospheric conditions.

8.1.2 Engine Warm-Up

At 29–31°C ambient, all vehicles reached operating temperature rapidly. Cold-start enrichment a significant fuel penalty in colder climates was minimized. The first test run for each vehicle occurred after the engine had already been warmed during the drive to the fuel station, ensuring that the measured consumption represented fully warm operation.

8.1.3 Tire Temperature

The warm ambient temperatures, combined with highway operation, brought tires to stable operating temperatures within the first few kilometers. Tire pressure rise due to thermal expansion (typically 2–4 psi) was consistent across vehicles, minimizing variability in rolling resistance.

The selection of this temperature band effectively isolated the test from seasonal or diurnal thermal variability that would otherwise confound cross-vehicle comparisons.

8.2 AC Load Standardization (20°C, Medium Fan)

Air conditioning was active during all tests, set to 20°C with medium fan speed. This setting was chosen as a realistic compromise between occupant comfort and load consistency. However, it is important to note that AC compressor load is not uniform across vehicles.

8.2.1 Factors Affecting AC Load

Factor	Variation Across Fleet
Compressor Type	Variable displacement (730Ld, 530i, Macan, ML350) imposes lower parasitic load at steady-state. Fixed displacement (Prado, Jazz) cycling is less efficient.
Cabin Volume	Prado and ML350 have significantly larger interior volumes, requiring higher BTU output and more engine power to maintain 20°C.
Refrigerant Type	R134a (all vehicles) provides a consistent thermal baseline across the fleet.
System Efficiency	Newer vehicles (G30 530i, Macan) benefit from optimized condenser designs and variable-speed electric fans, reducing the total electrical/mechanical draw.

Figure 33 Tabulated AC load factors

8.2.2 Estimated AC Load Impact

While I did not measure AC compressor power draw directly, industry data suggests:

- Variable displacement AC systems at steady-state highway cruise: **0.5–1.5 kW** parasitic load
- Fixed displacement systems: **2.0–3.0 kW** parasitic load
- At 100 km/h, 1 kW of AC load increases fuel consumption by approximately **0.2–0.3 km/L** for a typical petrol vehicle [14]

8.2.3 Implications for Results

The Jazz and Prado both equipped with older, fixed displacement AC compressors—likely experienced a higher AC parasitic penalty than the newer vehicles. However, given the magnitude of the observed efficiency gaps (the Jazz at 11.0 km/L vs. 530i at 20.0 km/L), AC load differences account for at most 0.5–1.0 km/L of the disparity. The primary efficiency drivers remain gearing and powertrain configuration.

8.3 Engine Thermal Equilibrium & Coolant Temperature

All vehicles reached and maintained stable coolant temperatures during testing, confirmed via on-board temperature gauges (where available) and qualitative observation.

8.3.1 Observed Thermal Behavior

BMW 730Ld

The diesel engine reached operating temperature within 3–4 minutes of highway driving. Coolant temperature stabilized at approximately 88–92°C and remained constant throughout the test. The electric water pump allowed precise thermal management without unnecessary parasitic draw.

BMW 530i

The B48 engine features an integrated exhaust manifold that routes exhaust heat into the coolant during warm-up, accelerating thermal equilibrium. At cruise, coolant temperature stabilized at 95–100°C a higher operating temperature that supports thermodynamic efficiency. The Stage 2 TCU tune does not alter thermal characteristics.

Mercedes ML350

The OM642 V6 diesel exhibited the slowest warm-up of the fleet due to its larger thermal mass and V6 configuration. However, by the start of the test run (post-fuel fill), the engine was fully warm. Coolant temperature stabilized at 85–90°C.

Porsche Macan

The EA888 engine uses a sophisticated thermal management system with separate coolant circuits for cylinder head and block. Warm-up was rapid, and coolant temperatures stabilized at 100–105°C the highest in the fleet consistent with Porsche's efficiency-focused thermal strategy.

Honda Jazz (Race Build)

The 2.0L R20A engine, transplanted from a Honda City, retained the Jazz's original cooling system. I monitored coolant temperature closely due to concerns about cooling capacity. Throughout all runs, coolant temperature remained stable at 85–90°C, indicating adequate cooling for highway cruise despite the elevated RPM. The full exhaust system may reduce under-hood temperatures slightly by evacuating exhaust gases more efficiently.

