Jevons' Paradox in a Supply and Demand Model

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Jevons' paradox is the possibility that an improvement in resource efficiency increases total use of the resource. The key distinction is between the *resource* and the *service* produced with it. For example, gasoline is a resource, while vehicle travel is the service; GPU compute is a resource, while AI output is the service.

The mechanism consists of two opposing effects. First, the *engineering effect*, where improved efficiency means each unit of the service requires less of the resource. Second, the *demand effect*: improved efficiency lowers the service price, which increases the quantity demanded for the service, and hence the quantity demanded for the resource. The engineering view holds service demand fixed, while the economic view allows demand for the service to vary with efficiency.

Jevons' paradox occurs when service demand rises proportionately more than efficiency. Improved efficiency leads to increased resource use when demand for the service is elastic, meaning the quantity demanded is relatively responsive to a decrease in price. When service demand is inelastic, higher efficiency leads to decreased resource use.

The engineering view takes service demand to be perfectly inelastic, so consumers demand the same quantity of service regardless of price; in this case, improved efficiency always reduces resource use. The 'paradox' occurs only to the non-economist.

1 Fuel efficiency

Let q denote the service of miles traveled, let R denote the resource in gallons of gasoline, and let η denote fuel efficiency in miles per gallon. Thus,

$$\eta = \frac{q}{R}.$$

Let p be the price of travel in dollars per mile and let w be the price of gasoline in dollars per gallon.

Demand for travel is

$$q^d(p) = Ap^{-\varepsilon},$$

where $A > 0$ and $\varepsilon > 0$. This is consumers' demand for miles traveled as a function of the price per mile.

Supply of fuel is

$$R^s(w) = Bw^{\sigma}, \qquad \sigma > 0.$$

This is producers' supply of gallons of gasoline as a function of the price per gallon, with $B > 0$.

The travel and fuel markets are linked by two equations. First, the production function converting gasoline into travel:

$$q = \eta R, \qquad R = \frac{q}{\eta}.$$

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Second, assuming gasoline is the only variable input, the marginal cost of one mile of travel is the efficiency-adjusted price of gasoline:

$$p = w/\eta.$$

1.1 The service market: vehicle travel

The travel-market graph has dollars per mile, p, on the vertical axis and miles traveled, q, on the horizontal axis. Again, the demand function for miles traveled is:

$$q^d(p) = Ap^{-\varepsilon},$$

Travel demand is primitive, but travel supply is derived from gasoline supply and the fuel-efficiency technology. Invert the gasoline-supply curve to obtain the gasoline price required to elicit the quantity R:

$$w^s(R) = \left(\frac{R}{B}\right)^{1/\sigma}.$$

Supplying q miles requires $R = q/\eta$ gallons. With gasoline as the only variable input and no markup, the marginal cost of another mile is the price of the gasoline used for that mile: $p = w/\eta$. Hence,

$$p^s(q;\eta) = \frac{w^s(q/\eta)}{\eta}.$$

Substituting inverse gasoline supply gives the inverse travel-supply curve:

$$p^s(q;\eta) = \frac{1}{\eta}\left(\frac{q/\eta}{B}\right)^{1/\sigma} = B^{-1/\sigma}q^{1/\sigma}\eta^{-(1+\sigma)/\sigma}.$$

Equivalently, direct travel supply is

$$q^s(p;\eta) = \eta R^s(\eta p) = B\eta^{1+\sigma}p^{\sigma}.$$

An individual travel supplier takes w as given and has marginal cost w/η. Aggregate travel supply nevertheless slopes upward because supplying more travel requires more gasoline, and the gasoline price needed to induce that supply rises with q. Higher fuel efficiency lowers $p^s(q;\eta)$ at every q, or equivalently shifts $q^s(p;\eta)$ to the right.

When efficiency increases, the travel price p falls at a given q due to two effects. First, the engineering effect, where each unit of travel requires less gas. Second, at a fixed q, gasoline demand falls, so the gasoline price w is lower.

