A New Metric for Measuring Progress in Vehicle Technology

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Objectives

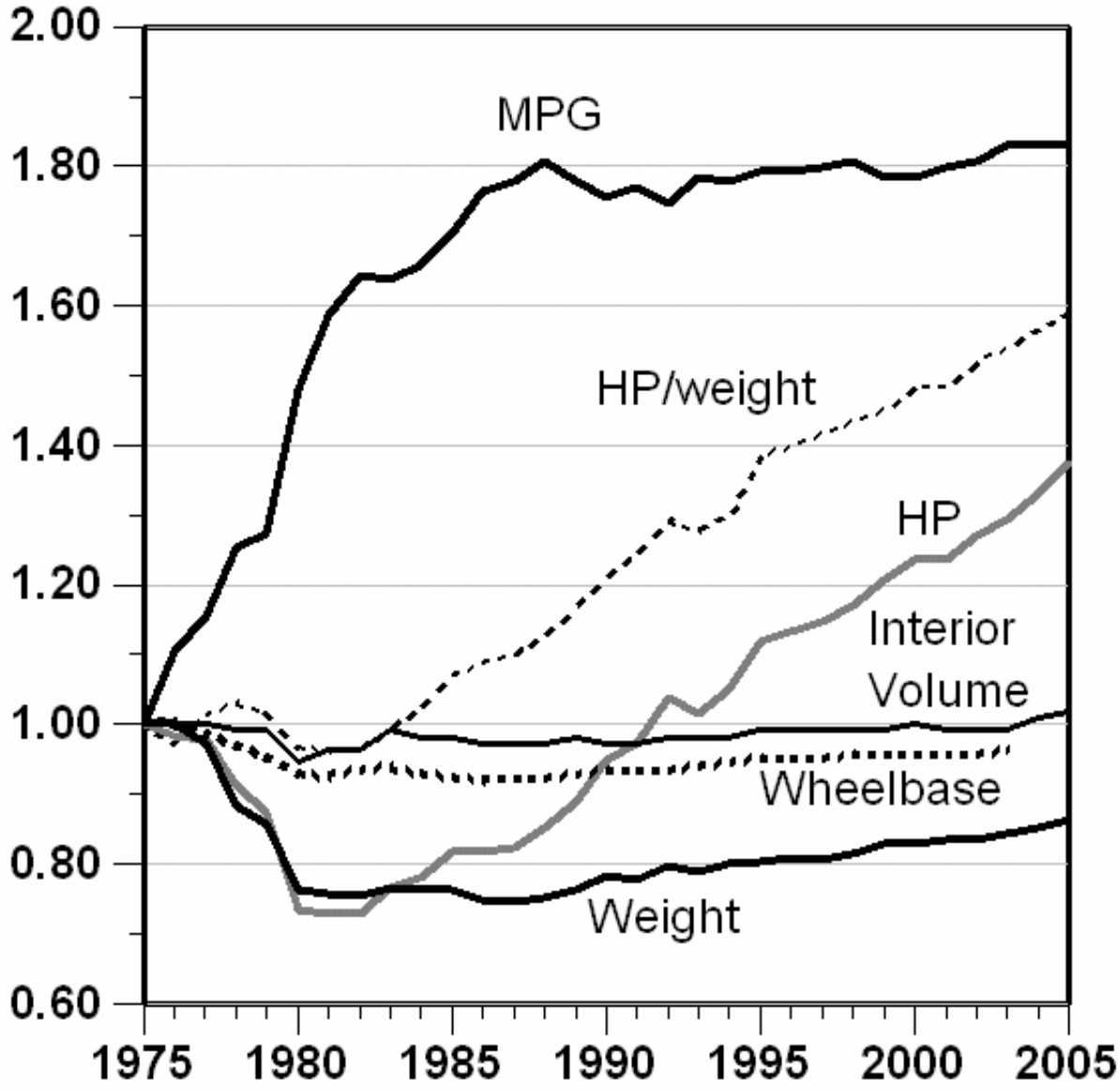
- Context is analysis of potential for automobile (car and light truck) efficiency improvement
  - Environmental concerns (GHG emissions)
  - Energy security concerns (oil consumption)
- Distinguish technical *efficiency* vs. *fuel economy*
  "The fuel efficiency of autos is continually increasing." (AAM 2005)
- Can we observe an intrinsic trend in automobile technical efficiency from historical data?