Toyota Prado

The 1GR-FE V6 uses a traditional mechanical fan clutch. At highway speeds, ram airflow through the radiator is sufficient, and the fan clutch disengages, minimizing parasitic loss. Coolant temperature stabilized at 85–90°C. The mechanical fan's engagement during low-speed operation does not affect highway test results.

8.3.2 Key Observation:

No vehicle exhibited coolant temperature instability or overheating during testing. All engines operated within their designed thermal operating ranges, ensuring that combustion efficiency was not compromised by suboptimal temperatures.

8.4 Thermal Impact on Fuel Consumption

The total thermal-related impact on fuel consumption across the fleet can be broken down into three components:

8.4.1 Engine Friction and Combustion Efficiency

At fully warm operating temperatures (85–105°C coolant), engine friction is minimized, and combustion efficiency is optimized. All vehicles operated in this regime throughout testing, eliminating thermal warm-up as a variable.

8.4.2 AC Compressor Parasitic Load

As noted, the Jazz and Prado likely incurred a higher AC penalty due to fixed displacement compressors and larger cabin volumes. I estimate the AC load penalty differential between the most efficient (530i) and least efficient (Jazz/Prado) AC systems at approximately 0.3–0.7 km/L; a measurable but secondary factor.

8.4.3 Cooling Fan and Auxiliary Loads

Modern vehicles with electric cooling fans (all except the Prado) cycle fans only when needed. At highway speeds, ram airflow typically satisfies cooling requirements, and electric fans remain off, imposing no parasitic load. The Prado's mechanical fan, even when disengaged, imposes a constant rotational drag estimated at 1–2 hp (0.75–1.5 kW) at highway RPM—a small but persistent penalty.

8.4.4 Thermal Contribution to Observed Efficiency Gaps

Vehicle	Thermal Factors	Estimated Impact on km/L	Dominant Non-Thermal Factor
BMW 730Ld	Efficient variable AC, electric fans	Neutral (baseline)	Diesel efficiency + gearing
BMW 530i	Efficient variable AC, electric fans, high coolant temp	Slight positive	TCU tune + aerodynamics
Mercedes ML350	Efficient variable AC, electric fans	Neutral	Weight + CdA
Porsche Macan	Efficient variable AC, electric fans, high coolant temp	Slight positive	PDK gearing
Honda Jazz	Fixed AC, undersized system relative to cabin	-0.3 to -0.7 km/L	Short-ratio gearbox (dominant)
Toyota Prado	Fixed AC, mechanical fan	-0.5 to -1.0 km/L	Weight + CdA + gearing

Figure 34 Thermal contribution

8.5 Conclusion on Thermal Factors

While thermal management and AC load contribute measurable differences to fuel consumption, they are **secondary variables** in this test. The 11.0 km/L result for the Jazz and 9.0 km/L for the Prado cannot be explained by thermal factors alone; these vehicles incur penalties from gearing (Jazz) and mass/aerodynamics (Prado) that dwarf the thermal contributions.

Conversely, the 530i's high operating temperature (100–105°C) and efficient AC system likely provide a small thermal efficiency benefit. Perhaps 0.2–0.5 km/L contributing to its ability to approach the 730Ld's diesel efficiency despite the petrol powertrain.

8.5.1 Thermal Management Summary

- Ambient temperature standardization (29–31°C) successfully eliminated seasonal and diurnal thermal variability
- AC load standardization (20°C, medium fan) provided consistent user settings, though actual compressor loads varied by vehicle
- All engines reached and maintained thermal equilibrium, ensuring combustion efficiency was not compromised
- Thermal factors contribute to efficiency differences but are secondary to gearing, aerodynamics, and powertrain configuration

9. Fuel Chemistry & Combustion Efficiency

The fuel used in each test serves as the energy input against which all efficiency calculations are measured. However, not all fuels deliver the same energy content per liter, and not all engines convert that energy to mechanical work with equal effectiveness. This section examines the chemical and combustion variables that influence the observed fuel economy results particularly the gap between diesel and petrol platforms, the implications of using regular fuel in tuned engines, and the role of remap calibration in part-throttle efficiency.

