Why is Production More Volatile than Sales? Theory and Evidence on the Stockout-Avoidance Motive for Inventory-Holding

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Abstract

This paper develops and tests a model of inventory behavior that focuses on the stockout–avoidance motive. The model allows for both cost and demand uncertainty. Empirical implications are derived and then tested on disaggregated automobile industry data. The data support the basic implications of the model. Evidence on the relative variance of demand and cost shocks suggests that demand shocks are more important.

WHY IS PRODUCTION MORE VOLATILE THAN SALES?

Theory and Evidence on the Stockout–Avoidance Motive for Inventory–Holding

The fact that the variance of production generally exceeds the variance of sales in industries that carry inventories has attracted considerable attention in recent years. A related fact is that inventory investment tends to be positively correlated with sales. While the class of production–smoothing models of inventory behavior can accomodate these facts by including a target inventory level that depends on current or expected future sales, these models have not fared very well in empirical research. The target specification has also been criticized as lacking any solid theoretical basis. Consequently other explanations for the procyclical behavior of inventories have emerged, including cost or productivity shocks, increasing returns, and strategic interaction of firms, among others.[1]

An earlier paper (Kahn, 1987) provided a more solid theoretical basis for target inventory behavior on the basis of a stockout–avoidance motive for inventory accumulation. It showed that with constant returns to scale and with production costs constant over time, positive serial correlation of demand implies both that the variance of production will always exceed the variance of sales, and that inventory investment may be correlated with sales. Of course, the fact that in theory demand uncertainty alone can lead to these results does not imply that it is in fact responsible. Eichenbaum (1988), for example, provides evidence that cost uncertainty is important in rationalizing inventory–behavior. At the same time, empirical models that focus on the cost side have not generally given the stockout–avoidance motive a

[1]The target inventory approach goes back at least to Lovell (1961). Miron and Zeldes (1987) and West (1986) provide fairly general evidence against the production–smoothing approach. Blinder(1986), among others, has argued in favor of cost shocks as an explanation for production volatility and as a means for "saving" the production–smoothing model. Ramey (1988) suggests allowing for increasing returns as an alternative approach.

specification. This is in part because of the difficulty of finding simple testable implications of the stockout–avoidance motive. Proper analysis of stockout–avoidance behavior requires considering the *profit–maximization* problem (not merely the *cost–minimization* problem) of the firm, because the ultimate motive for stockout–avoidance is the loss in profits from unrealized sales.

This paper generalizes the stockout–avoidance model in Kahn (1987) by allowing both short–run convexity and variation over time in the firm's cost function, derives some new testable implications, and then tests the model using automobile industry data. The results confirm the main predictions of the model. Moreover, using some identifying restrictions implied by the model, the paper offers subsidiary evidence that demand uncertainty accounts for more of the variation in sales and inventories in the industry than does supply uncertainty.

The plan of the paper is as follows: Section 1 introduces the model. Section 2 describes the data, and Section 3 contains the empirical results. Section 4 offers some concluding remarks.

1. The Model

This section develops a model of a firm's production decision under demand and cost uncertainty. The key assumptions are (1) that when the firm makes production decisions it is uncertain about the state of demand; and (2) there is a non–negativity constraint on inventories. Consequently sales in any one period are constrained by the firm's inventory stock. In deciding how much to make available for sale the firm must therefore trade off the cost of stocking out (lost profitable sales) and the cost of carrying inventory stock over to the subsequent period.

For simplicity the output price is assumed for now to be a constant markup over *ex ante* marginal cost (as defined below), and *potential* sales ("demand") conditional on price are assumed to be stochastic and exogenous. While these assumptions are special, their purpose is primarily just to facilitate the exposition; they will be relaxed to some extent in the estimation, and in any case the qualitative theoretical results are robust to variations in the economic environment.[2] Another simplifying assumption is that the firm cannot backorder its excess demand. Again the predictions of the model are not sensitive to allowing backorders (see Kahn, 1987) so long as there is some cost—even if the cost is only delayed revenue.

Upon observing the inventory stock at the end of period t–1, denoted N_{t-1}, and taking account of any other information regarding future demand, the firm chooses planned production for period t, Y^*_t. During period t it learns demand X_t, and then chooses its revised production for the period, denoted Y_t.[3] Sales Z_t satisfy

$$(1) \qquad Z_t = \min\{N_{t-1} + Y_t, X_t\}.$$

If demand turns out to be less than the total stock made available by the firm ($N_{t-1}+ Y_t$), the firm may carry the remainder into the next period as inventory $N_t= N_{t-1}+ Y_t- Z_t$. If, on the other hand, the firm "stocks out", the result is lost sales, and $N_t= 0$.[4] It will be convenient to assume that demand uncertainty is multiplicative, i.e. $X_t= E_{t-1}(X_t)U_t$, where U_t is an i.i.d. random variable with a mean of one.

With each decision the firm makes its objective is to maximize expected profits over an infinite horizon from that moment forward. The stock of goods the firm has

[2]The case of monopolistic price–setting is considered in Kahn (1987), and the case of a competitive equilibrium in which price adjusts *ex post* to clear the market is analyzed in Kahn (1986, Ch. 2). In all of these cases the qualitative results are very similar. Eichenbaum (1984) makes the point in the context of a different model that monopoly, oligopoly, and competition will produce observationally equivalent behavior.

[3]Blinder (1984) adopts something like this approach in allowing the firm to observe part of the current demand shock.

[4]Kahn (1987) allows for backorders, so that sales are not necessarily lost, only delayed. The results and empirical implications carry over to that case with only minor modifications.

available for sale each period is equal to its inventory as of the end of the previous period plus the current period's production. Actual sales equal either that period's total demand or the amount available for sale, whichever is smaller. The firm discounts profits in period t+1 as of period t by a discount factor denoted β_t.

The production costs facing the firm are assumed to be linear *ex ante* (i.e. linear in "planned production") and quadratic *ex post*. Planned production Y_t^* costs $c_t Y_t^*$. This would be the case if the firm had a constant returns to scale technology and were a price taker in factor markets. Upon learning the level of demand during period t, the firm revises its production decision by $Y_t - Y_t^*$ at a cost

$$(2) \qquad c_t(Y_t - Y_t^*) + (d/2)(Y_t - Y_t^*)^2.$$

The second term in (2) represents a symmetric cost of adjustment that arises solely from having actual production differ from its planned level. The idea behind (2) is that if production exceeds the planned level the firm might have to pay overtime wages or higher inexperienced labor, while if production is reduced below the planned level the firm might have to incur costs of laying off workers. The quadratic form is again just a simplifying assumption. Any strictly convex function would have similar implications.