Approach

- Review past work related to the question
- Exploratory analysis of historical aggregate data for U.S. cars and light trucks 1975-2005
  - EPA Fuel Economy Trends report (most parameters)
  - ORNL Transportation Energy Data Book (wheelbase)
- Examine combinations of available parameters guided by physical insight
  - consider “service” provided by a vehicle for a given unit of energy consumption

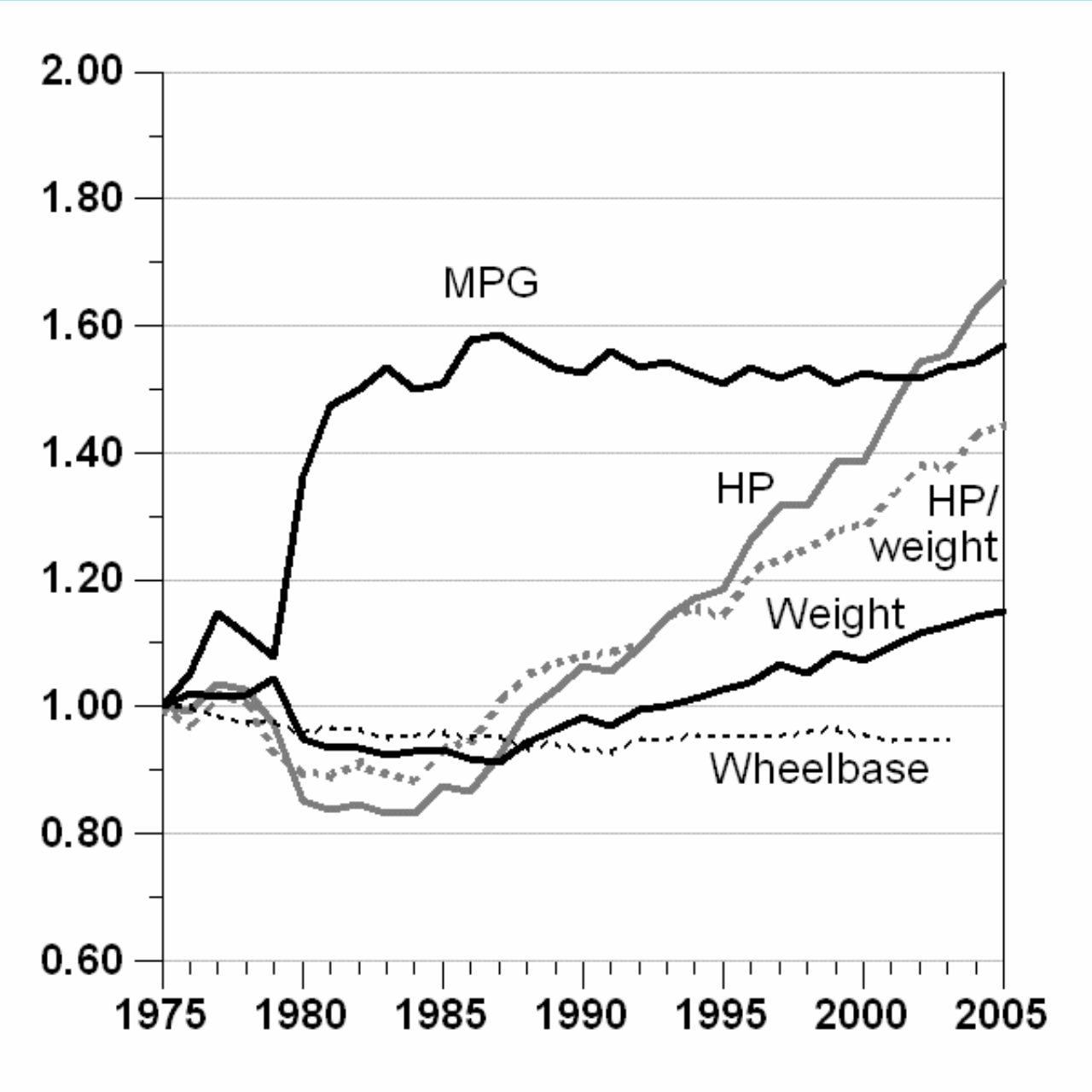
Trends in New Car (& wagon) Attributes

Index 1975=1



Trends in New Light Truck Attributes

Index 1975=1



New Light Duty Vehicle Fuel Economy and Ton·MPG

Fit by authors:

slope = 0.45 (±0.02) ton·mpg per year

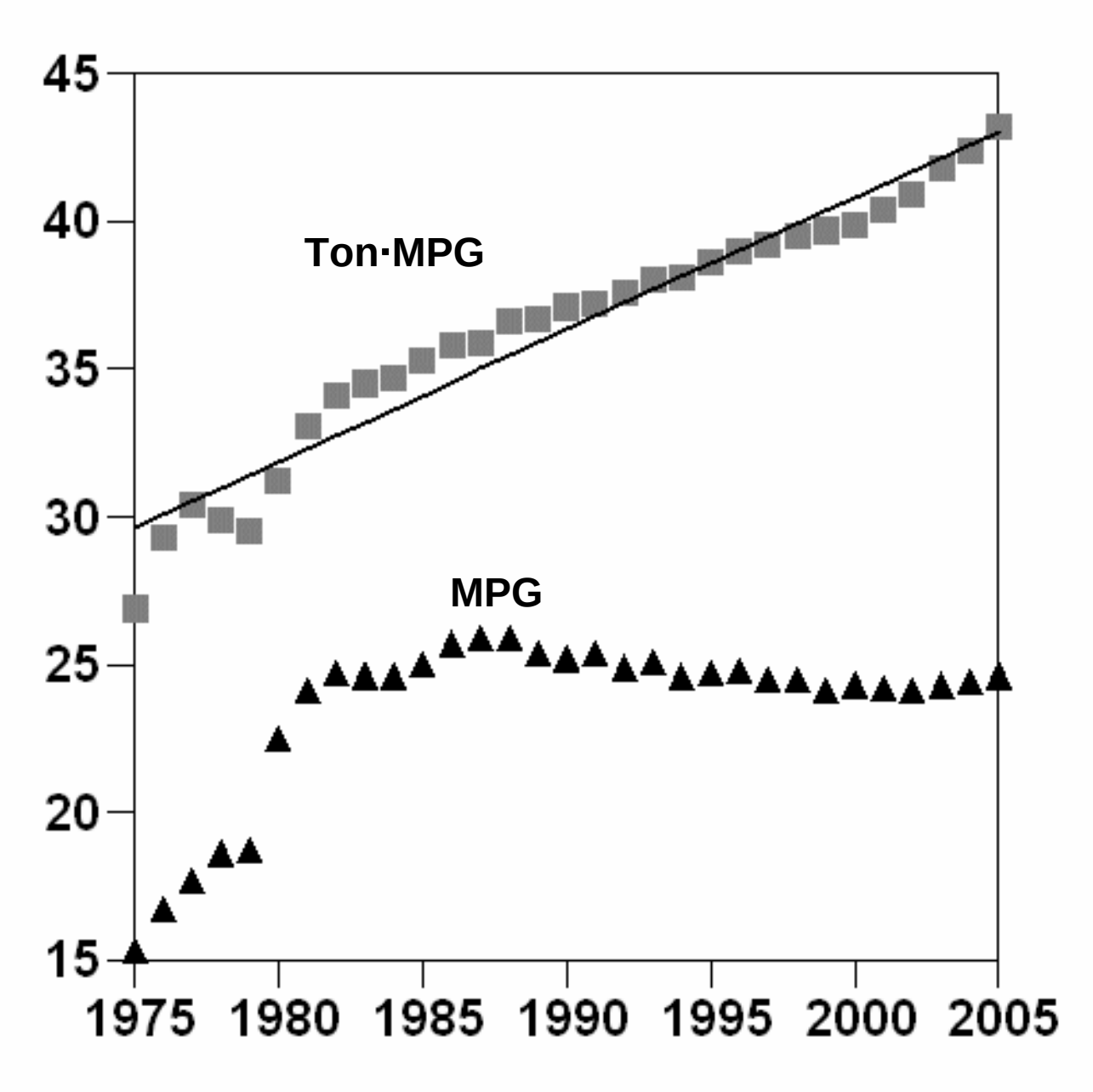
r^2 = 0.95

ton·mpg annual growth rates:

3.4%/yr 1975–1982

1.0%/yr since 1982

1.6%/yr since 1975



Data from Table 1 of Heavenrich (2005)

Efficiency Index Concept

- In general, a ratio of end-use service (utility) to energy input
  - e.g., Miles *(service)* per Gallon *(energy)*
- Fuel economy trades off against many other attributes related to services a vehicle provides
- A broader efficiency index can be constructed by incorporating other such service attributes
  - Performance (e.g., HP/weight ratio; others possible)
  - Capacity (a size measure, e.g., volume or wheelbase)

Limitations of ton·mpg Index

- More suitable for commercial vehicles, where service can be defined as carrying goods (or weight).
- For personal vehicles, service is better defined as performance and vehicle room or cargo space (size).
- Performance is a key aspect of powertrain efficiency, but ton·mpg does not itself differentiate fast and slow vehicles. The ton·mpg index fails to capture the remarkable gains in performance that have come from the recent round of “horsepower wars.”
- Mass efficiency refers to how well a vehicle delivers its services without excess mass. Ton·mpg fails to reflect such progress, which has occured through lightweight materials, advances in design and fabrication techniques, and improved packaging.