9.1 Fuel Source Standardization (Shell Regular)

I sourced all fuel from the same Shell station to ensure consistency in additive packages, fuel quality, and storage conditions. For petrol vehicles, I used Shell Regular Unleaded (91 RON, typical for the Indian market). For diesel vehicles (730Ld and ML350), I used Shell Regular Diesel.

9.1.1 Why This Matters:

Using the same station for all fills eliminates several potential variables:

- **Fuel batch consistency:** All fills occurred within a two-week window from the same storage tanks
- **Additive packages:** Shell's additive formulations are consistent across both fuel types at a given station
- **Storage and handling:** Temperature, humidity, and contamination risks are identical for all fills

9.1.2 Petrol Ethanol Content:

Shell Regular Petrol in India contains a small percentage of ethanol (typically 8–10%), [2] which reduces its volumetric energy density compared to pure petrol. This ethanol content is consistent across all petrol vehicles in the test (530i, Macan, Jazz, Prado), preserving comparative validity.

9.1.3 Diesel Consistency:

Shell Regular Diesel contains no ethanol and has consistent cetane numbers across batches. [2] Both diesel vehicles (730Ld and ML350) received fuel from the same pumps, eliminating any variability in diesel quality between the two.

9.2 Diesel vs. Petrol Energy Density Comparison

One of the most significant variables in this test is the inherent difference in energy content between diesel and petrol fuels. Diesel contains approximately 10–12% more energy per liter than petrol due to its higher carbon chain density and specific gravity. [3] [10] [11]

Typical Energy Densities:

Fuel Type	Energy Density (MJ/L)	Relative to Petrol
Petrol (91 RON, with 8–10% ethanol)	~32.0–32.5	Baseline
Diesel (regular)	~35.5–36.0	+10–12%

9.2.1 Implications for km/L Comparisons:

When comparing the 730Ld (22.5 km/L, diesel) and the 530i (20.0 km/L, petrol), the raw km/L figures understate the petrol engine's thermal efficiency. Adjusting for the energy density difference:

- If the 530i were powered by diesel with the same engine efficiency, its equivalent fuel economy would be approximately **22.0–22.5 km/L** virtually identical to the 730Ld.

This adjustment reveals that the thermal efficiency of the 530i's tuned petrol engine is remarkably close to that of the 730Ld's diesel, despite diesel's theoretical thermodynamic advantage (higher compression ratio, lean burn capability). The 530i's achievement is even more impressive given that it uses regular petrol (91 RON) rather than premium.

9.2.2 Energy-Adjusted Efficiency Perspective:

On an energy-equivalent basis, the 730Ld and 530i are effectively tied—a finding that highlights how gearing, aerodynamics, and transmission tuning can overcome the inherent energy density advantage of diesel.

For the ML350, its 16.0 km/L on diesel translates to approximately **14.5 km/L on a petrol-equivalent energy basis**, placing it slightly behind the Macan's 15.0 km/L in energy-adjusted terms. This reinforces the conclusion that the ML350's efficiency gap relative to the 730Ld is driven by vehicle architecture (weight, CdA, gearing) rather than fuel chemistry or powertrain calibration alone.

9.3 Octane/Cetane Implications for Tuned Engines

Both the 530i (Stage 1 ECU) and the ML350 (remapped diesel) are tuned engines that, in many markets, would be recommended to run higher-grade fuel. I tested both on regular fuel from the same Shell station 91 RON petrol for the 530i, regular diesel for the ML350. This decision reflects real-world usage patterns and ensures that the results are representative of how owners of tuned vehicles typically operate them.

9.3.1 BMW 530i: Stage 1 ECU on 91 RON

The B48 engine, in stock form, is calibrated for 91 RON minimum. The Stage 1 ECU tune increases boost pressure and advances ignition timing. On 91 RON, the engine's knock sensors may retard timing to prevent detonation, potentially reducing power and, in some cases, efficiency.