The firm stocks out if demand X_t exceeds the stock available for sale $N_{t-1} + Y_t$, whereas if $N_{t-1} + Y_t > X_t$, the remainder is carried over into the next period. This specification allows production to be adjusted upward or downward in the short run (i.e. within the period, after demand is observed), but adjustment costs limit the extent of the revisions. Thus stockouts and "unintended" inventory accumulation will occur even though the firm can offset moderate-sized demand shocks by revisions in production. It will be convenient for the exposition of the model (though not necessary for the results) to assume that at the time the firm chooses Y_t^* it knows c_t

and has a forecast of c_{t+1} denoted $E_t c_{t+1}$, and to assume that the innovation in c_{t+1} is uncorrelated with the demand shock U_{t+1}.

Consider first the decision with respect to Y_t. At the time the firm chooses Y_t it has just learned X_t, and knows Y^*_t, and N_{t-1}, c_t, and $E_t c_{t+1}$. The cost of an additional unit of output is $c_t + d(Y_t - Y^*_t)$. The gain to the firm from producing the additional unit depends on whether X_t exceeds $N_{t-1} + Y_t$. If $X_t > N_{t-1} + Y_t$, then the firm sells the additional unit immediately, and gains $p_t = (1+\mu)c_t$. In this case, then, production increases to the point that demand is satisfied, or to the point that

$$(3) \qquad p_t = c_t + d(Y_t - Y^*_t),$$

whichever is lower. Thus we have (after substituting for p_t)

$$(4) \qquad Y_t - Y^*_t = \min[X_t-(N_{t-1}+Y^*_t),\mu c_t/d] > 0.$$

On the other hand, if $N_{t-1} + Y_t \geq X_t$, then the additional unit is carried over into the next period, at which time one less unit can be produced. Thus the gain is $\beta_t E_t c_{t+1}$ in this case. Production is *reduced* either to the point that demand is satisfied, or to the point that

$$(5) \qquad \beta_t E_t c_{t+1} = c_t + d(Y_t - Y^*_t),$$

whichever is higher. Therefore

$$(6) \qquad Y_t - Y^*_t = \max[X_t-(N_{t-1}+Y^*_t),-(c_t-\beta_t E_t c_{t+1})/d] \leq 0$$

in this case. Intuitively, if the firm sees a difference between the planned available stock $N_{t-1}+ Y_t^*$ and demand X_t, it adjusts production to make up for this difference, but only within the limits given by (4) and (6). The firm's choice of $Y_t - Y_t^*$ is shown graphically in Figure 1. As d gets very large, the bounds on the intraperiod adjustment shrink to zero, and we revert to the model in my earlier paper (Kahn, 1987) that has production entirely predetermined.

Given this behavior for the determination of $Y_t - Y_t^*$, we can use a similar perturbational argument to characterize the choice of Y_t^*. For the present purpose it will suffice to show that the firm chooses Y_t^* so that $N_{t-1}+ Y_t^*$ reaches a target level that is a function of c_t, $E_t c_{t+1}$, β_t and demand expectations only.

The marginal cost of Y_t^* is c_t. Denoting the cumulative distribution function for X_t by F(), and defining $\gamma_t \equiv \mu c_t/d$, $\xi_t \equiv (c_t - \beta_t E_t c_{t+1})/d$, and $A_t^* \equiv N_{t-1}+ Y_t^*$, we have three possibilities for the effect on the firm's *ex post* profits of increasing Y_t^* by one unit:

(a) With probability $1 - F(A_t^* + \gamma_t)$ the firm stocks out in period t. Then the firm sells the additional unit for a net gain of μc_t.

(b) With probability $F(A_t^* - \xi_t)$ the firm carries over the unit to the next period, for a net loss of $c_t - \beta_t E_t c_{t+1}$.[5]

(c) With probability $F(A_t^* + \gamma_t) - F(A_t^* - \xi_t)$ the firm offsets the additional unit by its choice of $Y_t - Y_t^*$, for a net gain (positive or negative in this case) of $d(Y_t - Y_t^*) - c_t = d(X_t - A_t^*) - c_t$.

[5]For the firm to be at an interior solution we must have $\beta_t c_{t+1} < c_t$. Otherwise the firm would want to produce for both t and t+1 in period t.

Note that all of the expressions above can be expressed in terms of A_t^*. At the optimum, the expected marginal gain will be zero, which implies that A_t^* depends on c_t, $E_t c_{t+1}$, d, β_t, and the distribution of X_t. Letting $A_t \equiv A_t^* + Y_t - Y_t^*$, we can define a multiplicative adjustment term Ω_t by

$$A_t = A_t^* \Omega_t, \tag{7}$$

Note that Ω_t is correlated with the demand shock but uncorrelated with A_t^* and anything else in the period t–1 information set. The multiplicative specification of the adjustment term is simply for convenience, and to be consistent with the specification adopted below.

To get an explicit characterization of the target, given the assumption of multiplicative uncertainty in demand, we can solve the firm's profit maximization problem using standard techniques. Let G denote the cumulative distribution function (assumed to be continuous and strictly monotonic) for the forecast error U_t. The first-order condition for the maximization problem is

$$\mu c_t(1-G[(A_t^*+\gamma)/E_{t-1}(X_t)]) - (c_t-\beta_t c_{t+1})G[(A_t^*-\xi)/E_{t-1}(X_t)] \tag{8}$$

$$+ \int_{\frac{A_t^*+\xi_t}{E_{t-1}(X_t)}}^{\frac{A_t^*+\gamma_t}{E_{t-1}(X_t)}} [d(E_{t-1}(X_t)U - A_t^*) - c_t]dG(U) = 0.$$

Using a Taylor approximation of G around $\gamma_t = \xi_t = 0$, and applying the Mean Value Theorem to the integral in (8), we get the result that the optimal choice of A_t^* has approximately[6] the form

[6]As d gets large the representation in (9) becomes exact.

$$A_t^* = K^*(c_t,\beta_t E_t c_{t+1})E_{t-1}(X_t). \tag{9}$$

Equation (9) says that the amount the firm makes available for sale in period t equals a multiple K* of its expected new demand. Strictly speaking, K* could be any non–negative number, but should depend negatively on current marginal cost c_t (holding future costs fixed), and postively on discunted future marginal cost $\beta_t E_t c_{t+1}$ (holding fixed c_t). The same applies to the behavior of production, given expected demand and initial inventories.