Performance · Size · Fuel economy Index

- Represents the ability to move a given size vehicle with a given performance level per unit of energy:

$$\frac{\text{service}}{\text{energy}} = \frac{(\text{performance})(\text{size})(\text{distance})}{(\text{gallons})}$$

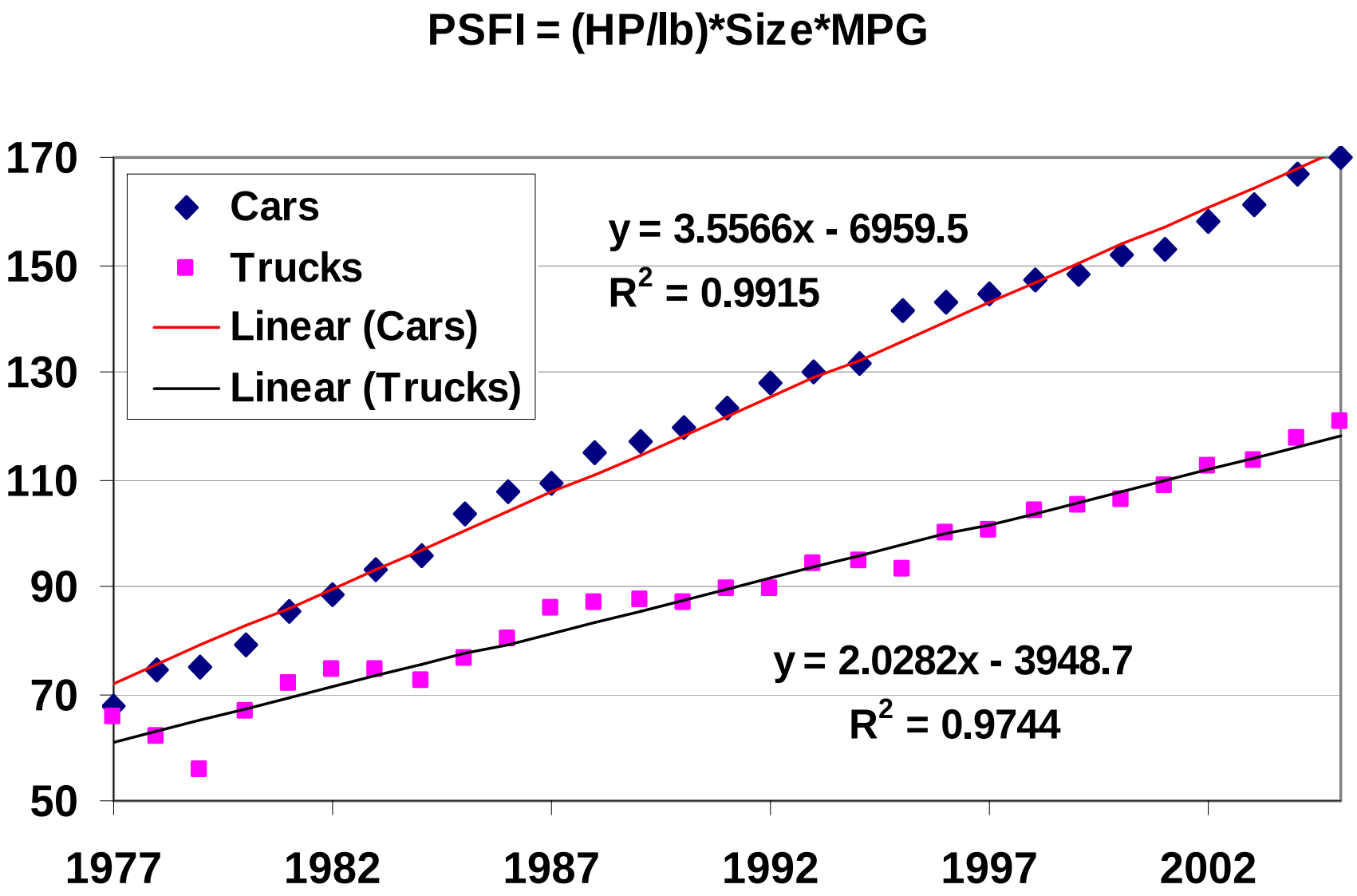
PSFI = (HP/LB)(FT^3)(MPG) for cars

PSFI = (HP/LB)(IN)(MPG) for light trucks

where size metrics are interior volume (ft^3) for cars and wheelbase (inches) for light trucks.

Note: An index such as this reflects all effects on aggregate fleet outcomes, including fleet mix, other vehicle amenities, economic factors, and so on -- not just engineering interactions.