That the 530i achieved 20.0 km/L on regular fuel suggests either:

- The tune is conservatively calibrated for 91 RON, prioritizing reliability and part-throttle efficiency over peak power
- The engine's knock control system is sophisticated enough to maintain optimal timing under highway cruise conditions where engine load is moderate
- The benefits of the Stage 2 TCU tune (reduced transmission parasitic losses) offset any timing-related efficiency penalties

Had I used premium fuel (95 or 97 RON), the 530i might have achieved marginally better economy perhaps 0.2–0.5 km/L higher but the regular fuel result represents a realistic baseline for this configuration.

9.3.2 Mercedes ML350: Remapped Diesel on Regular Diesel

Diesel remaps typically increase injection pressure and modify injection timing. Unlike petrol engines, diesels are not knock-limited, and fuel cetane ratings have less impact on steady-state power output. However, higher cetane fuel (premium diesel) can improve cold-start behavior and reduce combustion noise; its impact on steady-state highway economy is minimal.

The ML350's 16.0 km/L result on regular diesel is therefore representative of what an owner running standard fuel would experience. The gap between the ML350 and the 730Ld (22.5 km/L) cannot be explained by fuel quality; it is fundamentally a function of vehicle architecture mass, aerodynamics, and gearing.

9.3.3 Honda Jazz: Tuned 2.0L on 91 RON

The Jazz's 160 hp tune is calibrated for 91 RON, as the donor City engine was designed for regular fuel. No octane-related efficiency penalty applies.

9.3.4 Toyota Prado and Porsche Macan: Stock Engines on 91 RON:

Both vehicles are calibrated for regular petrol from the factory. Their results (9.0 km/L and 15.0 km/L respectively) represent baseline performance on standard fuel with no tuning variables.

9.4 Remap Calibration & Part-Throttle Efficiency

A critical distinction in tuning philosophy is whether a remap prioritizes peak power or overall drivability, including part-throttle efficiency. The two tuned vehicles in this fleet the 530i and the ML350 represent different approaches, and the fuel economy results reflect these differences.

9.4.1 BMW 530i: Stage 1 ECU + Stage 2 TCU: Balanced Calibration

The 530i's tune demonstrated exceptional part-throttle behavior during testing:

- **Smooth power delivery:** Throttle response was linear, with no surging or hesitation at steady-state cruise
- **TCU synergy:** The transmission calibration complemented the ECU tune, keeping the engine in its most efficient operating range and preventing unnecessary downshifts
- **Part-throttle mapping:** The tune appeared optimized for efficiency at low-to-moderate load, with power reserves accessible only when demanded

This suggests the tuner prioritized drivability and part-throttle efficiency alongside peak power gains. The result is a vehicle that delivers both increased performance (when demanded) and stock-like or better highway efficiency.

9.4.2 Mercedes ML350: Remapped Diesel: Power-Focused Calibration

The ML350's remap exhibited different characteristics:

- **Pronounced mid-range torque:** The tune delivered a noticeable surge of power when accelerating, indicating focus on peak torque delivery
- **No observable efficiency optimization:** At steady-state cruise, the remap did not appear to alter part-throttle behavior significantly from stock
- **Transmission interaction:** The 7G-Tronic's behavior was unchanged, and the torque converter remained unlocked under conditions where the ZF 8HP would lock

The ML350's remap appears calibrated primarily for increased power output rather than efficiency. While this delivers a tangible performance benefit (300 hp, 650 Nm), it does not improve and may slightly compromise highway fuel economy relative to a well-calibrated stock diesel.

9.4.3 The Efficiency-Focused Tuning Lesson:

The contrast between the 530i and ML350 results highlights an important principle:

tuning for efficiency is a deliberate calibration choice.

A remap focused solely on peak power may leave part-throttle efficiency unchanged or degraded, while a holistic tune that addresses both ECU and TCU calibration can preserve or enhance fuel economy while delivering performance gains.

The 530i's 20.0 km/L result suggests that a tuned petrol vehicle with favorable gearing and transmission behavior can approach the measured highway fuel economy of the diesel benchmark under the present test conditions.

10. Practical Highway Efficiency Implications

Hypermiling has developed a reputation for extremes: driving at dangerously low speeds, disabling air conditioning, pulse-and-glide maneuvers that disrupt traffic, and drafting behind trucks. This study was conceived from a different premise:

This paper examines whether meaningful highway fuel-economy gains can be achieved under normal comfort and safety constraints.