Equating travel demand and travel supply gives

$$Ap^{-\varepsilon} = B\eta^{1+\sigma}p^{\sigma}.$$

The travel-market equilibrium is therefore

$$\begin{aligned} p^*(\eta) &= \left(\frac{A}{B}\right)^{1/(\varepsilon+\sigma)}\eta^{-(1+\sigma)/(\varepsilon+\sigma)}, \\ q^*(\eta) &= A^{\sigma/(\varepsilon+\sigma)}B^{\varepsilon/(\varepsilon+\sigma)}\eta^{\varepsilon(1+\sigma)/(\varepsilon+\sigma)}. \end{aligned}$$

1.2 The resource market: gasoline

The gasoline-market graph has dollars per gallon, w, on the vertical axis and gallons of gasoline, R, on the horizontal axis. Recall the supply function is:

$$R^s(w) = Bw^\sigma, \qquad \sigma > 0.$$

This primitive gasoline-supply curve, combined with $q = \eta R$ and $p = w/\eta$, generated the travel-supply curve above.

Gasoline demand is derived from travel demand, since gas is the input used to produce travel. At gasoline price w, the competitive price per mile is $p = w/\eta$. Travel demand is therefore $q^d(w/\eta)$, and the gasoline required to provide that travel is $q^d(w/\eta)/\eta$:

$$R^d(w;\eta) = \frac{q^d(w/\eta)}{\eta} = \frac{A(w/\eta)^{-\varepsilon}}{\eta} = Aw^{-\varepsilon}\eta^{\varepsilon-1}.$$

The corresponding inverse gasoline-demand curve is

$$w^d(R;\eta) = \left(\frac{A\eta^{\varepsilon-1}}{R}\right)^{1/\varepsilon}.$$

The factor η^{-1} in derived gasoline demand is the engineering effect: each mile requires fewer gallons. The factor η^ε is the demand effect: a higher η lowers the price per mile and increases miles demanded. Combining the two effects yields

$$\frac{\partial \ln R^d}{\partial \ln \eta} = \varepsilon - 1 \qquad \text{at fixed } w.$$

This shows that increasing efficiency shifts the gasoline demand curve left or right depending on whether $\varepsilon < 1$ or $\varepsilon > 1$.[1]

Equating gasoline demand and supply gives

$$\begin{aligned} w^*(\eta) &= \left(\frac{A}{B}\right)^{1/(\varepsilon+\sigma)} \eta^{(\varepsilon-1)/(\varepsilon+\sigma)}, \\ R^*(\eta) &= A^{\sigma/(\varepsilon+\sigma)} B^{\varepsilon/(\varepsilon+\sigma)} \eta^{\sigma(\varepsilon-1)/(\varepsilon+\sigma)}. \end{aligned}$$

These gasoline-market outcomes reproduce the travel-market equilibrium because

$$\begin{aligned} p^* &= \frac{w^*}{\eta}, \\ q^* &= \eta R^*. \end{aligned}$$

1.3 Comparative statics: increase in efficiency

Improving fuel efficiency increases the equilibrium quantity of travel, with ambiguous effects on the quantity of gasoline. In particular,

$$\frac{\partial \ln q^*}{\partial \ln \eta} = \frac{\varepsilon(1+\sigma)}{\varepsilon+\sigma} > 0, \qquad \frac{\partial \ln R^*}{\partial \ln \eta} = \frac{\sigma(\varepsilon-1)}{\varepsilon+\sigma}.$$

Travel therefore rises after an efficiency improvement for every $\varepsilon > 0$. Gasoline use rises only when travel demand is elastic, $\varepsilon > 1$; it falls when $\varepsilon < 1$ and is unchanged when $\varepsilon = 1$. Thus fuel efficiency always shifts travel supply outward, whereas its shift of gasoline demand depends on the elasticity of travel demand.

[1] This also corresponds to the case of a single service firm, who is a price-taker facing the resource market. Alternatively, w is fixed when resource supply is perfectly elastic, with $\sigma \to \infty$.