As an aside, it is interesting to compare the target specification in (9) with that used by, for example, Blanchard (1983) and West (1986) in the linear–quadratic framework:

$$\hat{N}_{t-1} = KE_{t-1}(Z_t) \tag{9'}$$

where $\hat{N}_{t-1}$ is desired inventories, which in their specifications can differ from actual N_{t-1} because of costs of adjustment. There are minor differences: Equation (9) includes planned production as part of the stock, and has expected demand rather than expected sales. But the main difference is that in (9) K is a function of cost variables, while in (9') it is parametric. The assumption in those models that K is a fixed parameter necessarily implies that serially correlated deviations of $\hat{N}$ from its target either fall into the residuals or are attributed to adjustment costs. Moreover, while it is difficult to say for sure what the effect of misspecifying the target is on econometric estimates of production–smoothing models, it is at least possible that it is responsible for their poor empirical performance.

We can solve for sales in terms of demand expectations and innovations. Letting $K_t^*= K^*(c_t,\beta_t E_t c_{t+1})$, and recalling that $Z_t= \min\{A_t,X_t\}$, we have:

$$Z_t = E_{t-1}(X_t)V_t \tag{10}$$

where $V_t \equiv \min[K_t^*\Omega_t, U_t]$. Equation (10) says that actual sales equal demand or the stock available, whichever is smaller. A stockout occurs if $U_t > K_t$.[7]

The results contained in equations (9) and (10) are very powerful and intuitive. They say that the quantity A_t^*, the firm's planned stock available for sale in period t, is the product of two factors: costs in period t (absolutely and relative to period t+1), and expected demand in period t. Using small letters to denote the log of the corresponding capital letter (e.g. $z_t \equiv \log(Z_t)$), we have from (9) and (10)

$$z_t = a_t^* - k_t^* + v_t \tag{11}$$

$$= \begin{cases} a_t^* - k_t^* + u_t & \text{no stockout} \\ a_t^* + \omega_t & \text{stockout} \end{cases}$$

where, again, $v_t \equiv \log(\min[K_t^*\Omega_t, U_t])$, and U_t is orthogonal to anything known prior to time t—which includes the other right–hand–side variables.

There are two issues important issues that remain to be dealt with. First, we observe a_t, not a_t^*, and we know by (7) that the observable quantity is correlated with u_t for $d < \infty$. Second, to the extent stockouts occur the error term is truncated, and, worse, the truncation is related to other explanatory variables. We can handle both of these complications by incorporating a_t into (11) and by taking account of aggregation. If we substitute a_t for a_t^* we get

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[7]An assumption in the above derivation is that the solution is always at an interior point. To the extent that *changes* in marginal cost are forecastable, it is theoretically possible for the firm to be at a corner, in the sense of wanting to produce either zero (if costs are sufficiently high this period relative to the next) or up to its capacity (if costs are relatively low this period). Detailed analysis of these cases will not be considered here. Kahn (1986, Ch. 2) takes explicit account of the non–negativity constraint on production.

$$(12) \qquad z_t = a_t - k_t^* - \omega_t + v_t$$

$$= \begin{cases} a_t - k_t^* - \omega_t + u_t & \text{no stockout} \\ a_t & \text{stockout} \end{cases} .$$

Now we can take account of the fact that we do not have data that are disaggregated to the extent that we could observe stockouts. For example, we can distinguish goods by location as well as by other physical characteristics, yet we only observe aggregates over all locations. If demand is distributed randomly across locations we would not expect to see stockouts (i.e. zero inventories) in the data. The same reasoning applies to aggregation over other characteristics.

Let λ_t denote the proportion of markets in period t in which a stockout does not occur. In general, λ_t will be correlated with K_t^* (since the latter determines the *ex ante* stockout probability), and with u_t (since the demand shock affects the *ex post* stockout probability. Then with the aggregate data we have

$$(13) \qquad z_t = a_t - \lambda_t k_t^* - \lambda_t \omega_t + \lambda_t u_t.$$

Let w_t be the vector of observable determinants of k_t^* and λ_t. It will generally include factor prices, seasonals, productivity, and so forth. If $d = \infty$ (so $a_t = a_t^*$) then an OLS regression model of $z_t = a_t\delta_1 + w_t'\delta_2 + \epsilon_t$, with a heteroscedasticity correction for standard errors, should yield consistent estimates. The model predicts a coefficient of one on a_t, positive coefficients on current cost, and a negative effect of higher future costs. The model also predicts that the error term from this regression should be orthogonal to information in period t–1. Thus lagged sales, for example, should not help predict current sales, given the other explanatory variables, and there should be no serial correlation in the error term. If $d < \infty$, then it is necessary to use instruments for a_t. The theory tells us, though, that *any* variable in the period t–1 information set is a suitable instrument for a_t^*, even one that is correlated with cost shocks.

2. The Data

Estimation of the model of the previous section will use data on the production and sales of the American automobile industry from 1966 through 1983. The data through 1979 were provided by Olivier Blanchard, while the more recent data were collected directly from published and unpublished sources. The production and domestic sales data come from *Ward's Automotive Reports* and *Ward's Automotive Yearbook*. Data on shipments to dealers domestically and abroad come from the Motor Vehicle Manufacturers Association in Detroit. Data on inventories are constructed from the production and sales data as in Blanchard (1983).

Although these data are of very high quality (most notably because they measure physical quantities rather than accounting entries) there are two limitations. First, there are no data on backorders; a sale takes place when the vehicle changes hands, regardless of when it was ordered. Second, sales by dealers in other countries are not observed, only shipments to those countries. Hence total "sales" are really a combination of sales by U.S. dealers and shipments to other countries. Treating shipments to other countries differently (e.g. treating them as orders, known at the time of the production decision) did not appreciably alter any results.

A second issue is the appropriate frequency of the data. The model says nothing about what the decision period is, so it is necessary to make an assumption. Higher frequency data are not necessarily preferred to lower frequency data. The estimation will focus primarily on quarterly data, but results based on monthly data will be described as well. Of course, in reality there probably is not a fixed, exogenous decision period; the hope is that the determinants of the decision period do not change much over time, so that the fixed period is a reasonable approximation.

An important fact about these data is that there is little or no evidence of a linear trend over the period 1966 to 1983. Thus issues of detrending versus first differencing, cointegration, and nonstationarity do not appear to be important for these variables. The results described below are not attributable to low–frequency comovements between variables that are trending together or are nonstationary for other reasons, and they do not sensitive to detrending methods.