The test protocol 80–100 km/h, AC at 20°C with medium fan, a deliberate acceleration-coast driving technique was designed to answer this question. The results demonstrate that significant efficiency gains are achievable without the compromises typically associated with hypermiling. [14]



Figure 35 Representative high-efficiency production vehicles

10.1 Definition of Highway Cruise Efficiency

Traditional hypermiling often prioritizes measures that this study deliberately avoided. Instead of reducing speed to 60–70 km/h, I maintained 80–100 km/h to preserve traffic flow and safety.

Instead of disabling AC, I ran it at 20°C because the load is secondary to gearing and aerodynamics, and comfort improves driver consistency. Instead of extreme tire pressures, I used OEM specifications that balance rolling resistance, safety, and wear. Instead of drafting, I maintained independent speed.

10.1.1 The Core Insight

The 20.0 km/L achieved by the 530i and 22.5 km/L by the 730Ld were not products of extreme technique. They came from vehicle selection prioritizing low CdA, efficient transmissions, and optimized gearing combined with transmission awareness, throttle discipline, and a deliberate acceleration-coast strategy that leveraged deceleration fuel cutoff.

10.2 Platform Influence on Fuel Economy

The 9.0–22.5 km/L spread across the test fleet confirms that vehicle choice determines the efficiency ceiling. No amount of driving technique can make a Prado perform like a 730Ld.

The optimal tier 730Ld and 530i combine low CdA, tall gearing, efficient transmissions, and either diesel or optimized petrol powertrains, delivering 20.0–22.5 km/L. The moderate tier ML350 and Macan represents SUV architecture with competent but not exceptional transmissions, delivering 15.0–16.0 km/L. The Jazz falls into a compromised tier; its short-ratio gearbox negates its low mass and imposes a severe penalty. The Prado sits at the inefficient tier, burdened by high mass, high CdA, and a dated transmission.

10.2.2 Key Takeaway

Start with the right platform. A sedan with low CdA and a transmission featuring tall gearing and aggressive torque converter lockup provides a foundation that driving technique can build upon.

10.3 Impact of Speed Variation Strategy

A defining element of this study's methodology was the specific driving technique used during all test runs. I employed a deliberate acceleration-coast cycle: accelerating smoothly from 80 km/h to 100 km/h using moderate throttle, then allowing the vehicle to coast naturally down to 80 km/h without braking and without downshifting. This cycle was repeated continuously. Occasional overtaking required brief acceleration beyond 100 km/h, after which I resumed the cycle.

10.3.1 Why This Technique Works

During the coast phase, modern fuel-injected vehicles employ deceleration fuel cutoff the ECU cuts fuel entirely when the vehicle is in gear, throttle is closed, and RPM is above a threshold. The engine consumes zero fuel while the vehicle maintains momentum. Additionally, spending less time at 100 km/h reduces average aerodynamic drag, since drag increases with the square of speed. Gentle throttle application avoids enrichment zones in the engine mapping, and the technique encourages torque converter lockup while preventing unnecessary downshifts.

10.3.2 Measured Gains

Compared to constant 100 km/h cruising (estimated from steady-state segments), the acceleration-coast technique yielded gains of 1.0–1.5 km/L for the 730Ld and 530i, and 0.5–1.0 km/L for the Jazz. Unlike traditional pulse-and-glide, this technique maintains safe highway speeds, uses no neutral coasting, employs no braking, and is legal everywhere.

10.4 Influence of Transmission Calibration

The 530i's Stage 2 TCU tune enabling earlier torque converter lockup and preventing unnecessary downshifts suggests that transmission behavior is as important as engine efficiency.

For drivers without TCU tuning, adopting a similar style yield gain. Encourage lockup with steady throttle inputs; small lifts can cause unlocking. Anticipate grades allow slight speed loss rather than adding throttle that triggers a downshift. Understand your transmission's logic and drive to work with it, not against it.

10.5 Effect of Operating Speed on Drag Losses

This speed range represents the intersection of efficiency, safety, and practicality. Below 80 km/h, highway travel becomes hazardous. Above 100 km/h, aerodynamic drag increases exponentially.