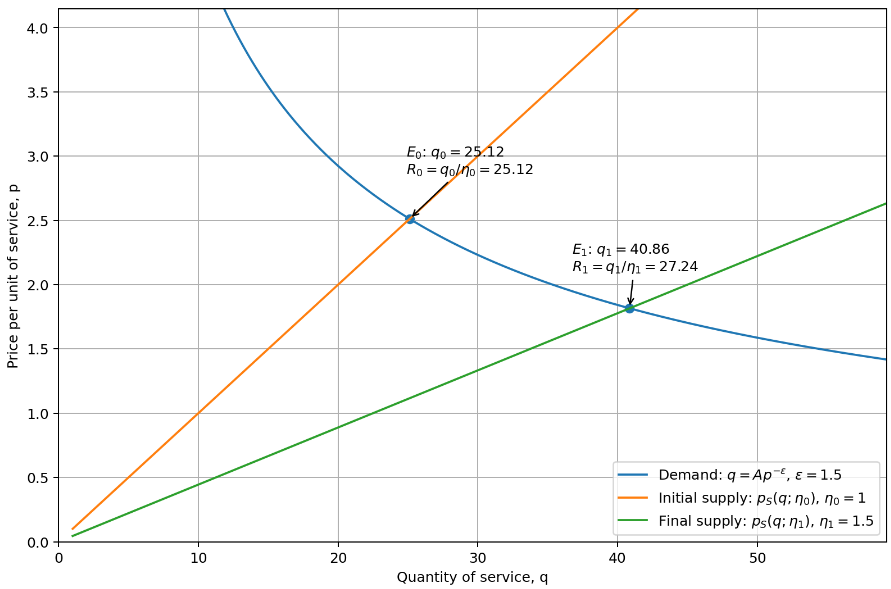
2 Graphs

An increase in efficiency shifts the supply of the service, decreasing its price as we move down the service demand curve. How this affects resource use R^* depends on the elasticity of service demand.

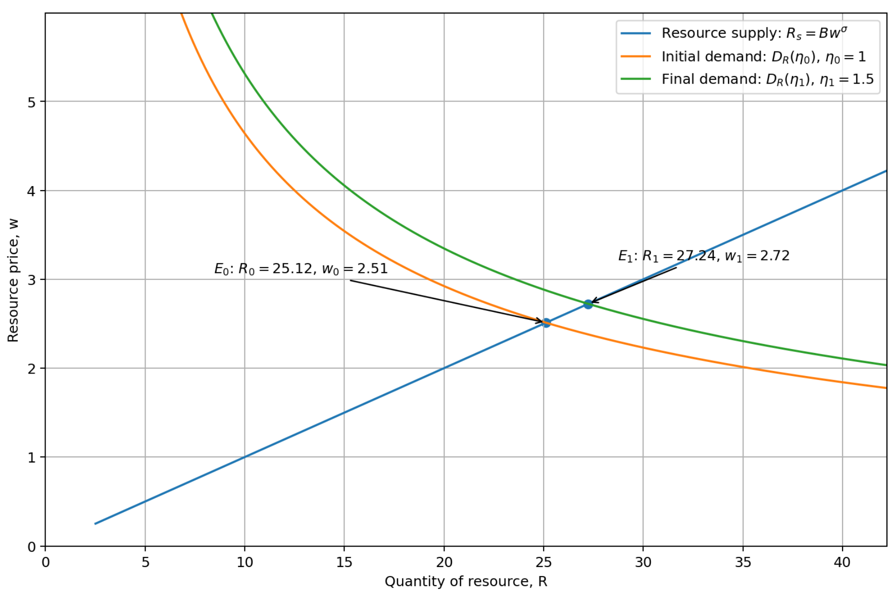
2.1 Elastic service demand

When $\varepsilon > 1$, resource demand shifts right, and R^* increases. This is the 'paradox' case.

Figure 1: Elastic service demand ($\varepsilon = 1.5$).