The ex–post real interest rate used in the analysis is the 3–month T–Bill rate, averaged for the month immediately preceeding the period for which production is being decided, and adjusted for inflation by subtracting the inflation rate (based on the implicit price deflator for personal consumption expenditures) over the subsequent 3 months. The estimation also incorporates other observable determinants of k*. Productivity is measured by output per manhour, where manhours are taken from 3–digit level industry data. Other variables include measures of wages and other input prices (steel and electricity) obtained from the Citibase data bank, all in logs and deflated by the personal consumption implicit price deflator. For the wage both the average hourly earnings series (3–digit industry level) and an an estimated marginal wage series (using the technique described in Bils (1987)) were tried. The qualitative results were not sensitive to the choice of wage measure; the results with the marginal wage are reported. Finally, data on new car prices are based on the Consumer Price Index new cars component.

The production and sales data are organized by division, with (following the usage in Blanchard (1983)) five General Motors divisions: Chevrolet (CV), Pontiac (PT), Oldsmobile (OD), Buick (BK) and Cadillac (CD); two Ford divisions: Ford (FD) and Lincoln–Mercury (LM); two Chrysler divisions: Chrysler–Plymouth (CP) and Dodge (DG); and, finally, American Motors (AM). Production is the total of U.S. and Canadian production. Table 1 provides summary statistics of the data at the quarterly frequency. Note that both manufacturers and dealers hold inventories, but that most of the inventories are held by dealers. Note also that inventory–sales ratios are typically two to three months, but that there is substantial variation in this across divisions. The variance of production always greatly exceeds the variance of sales, whether before or after seasonal adjustment.[8]

The model essentially applies to seasonally unadjusted data. This is especially so regarding seasonal demand fluctuations. Since a_t^* is based on a forecast of demand, it would take account of any seasonality, so there would be no need to control for it in estimation. Similarly, to the extent seasonality in production is induced by seasonality in observable cost variables we should also be able to control for it directly by including non–seasonally adjusted cost variables in the equation. It is very unlikely, though, that observable costs vary in such a way as to account for very much of the seasonal variation, a large part of which is due to the model changeover period in the third quarter. So despite the potential gains from using seasonally unadjusted data, because so much of the seasonal variation has to do with the model changeover period the estimation will focus on seasonally adjusted data (using dummy variables). The results were not sensitive to different methods for seasonal adjustment.

Figure 2 plots aggregate data on production, sales, and inventories, not seasonally adjusted. Note that the data appear stationary except for an apparent change in the seasonal pattern of production over time (after 1971 the maginitude of the decline in activity during the third quarter retoolin period diminished), and possibly the dropoff in all variables in the last few years of the sample. Direct estimation and testing rejected the hypothesis of a unit root in the process for sales. None of the results above or in what follows appear to be sensitive to the choice of methods for accounting for seasonality.

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[8]Dummy variables were used to seasonally adjust the data.

Figure 3 displays two other variables included in the analysis: The output price and the price of steel. The behavior of these variables has one rather ominous feature: There is a definite downward trend in the output price, and the price of steel is an integrated process with some upward drift. These characteristics would tend to cause problems for any model of the industry, since they imply divergence between cost and output price, with the former ultimately dwarfing the latter. Examination of the wage and productivity data showed that they could not explain this because they appeared to be relatively flat over the sample. There are two likely (and related) explanations. First, the output price index is probably not accurately adjusted for changes in what constitutes "an automobile" over time. While the Bureau of Labor Statistics makes some effort to adjust for quality by valuing new standard equipment, there is no adjustment for other measurable characteristics such as size, weight, and performance, all of which have been trending downward at least since the mid–seventies.[9] This suggests (perhaps) that the series should be detrended, if one believes that the downward trend (given the behavior of the other variables) must reflect this bias in the measurement of quality. The related point is that average steel content per automobile has dropped sharply since the mid–seventies, undoubtedly both in response to demand for (and regulations requiring) smaller automobiles. This would tend to offset the impact of the upward drift in steel prices, and suggests that the steel price should be adjusted for the changing steel input over time. The results below will be presented with these adjustments, though it turns out that they do not affect the results very much. Data on average steel input per automobile are available from Ward's Automotive Yearbook sporadically. These were combined with data on average weights of a

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[9]Nor is there any adjustment for fuel efficiency, which has improved over the same period. While it is not completely obvious that the bias in the index is downward, one can make a case that the typical automobile in 1983 would measure less in a hedonic sense than the typical automobile in 1972 after controlling for the those improvements that the BLS does allow for.

representative sample of automobiles to get a proxy for average steel content over the whole time period.

3. Empirical Results

3.1. Estimation

This section reports results of the regression suggested by equation (13). As stated earlier, the model predicts that the quantity A_t is proportional to expected demand in period t, where the proportionality factor K_t^* will depend on supply–side factors including marginal cost and real interest rates. One of the attractive features of the model is that it says that one does not have to resort to estimating a sales process or finding some proxy for firms' expected demand because such expectations are already reflected in an observable quantity, namely A_t. To the extent that the firm can adjust production to news within the period it will be necessary to use instruments for A_t, but the theory suggests that anything in the period t–1 information set is an acceptable instrument. Estimation simply involves regressing z_t on a_t, a constant term, seasonal dummies, and cost variables. The cost variables are included for the current period and one period ahead, with the latter instrumented with lagged values. The seasonal dummies are intended primarily to take account of variations in cost over the year due to model changeovers, holidays, and the like. As stated earlier, seasonality in *demand* should not be reflected in the coefficients of the seasonal dummies, since that should be controlled for by movements in a_t. The estimates also relax the assumption that price is a constant markup over marginal cost by including p_t and p_{t+1} on the right hand side. If p_t were predetermined as assumed in the derivation of the model it should enter negatively. To allow for the possibility that p_t in fact may respond to contemporaneous news about demand, in (along with p_{t+1}) will always be instrumented by variables in the lagged information set.

Some simplification of the equation can be obtained by taking account of the implications of optimizing behavior by the firm. Under the assumption that the firm has smooth substitution possibilities across factors of production, it is sufficient (by the Envelope Theorem) to include just the price of just a single factor (along with the input requirement). This is because at the cost–minimizing point the cost of increasing output by one unit using the optimal combination of inputs ought to be the same as if the firm only changed one input. Even if the technology is not smooth, the same argument may apply to a subset of factors. For example, it seems implausible that an additional automobile could be produced by adding labor alone. But the Envelope Theorem argument suggests that including, say, the wage and the price of steel ought to control for marginal cost, under the assumption that automobiles are produced primarily from labor, capital equipment, electricity, and steel.[10] None of the results presented below are sensitive to this specification of the model, though the precision of the estimates of coefficients on factor prices went down as more were included in the estimation.