At 90 km/h, drag increases 27% over 80 km/h; at 100 km/h, it increases 56%. The Hypermiler's strategy should favor the lower end of the range 80–90 km/h when conditions permit. Accept slight speed loss on inclines rather than adding throttle to maintain exact speed.

10.6 Consideration of Accessory Loads

This study deliberately ran AC at a comfortable setting, challenging hypermiling dogma that treats AC as unacceptable.

Based on prior literature and general system behavior, AC load is expected to impose a modest penalty; however, this effect was not isolated experimentally in the present study. Older fixed displacement systems (Jazz, Prado) impose 0.5–1.0 km/L. However, a 530i with AC on still outperforms an ML350 with AC off. The penalty is modest and secondary to vehicle selection and driving technique. Run AC comfortably; the marginal gain from disabling it is dwarfed by other factors.

10.7 Calibration Effects on Cruise Efficiency

The 530i's 20.0 km/L challenges the assumption that tuning compromises economy. The Stage 1 ECU preserved part-throttle lean mixtures; the Stage 2 TCU prioritized lockup and prevented unnecessary downshifts. The result was near-diesel efficiency with increased power available when demanded.

Conversely, the Jazz's race build suggests the opposite. The short-ratio gearbox is likely a major contributor to its 50% penalty relative to stock, elevating cruising RPM beyond 4,000 and pushing the engine outside its optimal efficiency range. Modifications focused solely on performance impose penalties that no driving technique is unlikely to fully offset.

10.8 Operational Efficiency Recommendations

1. **Choose the right vehicle.** Prioritize low CdA, tall gearing, and an efficient transmission. The difference between optimal and inefficient platforms can be 50–100%.
2. **Know your transmission.** Understand lockup behavior and downshift thresholds. Avoiding unnecessary downshifts and encouraging lockup yields 5–15% improvement.
3. **Employ the acceleration-coast technique.** Accelerate gently from 80 to 100 km/h, then coast in gear to 80 km/h. This leverages fuel cutoff and reduces average drag, yielding 1.0–1.5 km/L gains.
4. **Maintain steady speed within your chosen band.** Accept slight speed loss on grades rather than adding throttle to maintain exact speed.
5. **Run AC at a comfortable setting.** The penalty of 0.2–1.0 km/L is secondary to gains from vehicle selection and driving technique.
6. **Use OEM tire pressures.** No extreme inflation needed.
7. **Consider TCU tuning if modifying.** Transmission calibration is as important as engine calibration for highway efficiency.
8. **Avoid short-ratio gearboxes if highway driving is a priority.** The Jazz's experience suggests a 30–50% penalty that no driving technique can overcome. [14]

10.9 Interpretation of Highway Efficiency Results



Figure 36 Aerodynamically modified Honda Insight featuring an extended rear for drag reduction.

This study suggests that hypermiling need not be an exercise in sacrifice. The 530i achieved 20.0 km/L and the 730Ld achieved 22.5 km/L under normal, comfortable conditions: highway speeds of 80–100 km/h, AC at 20°C, and a driving technique requiring no extreme maneuvers.

The real gains came from vehicle selection, transmission awareness, the acceleration-coast technique, speed discipline, and throttle smoothness not from disabling AC or driving at unsafe speeds.

The Jazz serves as a cautionary tale: performance-focused modifications impose penalties no driving technique can overcome. The 530i suggests that with proper calibration, a vehicle can deliver both performance and efficiency.

11. Final Conclusion & Engineering Recommendations

This study set out to answer a simple question:

What does real-world highway fuel efficiency look like across a diverse range of vehicles under controlled conditions that prioritize comfort, safety, and practicality?

The answer, drawn from six vehicles and three test runs each, reveals that efficiency is a complex interplay of vehicle architecture, gearing, transmission calibration, driving technique, and the choices made by manufacturers and modifiers.

11.1 Summary of Key Findings

The Efficiency Spectrum is Wide. From the Prado's 9.0 km/L to the 730Ld's 22.5 km/L, the fleet demonstrated a 150% spread under identical conditions. Vehicle selection is the single most consequential decision an efficiency-minded buyer can make.

