Production and Inventory Control at the General Motors Corporation During the 1920's and 1930's

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This paper analyzes dynamics of production and inventories at the General Motors Corporation during the 1920's and 1930's. We begin by examining anecdotal evidence on the nature of the production control system in force during that period. Motivated by that evidence, we then extend the conventional linear-quadratic model of production behavior to take account of annual shutdown. Finally, we apply the modified model to newly available data on monthly unit production, sales, and inventories during 1924–1940. GM appears to have been aiming to maintain a targeted level of inventory relative to expected sales and, secondarily, to smooth production. (JEL E22, N62)

This paper studies the development and implementation of production control methods at the General Motors Corporation (GM) during the 1920's and 1930's. Especially during the early portion of this period, GM faced large seasonal fluctuations in the demand for its automobiles (much larger, in fact, than it faces today) which seemingly should have provided an ideal opportunity for production smoothing. A rich body of anecdotal evidence shows that GM's senior management thoroughly understood the costs and benefits of production smoothing and that they implemented a program of production control that was well conceived, in principle, for the purpose of smoothing production relative to sales. We evaluate the success of the program using newly available data on units of production, inventories, and sales.

The first section of the paper reviews the design of the inventory and production control procedures in place at GM during the 1920's and 1930's. Much of our information about the development of production control at GM comes from a retrospective study conducted in 1946 by F. Leslie Hayford, a GM economist who had played a leading role in the design of the system and who was later called out of retirement by GM's senior management to describe its main features and evaluate its success. We use Hayford's report together with contemporary public statements of other GM executives to document the essential objectives and operating characteristics of the GM system and to describe the economic environment in which the company perceived itself to be operating.

Section II turns from the anecdotal record to an analytical model of inventory and production behavior. The discussion in this section focuses on the predictions of the model for the long-run comovements of production, sales, and inventories and the implications of those comovements for the conduct

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1As measured by total assets in 1929, General Motors was the third largest industrial firm in the United States, exceeded only by US Steel and Standard Oil of New Jersey (Forbes, 1977). According to registrations data, GM had slightly less than a third of the domestic new-car market in 1929.
of hypothesis testing. In Section III, we modify the basic model by introducing a crude form of annual shutdown. In particular, we explore the implications of specifying that the firm can produce new cars only in selected months of the year, even though it can sell them in all months of the year. The model delivers some useful guidelines as to how estimation and hypothesis testing should be conducted when annual shutdown is important.

Section IV uses newly available data on unit sales, production, and inventories at GM from 1924 to 1940 to assess empirically the new production control procedures. We begin by taking a graphical approach to the analysis, and we use a series of charts to demonstrate five important features of the data. First, GM faced an ideal opportunity to smooth its production relative to its sales in the 1920's and 1930's because there was a great deal of seasonal fluctuation in its sales. Second, inventories, sales, and production moved together over the long run, consistent with the prediction of the model. Third, the variability of production relative to sales was inflated by the occurrence of shutdown each year. In fact, excluding the months when GM's plants were at least partly shut for inventory-taking or retooling, monthly production in many of the years in our sample was less variable than monthly sales; this seldom was so when those months were not excluded. Fourth, notwithstanding the rhetorical commitment of senior managers to "level production," production policy at GM seems to have been geared mainly toward maintaining a tight correspondence between inventories and near-term expected sales; production-smoothing considerations appear to have influenced the behavior of production only at the margin. Finally, the behavior of production appears to have changed about midway through our sample; in particular, the variance of production increased relative to the variance of sales after about 1932.

After completing our graphical inspection of the data, we present some formal statistical results, which we derive by estimating the Euler equations from the modified model of the cost-minimization problem. On the whole, the statistical results corroborate the graphical evidence; we interpret the exceptions to this pattern as reflecting mainly on the small-sample properties of the econometric estimates, rather than on the economic validity of the model. The last section of the paper presents conclusions.

I. Production Control and Planning in General Motors: 1921–1946

General Motors entered the 1920's on a tide of optimism. Believing that the postwar surge in demand would be sustained, the corporation accumulated large stocks of raw materials and made unusually large commitments to buy more (Hayford, 1946 p. 2). The economy slowed sharply, however, leaving the corporation in a precarious position financially and leading some of its officers to push for a new program to control production more closely:

At the beginning of [1921] material commitments were abnormal, inventories greatly over-expanded, and some $80 million had been borrowed from banks. Financial control and coordination of the Corporation's activities were imperative.