Table 2 gives the results of estimation under the assumption that supply disturbances (and variation in markups) are not important, i.e. that k^* is a constant. Not surprisingly, this model is rejected decisively due to the presence of serial correlation in the residuals. In nine out of ten divisions the hypothesis of no serial correlation is rejected at the 5% level. Allowing for $d < \infty$ by instrumenting a_t (not reported here) produced only a slight (statistically insignificant) improvement. These results accord with the findings of others (e.g. Eichenbaum, 1988) that cost shocks do have an important role in accounting for inventory behavior, and they imply that if the model is to have a chance at success, it will be necessary to allow for components of the supply side to enter the equation.

[10]Examination of a 3–digit level input–output matrix suggested that this is a good approximation. Other materials represented a tiny fraction of total inputs.

Table 3 gives the results of estimating the more general model using Seemingly Unrelated Regression with instrumental variables, under the assumption that a_t is predetermined (i.e. d is large). (The equations were also estimated by single equation methods with similar results.) Some general conclusions emerge. First, the estimated coefficient on a_t is generally close to one, though in some cases it does differ significantly. It does not appear to differ systematically from one, though. The average of the estimates is 0.973. Moreover the standard errors may be biased downward because (due to computational difficulties with the SUR estimation) it was not possible to correct them for heteroscedasticity.

As for the other coefficients, recall that the the contemporaneous cost variables should enter positively, output price and productivity should enter negatively, and expected future variables should enter opposite to their contemporaneous effects. Only the coefficients on p_t and p_{t+1} show any consistent pattern, and they are indeed as the model predicts. The other coefficient estimates are usually insignificant, though unfortunately when they are significant they are frequently of the wrong sign. While the poor performance of the cost variables is disappointing, it is consistent with (and no worse than) findings by other researchers with other models and data (e.g. Miron and Zeldes (1988), Ramey (1988)). The difficulty in getting factor prices to enter as predicted does not indicate a problem specific to this model but rather a more basic puzzle.

More importantly, however, there is very little evidence of serial correlation of the residuals: One cannot reject the hypothesis of no serial correlation in any of the divisions, though some of the D.W. statistics fall in the ambiguous range of the critical region. Thus the results suggest that serial correlation in the residuals can largely be eliminated by properly controlling for contemporaneous costs. That is, the cost, price, and productivity variables collectively seem to do the job of accounting for serially correlated deviations of inventories from their target, despite the obvious difficulties in getting very precise measurements of the the variables.

The results from Section 1 imply that if intraperiod adjustment of production is possible for the firm, then the regression from Section 3.2 is misspecified, since the regressor is correlated with the error term. Since we do not observe y_t^*, the natural thing to do would be to use instrumental variables for a_t^*, with variables in the period t–1 information set as instruments. These should be uncorrelated with the period t error, but correlated with a_t^*). This was done using lagged values a_t as instruments and the results were very similar to those without instruments.

Perhaps the most powerful prediction of the theory is that lagged sales should not help to predict current sales once a_t has been included in the estimation and costs have been controlled for, even though the z_t series themselves may be (and in fact are) highly positively serially correlated. The last set of estimates therefore includes lagged sales as another test of the model, using SUR estimation. In only two out of ten cases was z_{t-1} siginificant, and in those the coefficients were small relatively small (0.160 and –0.099). Similar results obtained with other specifications. While this is not a complete victory for the theory, it is perhaps a surprisingly good outcome considering the difficulty in capturing cost variations in the data.

The model was also estimated at the monthly frequency. The results indicated significant serial correlation of the residuals, and estimates of the coefficient on a_t while still averaging close to one, varied more from equation to equation. Thus the model appeared not to characterize monthly data as well as it does the quarterly data. This is not evidence against the model, since the theory does not predict that it should hold at frequencies higher or lower than whatever the appropriate decision period is, but it is reported in the interest of fair play.

3.2 Demand Shocks or Supply Shocks?

One of the motivations for the model is that it offers an explanation, as shown in Kahn (1987), for production volatility and procyclical inventory investment that does not rely on unobservable cost or productivity shocks (hereafter referred to as "supply shocks"). To show that production volatility does not *require* the presence of supply shocks does not of course mean that supply shocks are not the explanation. Thus it would be useful to have some way of gauging the relative importance of the two kinds of uncertainty. This part of Section 3 examines some circumstantial evidence that bears on this question.

The idea in what follows is that the quantity a_t in part reflects expected demand in period t, and in part reflects fluctuations in supply. In the absence of supply shocks a_t would track expected demand, so its variance would be less than the variance of realized sales z_t (assuming the two variances exist—see the discussion below). On the other hand, if supply shocks were very important, a_t would exhibit movements that are independent of expected demand, so that the variance relationship could be reversed. Thus the relative variances of a_t and z_t could provide information about the relative importance of supply and demand shocks in the industry. This is analyzed in detail below.

An important implication of the model is that the quantity a_t in part reflects demand expectations for period t as of period t–1. A very basic property of a time series of efficient one-step-ahead forecasts is that they will be less volatile than the corresponding time series of realizations. We can exploit this property to get evidence on the relative importance of demand and supply shocks. From before we have (letting $\theta_t = \lambda_t u_t + (1-\lambda_t)k_t^*$)

$$(14) \qquad z_t = \log(E_{t-1}X_t) + \theta_t$$

$$(15) \qquad a_t = \log(E_{t-1}X_t) + \omega_t + k_t^*.$$

Take the simplest case where d is large, so that σ_ω^2 is negligible. Let

$\bar{x}_{t-1} = \log(E_{t-1}X_t)$. Then we have

$$(16) \qquad \sigma_z^2 - \sigma_a^2 = \sigma_\theta^2 - \sigma_k^2 - (\sigma_{xk} - \sigma_{x\theta}).$$

If either demand is i.i.d. or costs and productivity are constant, then both covariances in (16) will be zero. Suppose that cost and productivity shocks are relatively important in explaining the variances of sales and inventories. This would suggest that $\sigma_{xk} \geq 0$, i.e. that expected sales are negatively correlated to expected or known costs. One can show that to a first approximation $|\sigma_{xk}| > |\sigma_{x\theta}|$, which implies that $\sigma_{xk} - \sigma_{x\theta}$ has the same sign as σ_{xk}.[11] If $\sigma_{xk} \geq 0$ then the quantity $\sigma_z^2 - \sigma_a^2$ is a *lower* bound on the difference between the variances of demand and cost shocks (or, more precisely, on the difference in their respective contributions to the variances of sales and inventories). Thus a finding that $\sigma_z^2 - \sigma_a^2$ is strongly positive would tell us that either demand shocks are more important than cost/productivity shocks, or that cost is positively correlated with previously expected demand (which itself is suggestive of demand–driven rather than supply–driven fluctuations), or both.