(a) Efficiency improves from $\eta_0 = 1$ to $\eta_1 = 1.5$

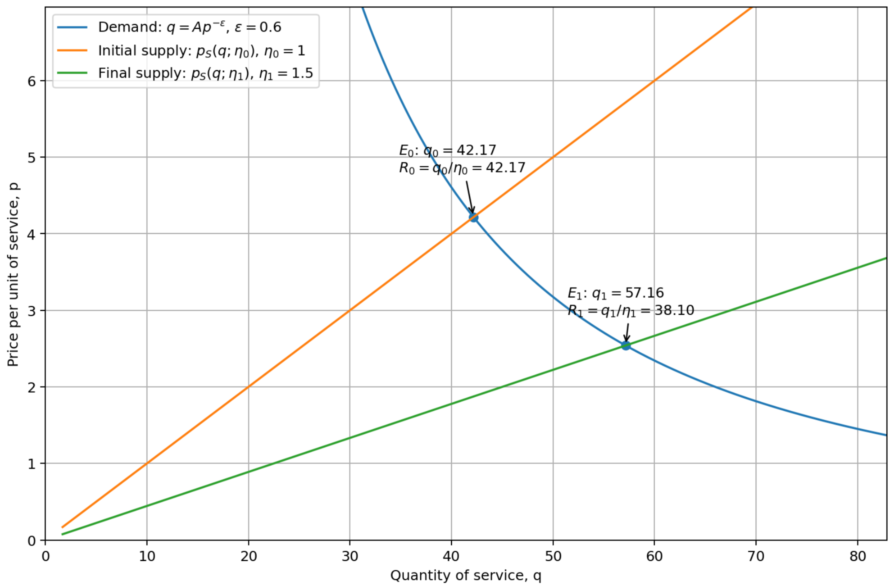


(b) Derived resource demand shifts outward, raising equilibrium resource use.

2.2 Inelastic service demand

When $\varepsilon < 1$, resource demand shifts left, and R^* decreases. The 'paradox' does not occur.

Figure 2: Inelastic service demand ($\varepsilon = 0.6$).



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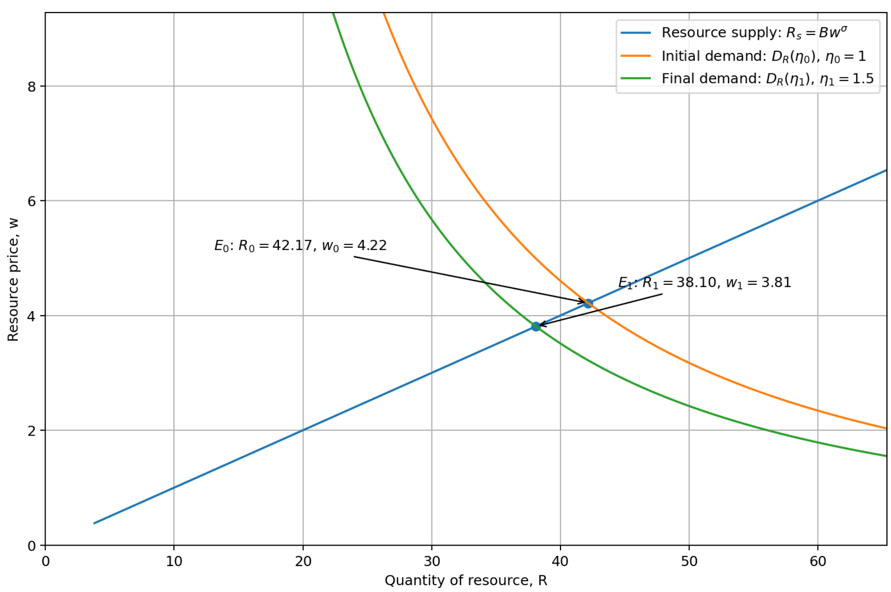

(b) Derived resource demand shifts inward, lowering equilibrium resource use.