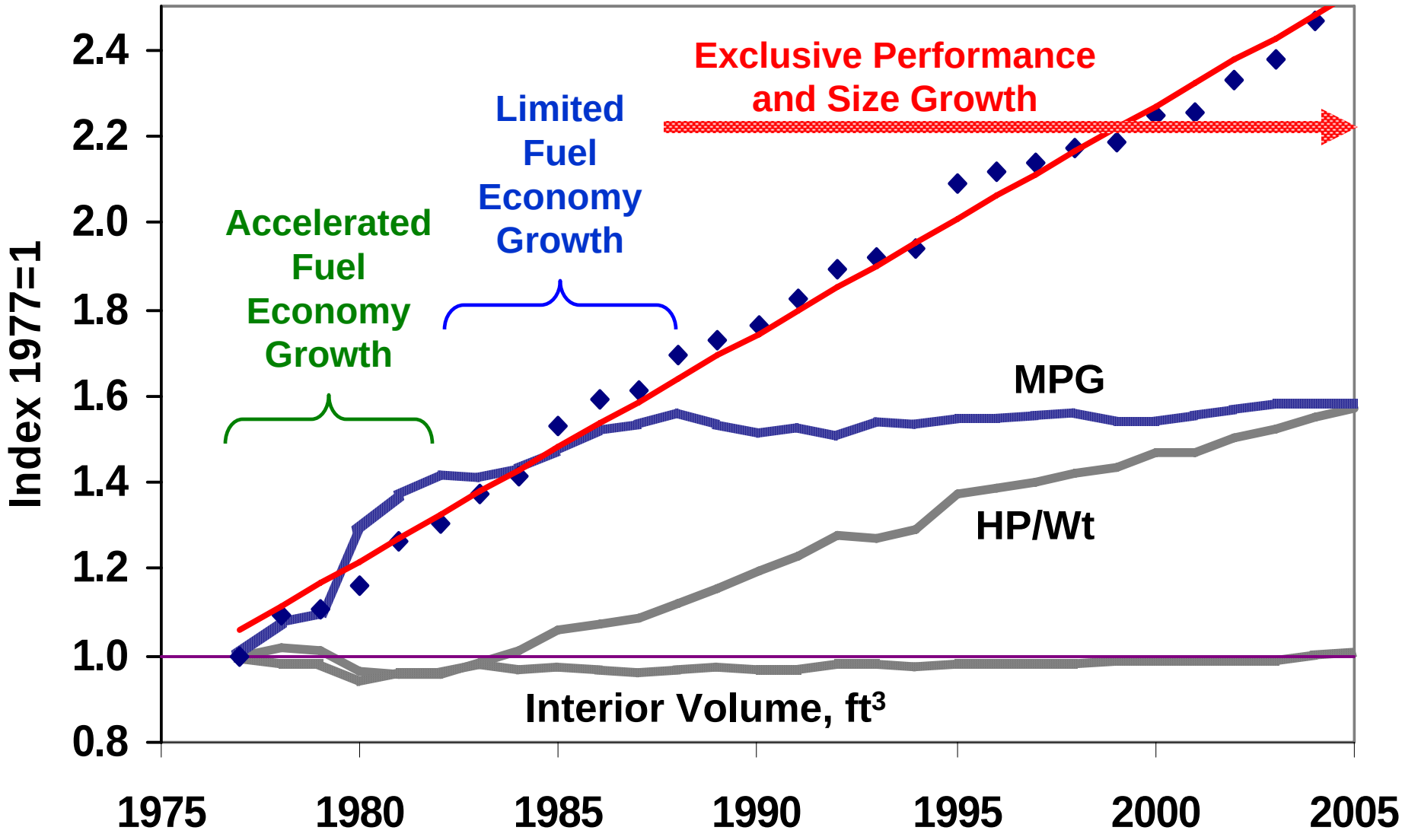
PSFI Trends and Linear Fit



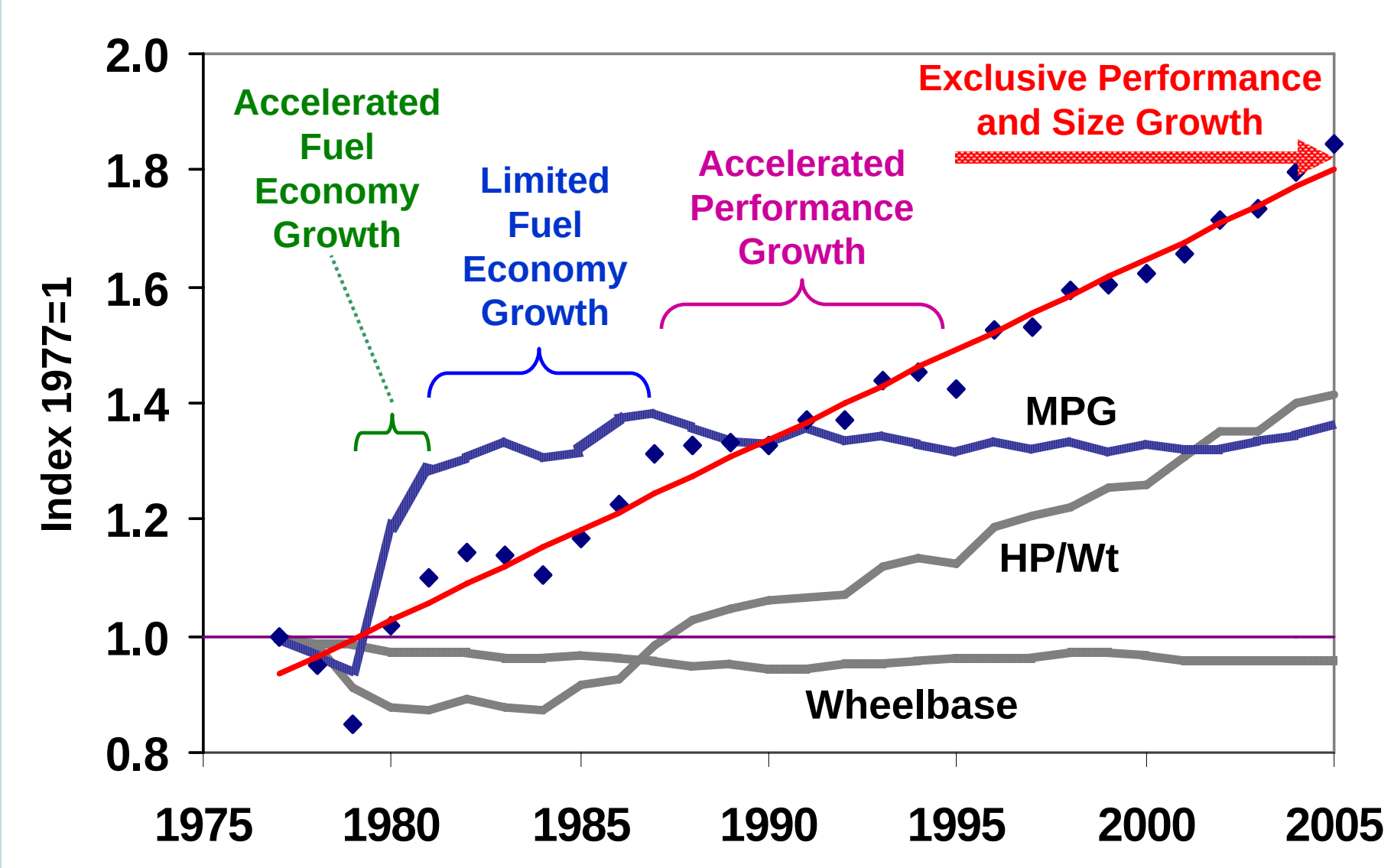
Light Trucks: Size Data Limitations

- The only readily available aggregate data series is for wheelbase
- Since mid-1980's (introduction of the minivan, followed by the truck-based SUV), significant customer-valued capacity enhancement has been seen in light trucks.
- Wheelbase is likely to significantly understate the size-related increases in vehicle amenity that trade off with fuel economy and performance.