It is easy to see that allowing for $\sigma_\omega^2 > 0$ does not alter this analysis, since intra–period adjustment affects both z and a in the same way. Thus under the maintained hypothesis that the model is correct, we can gauge the relative importance of demand and supply shocks, even without measuring either directly. Again, the intuition is that both a_t and z_t move with expected demand (conditional on p_t), but a_t responds to cost variation in period t *beyond* the price–induced respons by z_t, whereas z_t. If cost shocks are negligible then the difference between σ_z^2 and σ_a^2 represents demand forecast error variance, whereas if demand shocks are negligible then any excess of σ_a^2 over σ_z^2 has to do with supply shocks.

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[11]This is because $\bar{x}_{t-1}$ is orthogonal to u_t, which is a component of θ_t but not of k_t^*.

To see how robust this argument is, imagine what might be the worst case scenario: Demand extremely price sensitive, and supply disturbances much more important than demand disturbances. Then we would expect to see z_t fluctuating a lot, but mostly because of price changes associated with cost shocks. Nonetheless, as much as z_t fluctuates, a_t should fluctuate even more, because the choice of a_t takes into account *both* the price–induced changes in expected sales and the changes in the cost of holding inventories relative to expected sales. Thus even with large cost–induced fluctuations in sales, the test is still powerful against the alternative of relatively important demand disturbances.

Table 4 provides estimates of the ratio of the unconditional variances of z_t and a_t for the ten divisions, using non–seasonally adjusted data, seasonally adjusted data, and data adjusted for a quadratic trend. The trend adjustment was tried because a glance at Figure 2 suggests that the processes, while not exhibiting a pronounced trend, may not be stationary.[12] In nearly all cases σ_z^2 is significantly greater than σ_a^2, which suggests that demand variability is more important than cost variability in the sense described above. Of course this analysis assumes the correctness of the model, which has not been established, but it is likely that other models that have both demand and cost variability would predict a similar relationship to hold. The intuition is that cost variability induces movements in inventories that are independent of changes in expected sales. On the other hand, changes in expected demand induce corresponding movements in both z and a, while demand surprises induce variance in z but not in a. Thus the fact that $\sigma_z^2 > \sigma_a^2$ suggests the relative importance of demand uncertainty.

Further evidence on this question can be found by looking at how much of inventory movements can be explained by expected demand. To examine this, Table

[12]Note in particular the evident lowering of the mean of the variables in the early 1980s.

5 gives the results of regressions of a_t on z_t instrumented by lagged demand disturbances as identified in subsequent regressions. That is, the residuals from the regressions described above in Table 3 are identified as demand disturbances (forecast errors), and two lagged residuals are used to instrument z_t in this regression. Thus the interpretation of the R^2 in these regressions is the proportion of the variance of movements in a_t accounted for by changes in expected demand. The fact that between 80 and 93 percent of the variance in a_t can be explained by ***anticipated*** movements in z_t that are identified as demand–driven, combined with the fact that $\sigma_z^2 > \sigma_a^2$, suggests that the stockout–avoidance motive dominates inventory behavior.

Two final comments are in order here. First, the discussion above refers somewhat loosely to the relative importance of demand and supply shocks. "Importance" refers to their impact on the variances of sales and inventories, not to the variances of the shocks themselves. The variance of supply shocks may be much greater than the variance of demand shocks, yet because of low supply elasticities they could have little impact on the industry. Second, the evidence that demand shocks are more important applies to the industry, not necessarily to the economy as a whole. Obviously supply shocks in one industry can induce demand shocks in another. Nonetheless it is tempting to draw conclusions from these findings about the relative importance of demand and supply shocks in the economy more broadly, since the automobile industry is such a large and cyclically significant part of the economy.

4. Conclusions

The question that motivates this research is whether the behavior of inventories, production, and sales is consistent with a slightly more elaborate version of a traditional inventory model—where "traditional" means a constant returns to scale technology, with demand uncertainty the primary source of variance in the variables of interest. The particular model developed in the paper has monopoly power in that price exceeds marginal cost and sales are constrained by demand for individual firms, but these are subsidiary assumptions and are neither necessary nor sufficient to get the qualitative predictions of the model. Nonetheless, Hall's (1988) recent evidence that price does exceed marginal costs in manufacturing industries suggests that the model in the paper might be a reasonable starting point. Hall's results do not, however, imply that constant returns to scale is a bad assumption, since positive markups may be present for any number of reasons. For example, product differentiation models with fixed costs and nondecreasing marginal costs are consistent with the pricing behavior assumed in Hall's paper, but would not imply production "bunching" of the sort found in models with increasing returns.[13]

Direct estimation of the basic equation derived in Section 1 yielded coefficient estimates very much in line with what the theory predicted. Additional tests tended not to reject restrictions implied by the model, such as the prediction that lagged sales should not help explain current sales once initial inventories and costs are controlled for. While success was not universal, the model performed well enough to give some support to the interpretation of the evidence in Table 4: The sources of fluctuations in the industry appear to come more from the demand side than from the cost side. Of course even if this were so it would not mean that the ultimate source of macroeconomic fluctuations is primarily demand shocks, since the paper looks at only one industry. But the industry it looks at is a large and important one from the point of view of aggregate fluctuations, so it may be reasonable to extrapolate from these results to shed light on the issue whether the ultimate source of macroeconomic fluctuations is predominantly shocks to technology or to demand.

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[13]More precisely, the bunching occurs in the product space, not over time.

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Figure 1: Intraperiod Adjustment