Gearing Dominates All. The Jazz's 11.0 km/L result despite its low mass and respectable CdA stands as the clearest finding. The short-ratio gearbox elevated cruising RPM beyond 4,000, imposing a 50% penalty relative to a stock configuration. Gearing optimized for acceleration exacts an unforgiving toll at highway speeds.

Transmission Calibration Matters as Much as Engine Efficiency. The 530i's Stage 2 TCU tune enabling earlier torque converter lockup and preventing unnecessary downshifts contributed significantly to its 20.0 km/L result. Transmission behavior is an underappreciated lever for efficiency.

A Well-Tuned Petrol Can Approach Diesel Efficiency. On an energy-equivalent basis, the 530i's 20.0 km/L is virtually identical to the 730Ld's 22.5 km/L. Modern petrol engines, with optimized gearing and transmission calibration, can achieve thermal efficiency approaching diesel.

SUV Architecture Carries a Persistent Penalty. The ML350 and Macan clustered at 15.0–16.0 km/L, a 25–30% penalty relative to the sedans. Higher CdA and mass impose a gap that powertrain improvements alone cannot close.

Hypermiling at Highway Speeds Is Achievable. The acceleration-coast technique accelerating from 80 to 100 km/h, then coasting in gear back to 80 km/h yielded gains of 1.0–1.5 km/L over constant-speed cruising, achieved without sacrificing comfort, safety, or traffic courtesy.

11.2 Engineering Recommendations

11.2.1 For Vehicle Manufacturers

- Prioritize tall gearing in top gear. The 730Ld's overall ratio of 1.88 enabled 1,450 rpm at 100 km/h and should serve as a benchmark.
- Optimize torque converter lockup strategy. The ZF 8HP's aggressive lockup significantly reduces parasitic losses. [9]
- Consider CdA as a primary design metric. The 530i's 0.57 m² suggests exceptional aerodynamic efficiency.
- Offer selectable transmission modes, including an "efficiency" mode with aggressive lockup and minimized downshifts.

11.2.2 For Tuners and Modifiers

- Calibrate for part-throttle efficiency, not just peak power. The 530i's tune seems to have preserved lean mixtures at low loads.
- Prioritize TCU tuning alongside ECU tuning. Transmission calibration yielded measurable efficiency gains.
- Warn clients of the highway penalty from short-ratio gearboxes. The Jazz's 50% penalty suggests a trade-off that should be understood before modification.

11.2.3 For Hypermilers and Efficiency-Minded Drivers

- Start with the right vehicle. A sedan with low CdA and tall gearing provides a foundation no driving technique can replicate from an inefficient platform.
- Learn your transmission. Understand lockup and downshift behavior, and drive in a way that encourages efficiency.
- Use the acceleration-coast technique. Accelerate gently to 100 km/h, coast in gear to 80 km/h. This leverages fuel cutoff and reduces average drag.
- Run AC comfortably. The penalty of 0.2–1.0 km/L is secondary to gains from vehicle selection and driving technique.
- Accept slight speed loss on grades. Adding throttle to maintain exact speed often triggers downshifts and enrichment.

11.2.4 For the Performance Enthusiast Who Also Values Efficiency

- Consider a dual-purpose build. The 530i suggests that proper calibration can deliver both performance and efficiency.
- Avoid short-ratio gearboxes if highway driving is a priority. Accept the penalty knowingly rather than discovering it after the build.
- Invest in transmission tuning. The TCU tune delivered gains that were measurable in both driving quality and fuel economy.

11.3 Limitations and Opportunities for Future Research

1. **OBD-II Telemetry:** Real-time data on engine load, fuel trim, and transmission behavior would enable deeper analysis of *why* certain vehicles performed as they did.

2. **Stock Baselines:** Testing the 530i and ML350 in stock configuration would quantify the exact contribution of the tunes. A stock Jazz would isolate the gearbox penalty.
3. **Expanded Fleet:** Adding a modern hybrid and a pure EV would anchor the dataset against current efficiency benchmarks.
4. **Controlled Grade Testing:** The flat ECR route was ideal for consistency, but varied terrain would reveal how different vehicles perform under load.

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