Normalized PSFI and its factors, Cars 1977-2005



Normalized PSFI and its factors, Light Trucks 1977-2005

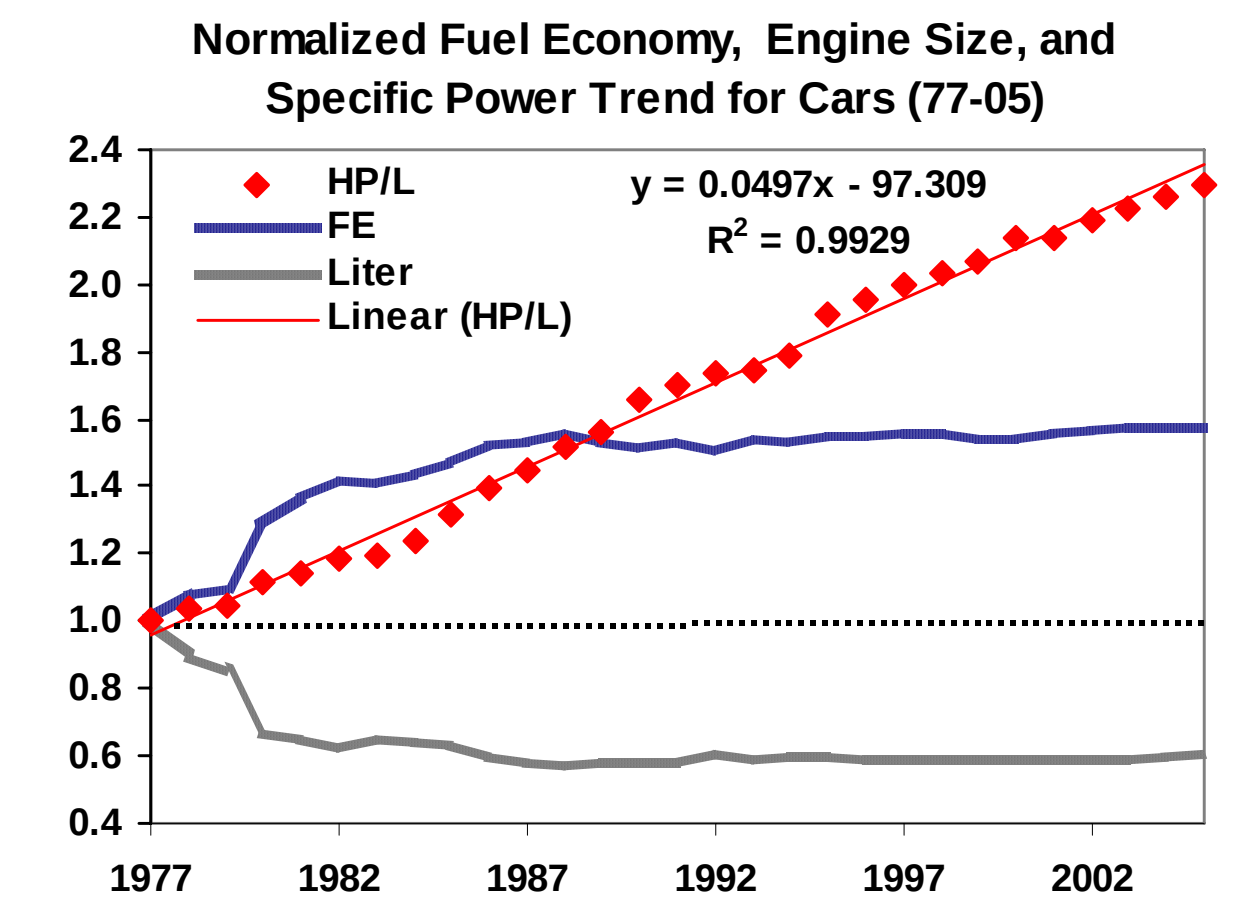


Phases of Technical Efficiency Improvement

Different design priorities yield different emphases among potential the benefits of technology improvement:

- Accelerated fuel economy growth, at expense of other attributes such as size and performance
- Limited fuel economy growth, along with gains in other attributes
- Exclusive performance and size growth, with fuel economy largely unchanged
- Accelerated performance and size growth, at expense of fuel economy
- **Exclusive fuel economy growth**
  - **common assumption for technology assessment, but …**
  - **not clearly observed in historical market outcomes**