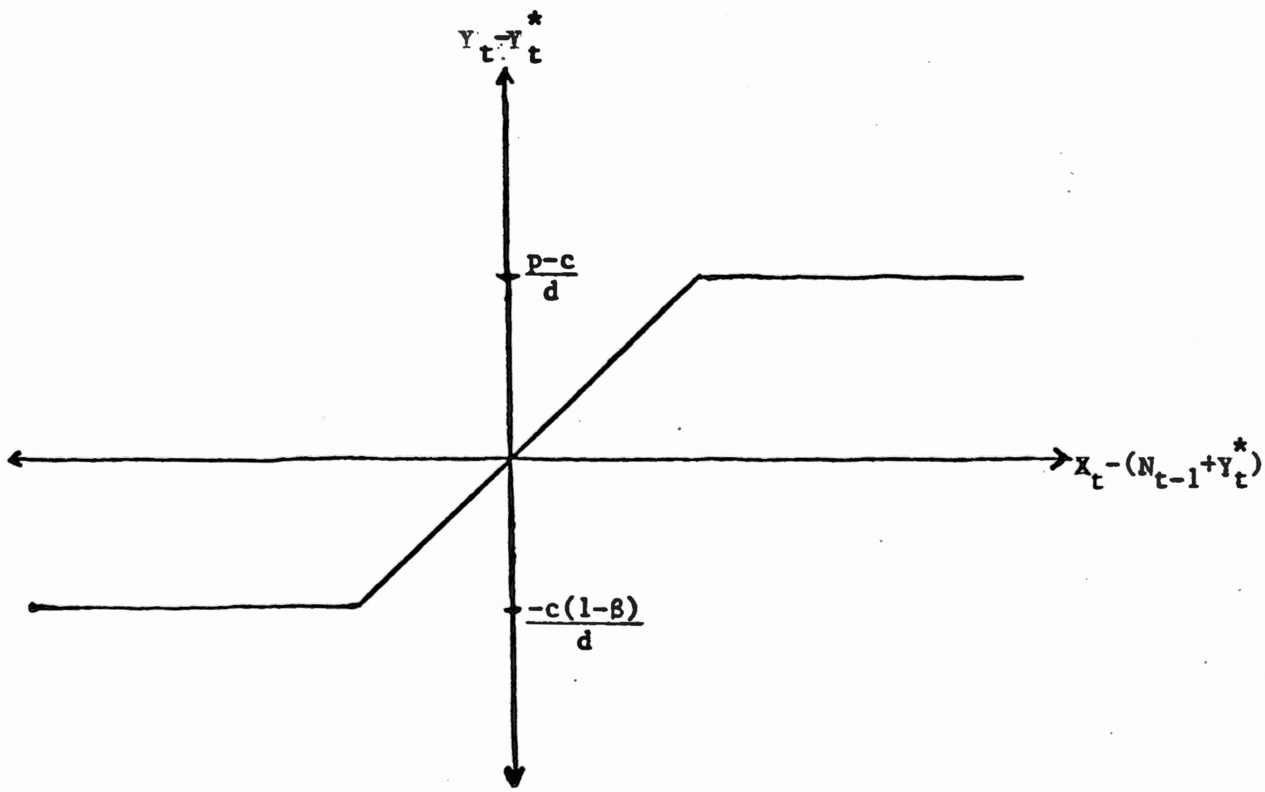

FIGURE 2: INVENTORIES, PRODUCTION AND SALES

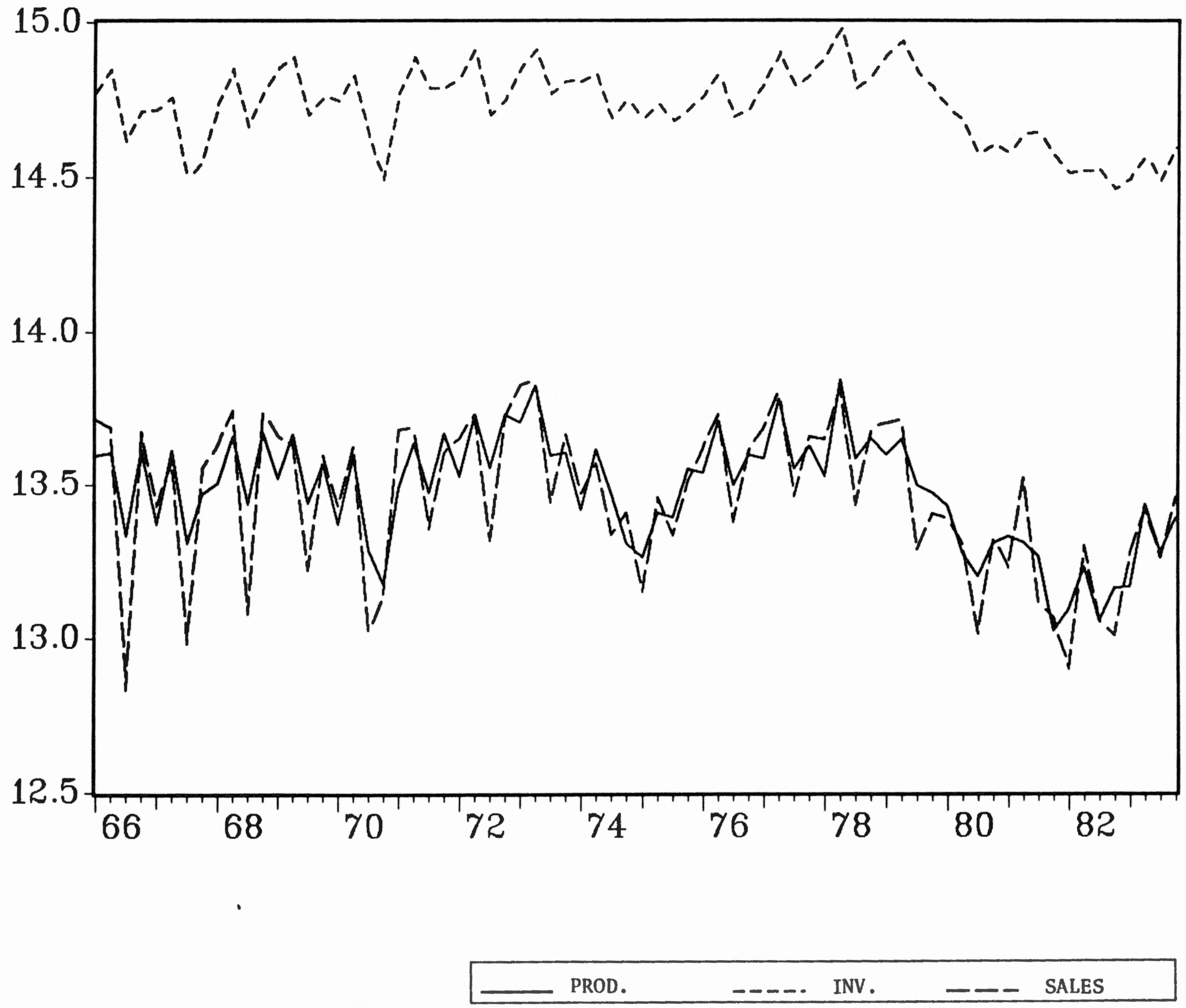

FIGURE 3: PRICES OF STEEL AND NEW CARS

Table 1: Summary Statistics

	Means					Standard Deviations			
						NSA		SA	
Div.	Prod.	Sales	Manuf. Inv.	Dealer Inv.	Inv./ Sales	Prod.	Sales	Prod.	Sales
CV	544,007	544,688	19,672	402,250	0.794	145,457	116,376	124,912	109,574
PT	199,080	198,682	5,407	125,789	0.683	63,770	46,856	54,984	43,686
OD	204,365	203,579	17,646	111,579	0.670	64,517	53,387	56,746	51,030
BK	179,261	178,113	8,174	114,166	0.694	49,533	36,613	40,953	33,712
CD	66,928	66,565	2,196	32,515	0.536	21,963	16,913	17,510	15,556
FD	446,754	448,404	8,591	331,389	0.785	136,665	115,749	124,100	111,549
LM	138,673	136,313	15,541	111,403	0.948	44,448	35,357	41,936	34,444
CP	208,761	209,528	37,841	222,490	1.298	63,252	55,563	59,208	53,668
DG	129,830	131,474	19,838	143,632	1.241	36,562	33,555	34,966	32,102
AM	67,159	67,490	8,560	55,214	1.027	25,019	23,162	23,890	22,481

Table 2: Model without Supply Disturbances

	CV	PT	OD	BK	CD
a_t	1.123	1.051	1.252	0.899	0.932
	(0.037)	(0.031)	(0.036)	(0.036)	(0.042)
D.W.	1.801	1.050*	1.281*	1.271*	1.244*

	FD	LM	CP	DG	AM
a_t	1.018	0.992	1.189	0.760	1.320
	(0.029)	(0.044)	(0.041)	(0.030)	(0.045)
D.W.	0.792*	0.679*	0.913*	0.930*	1.004*

Note: Standard errors are in parentheses. An asterisk by the D.W. statistic indicates rejection of no serial correlation at the 5% level.

Table 3: SUR Instrumental Variables Results

	CV	PT	OD	BK	CD	FD	LM	CP	DG	AM
a_t	1.187*	0.987*	1.144*	1.005*	1.087*	0.961*	0.929*	0.816*	0.758*	1.131*
	(0.054)	(0.042)	(0.064)	(0.060)	(0.050)	(0.049)	(0.058)	(0.072)	(0.063)	(0.082)
r_t	0.376	–0.273	0.510	0.469	–0.206	–0.607	–0.410	0.065	–0.861	–0.761
	(0.414)	(0.593)	(0.663)	(0.628)	(0.617)	(0.426)	(0.500)	(0.530)	(0.529)	(0.714)
w_t	0.051	0.278	0.033	0.022	–0.331	0.209	0.268	0.651*	0.544*	–0.057
	(0.168)	(0.237)	(0.266)	(0.248)	(0.244)	(0.168)	(0.201)	(0.207)	(0.212)	(0.270)
w_{t+1}	0.151	0.276	0.487	0.280	0.643*	0.333*	0.531*	0.215	0.109	–0.149
	(0.155)	(0.229)	(0.257)	(0.245)	(0.243)	(0.168)	(0.194)	(0.200)	(0.204)	(0.269)
s_t	–0.583*	–0.045	0.710	0.294	–0.987*	–0.711*	–0.280	–0.651	–0.325	–0.811
	(0.296)	(0.435)	(0.489)	(0.464)	(0.454)	(0.312)	(0.364)	(0.380)	(0.387)	(0.512)
s_{t+1}	0.483	–0.259	–0.414	–0.141	0.709	0.087	0.075	0.233	–0.190	0.793
	(0.323)	(0.477)	(0.534)	(0.507)	(0.498)	(0.342)	(0.397)	(0.415)	(0.425)	(0.561)
p_t	–0.013	–1.125*	–0.381	–0.077	–2.306*	–1.670*	–1.336*	–2.394*	–1.928*	–2.217*
	(0.326)	(0.481)	(0.541)	(0.510)	(0.500)	(0.346)	(0.418)	(0.448)	(0.444)	(0.673)
p_{t+1}	0.145	0.671*	0.260	0.781*	1.076*	0.701*	0.703*	1.269*	0.238	0.133
	(0.127)	(0.166)	(0.193)	(0.190)	(0.179)	(0.161)	(0.139)	(0.207)	(0.253)	(0.234)
π_t	0.406*	0.017	0.093	0.130	0.173	–0.046	0.122	0.263*	0.113	0.220
	(0.076)	(0.112)	(0.125)	(0.120)	(0.117)	(0.081)	(0.093)	(0.099)	(0.101)	(0.142)
π_{t+1}	–0.053	0.222	0.231	0.199	0.008	0.154	0.105	0.277*	0.083	0.221
	(0.076)	(0.115)	(0.126)	(0.121)	(0.118)	(0.080)	(0.094)	(0.097)	(0.099)	(0.132)
R^2	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
D.W.	2.014	1.582	1.685	1.535	2.333	2.030	1.809	2.053	1.835	1.320

*Significant at 5% level. Instruments: a_t, a_{t-1}, r_{t-1}, w_t, w_{t-1}, s_t, s_{t-1}, p_{t-1}, p_{t-2}, π_t, π_{t-1}. r = ex post real interest rate, w = marginal wage, s = price of steel x avg. input, p = price of new cars (detrended), π = labor productivity.

Table 4: Evidence on Demand Versus Cost Shocks

	Not Seasonally Adjusted	Seasonally Adjusted	Trend[a] Adjusted
	σ_z^2/σ_a^2	σ_z^2/σ_a^2	σ_z^2/σ_a^2
CV	1.611**	1.606**	1.947**
PT	1.360*	1.452**	1.277*
OD	1.686**	1.778**	1.724**
BK	0.966	0.962	1.344*
CD	1.044	1.061	1.551**
FD	1.365*	1.414**	1.556**
LM	1.105	1.091	1.355*
CP	1.875**	1.848**	2.154**
DG	0.830	0.785†	2.400**
AM	2.000**	1.985**	2.179**
Industry	1.449**	1.487**	1.515**

[a]A quadratic trend was removed from each series to account for a possible shift in the mean over time, which would make the variance not meaningful. Note that this has little effect on the GM and Ford divisions, but a dramatic effect on the Chrysler and American Motors divisions.

*Indicates rejection of hypothesis that $\sigma_z^2 \leq \sigma_a^2$ at the 5% level.

**Indicates rejection of hypothesis that $\sigma_z^2 \leq \sigma_a^2$ at the 1% level.

†Indicates rejection of hypothesis that $\sigma_a^2 \leq \sigma_z^2$ at the 5% level.

Table 5: Further Evidence on Cost versus Demand Shocks

	CV	PT	OD	BK	CD
z_t	0.751	0.775	0.699	0.905	0.859
	(0.028)	(0.040)	(0.032)	(0.055)	(0.052)
R^2	0.917	0.849	0.876	0.836	0.803

	FD	LM	CP	DG	AM
z_t	0.797	0.855	0.699	1.044	0.675
	(0.031)	(0.046)	(0.026)	(0.047)	(0.023)
R^2	0.910	0.839	0.914	0.882	0.928

Note: z_t was instrumented with residuals from the regressions described in Table 3. Standard errors are in parentheses.

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