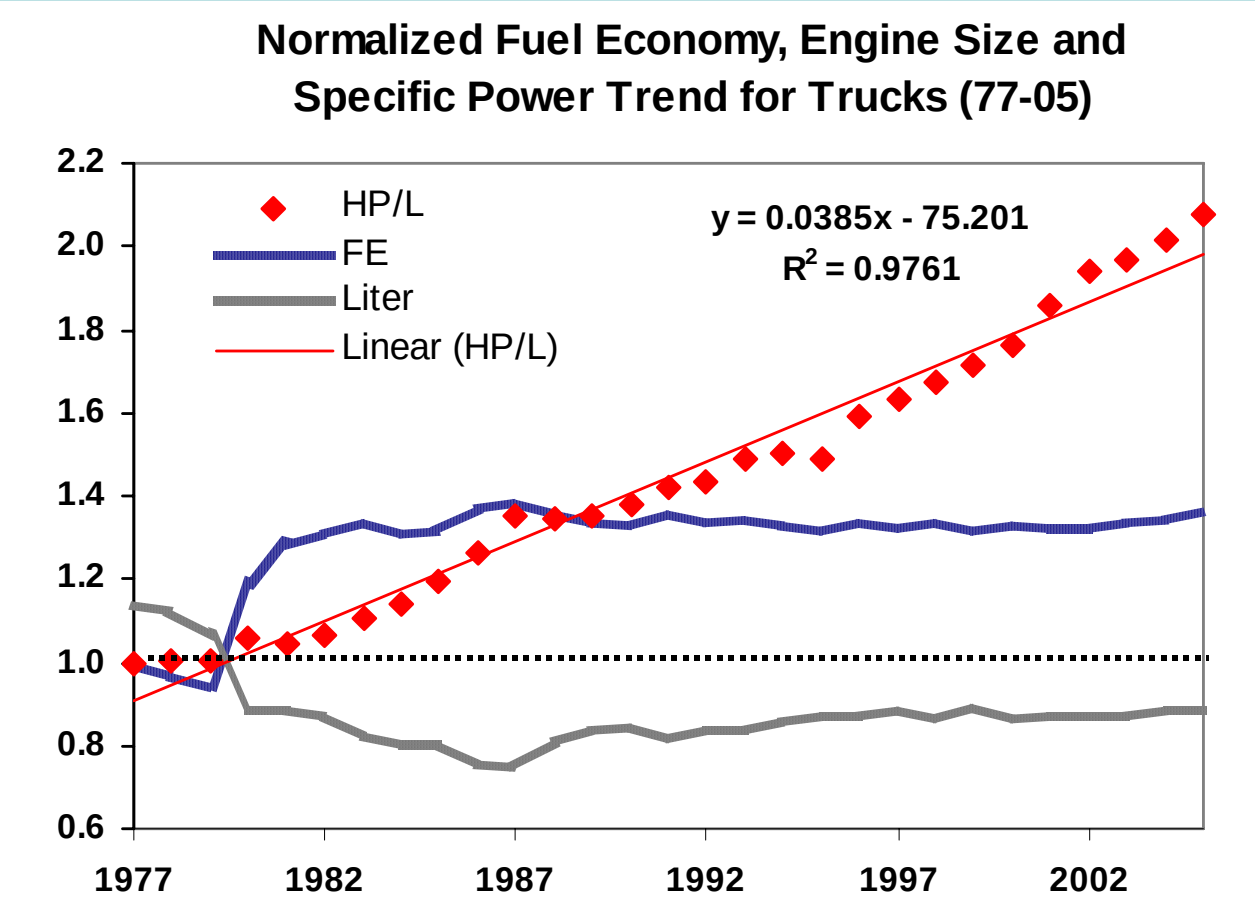
Linear Trend Is Consistent with Trends in Engine Specific Power (cars shown here)



Engine specific power (HP/L) has increased linearly at 5.5% annually for cars since 1975.

- Physical model shows that fuel economy is primarily a function of engine size and vehicle mass.
- Thus, fuel economy directly trades-off against engine size.
- Cars have seen no engine downsizing since 1988 – it's been an era of "horsepower wars."

Engine Specific Power Trends for Light Trucks



- Less uniform than the car trend, but presents the same general picture.
- No light truck engine downsizing after 1987; since then there has been a modest upsizing trend in most years.
- Nearly 20 years of a "horsepower war," along with upsizing and upweighting.

For light trucks, engine specific power (HP/L) has increased at a 4.3% annual linear rate on average since 1975.

Implications of a Linear PSFI Trend

- Are observed trends in these factors linked to an underlying rate of technical efficiency gain?
- If so, then a linear model suggests trade-offs:

PSFI = P·S·F = a + bt where t = time (years)

$$\frac{\partial F}{\partial t} = \frac{\hat{b}}{P \cdot S}$$

The rate of fuel economy improvement (consistent with observed historical trends) may be inversely related to absolute levels of performance and size.

PSFI Slope Estimates

- Cars: **3.56 (±0.06)** [HP/lb] · ft^3 · MPG / year
- Light Trucks: **2.03 (±0.06)** [HP/lb] · in · MPG / year

The implied, trends-continued rates of "exclusive" fuel economy improvement depend on base year levels of size and performance:

	Implied MPG gain/year (and %/year)		
base year:	1980	1988	2005
Cars	**1.06** (4.5%)	**0.89** (3.1%)	**0.61** (2.1%)
Light Trucks*	**0.57** (3.0%)	**0.50** (2.3%)	**0.36** (1.7%)

**N.B. – Light truck values are under-estimated because wheelbase understates the size gain from market shifts to minivans and SUVs.*

Conclusions

- Exploratory analysis suggests new approach for viewing historical trends in fuel economy and related attributes.
- Observed linear trends in a Performance • Size • Fuel economy Index (PSFI) provide evidence for a hypothesized underlying technical efficiency trend.
- Data limitations imply guarded interpretations, especially for light trucks (where wheelbase is a poor size metric).
- The common analytic assumption of exclusive fuel economy growth was not observed historically.
- **Further analysis is needed:**
  - **Link to physical modeling and technology considerations.**
  - **Better data need and opportunities to explore other definitions of technical efficiency given additional data.**