[Donaldson Brown, Vice President in Charge of Finances, as quoted in Hayford (1946 p. 4)]

Before a new control program could be implemented, however, better data on the company's current situation had to be collected. Early in 1921, Brown appealed to Alfred Sloan (then Operating Vice President and later President of the corporation) for help in obtaining data on stocks in the hands of dealers and distributors (Hayford, 1946 pp. 8–9). Later in the same year, Brown raised the possibility of also collecting data on deliveries by dealers to retail customers. Although Brown's efforts initially were resisted by others within the corporation, eventually he prevailed, and by October 1922

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2This section takes its title from the report written by F. Leslie Hayford in 1946.
1921 the divisions were reporting "production and factory sales by ten-day periods; and, as of the end of each month, orders on hand and stocks at divisions and in dealers' hands" (Hayford, 1946 p. 13). Hayford further reported that "although dealers did not begin reporting their deliveries to consumers until 1925, the Central Office and the divisions were making use of 'calculated' deliveries to consumers figures long before that time" (p. 15). Indeed, GM began publishing monthly data on retail sales in July 1924.

During late 1923 and early 1924, inventories once again piled up because the divisions had been overly optimistic about the sales prospects. Whereas the 1920–1921 downturn had spurred the corporation to revise its policy on purchases of materials, this second crisis caused them to act on controlling inventories of finished cars; by mid-1924 a new control program was in place (Hayford, 1946 p. 28). In the opinion of the creators of the new control program, its distinguishing characteristic was that it tied production schedules over the forecast period (current month plus three months following) to anticipated deliveries to consumers for the model year as a whole (Hayford, 1946 p. 2). Fluctuations in the business cycle were taken into account only insofar as they were expected to influence current-model-year sales. Model changeover effectively limited the planning horizon to no more than one year.

Under the new production control program, the divisions were required to file with the central office a monthly "Analysis of Production Requirements." The function of this analysis was to record each of the elements of the inventory accumulation identity: stocks on hand at the beginning of the forecast period, projected retail deliveries during the forecast period, desired stocks at the end of the forecast period, and—as a residual—the "indicated maximum production required." The divisions were encouraged to give close and frequent scrutiny to their sales projections. In the words of the 1924 Procedure (the corporate handbook that detailed the mechanics of the control program), these projections "should be subject to constant consideration on the part of the division and subject to change whenever warranted by conditions of any kind" (Hayford, 1946 p. 43).

A key element of these monthly production statements from the divisions was the target level for stocks at the end of the forecast period. According to the 1924 Procedure, this target level was to be "calculated to provide a sufficient number of cars or trucks to meet the requirements of Deliveries to Consumers with the plants operating on the so-called 'level production' basis." In turn, "level production" was to be calculated by assuming "that 8.7 percent of the year's production for domestic requirements will be produced in each month of the year except December, for which month 4.3 percent is assumed, to allow for inventory taking" (Hayford, 1946 p. 39 [quoting from the Procedure of August 1924]).

Alfred Sloan summarized the objectives of the new system in the Annual Report to the stockholders for 1924:

During 1924 the Corporation adopted a production policy as affecting stocks of finished cars which its dealers and distributors will be expected to carry. This policy is predicated upon the sale of cars to consumers as a fundamental index. Such sales are subject to seasonal fluctuations, and the merchandising policy of the Corporation requires that dealers and distributors shall accumulate stocks during seasons of relatively low retail deliveries in order to facilitate prompt deliveries in seasonal periods of heavy retail demand as well as to maintain manufacturing and distributing economies afforded by a reasonably level rate of production. The amount of such stocks varies with the seasons of the year and is based upon a careful analysis of the trend of retail demand.... It is believed that the Corporation in the future will be free from the evils resulting from excess accumulation of stocks involving unnecessary storage, interest and carrying charges as well as drastic curtailment of production schedules such as have occurred at times in the past. [p. 9]
In 1926, Albert Bradley—then Assistant Treasurer of the corporation and later Chairman of the Board—described the potential benefits of the control program in an address before the American Management Association:

If this problem [the marked seasonality in demand] is solved by adjusting production to correspond closely with sales two major objections arise. Productive capacity required to take care of April's sales, for example, would be twice that needed if production were evenly distributed throughout the year, thus increasing capital investment, depreciation, taxes, and similar items and making necessary much larger earnings in order to provide an equivalent return on the investment. Labor offers a second objection to this course, for not only are workmen entitled to steady employment which might be impossible with such wide fluctuations in output, but it is unlikely that the necessary amount of labor would be available when needed for peak production and it is certain that a factory operating under such conditions would be hard pressed to keep its skilled workers, so that the quality of the product might suffer.

[Bradley, as quoted in Automotive Industries, 18 March 1926, p. 489]

Such statements notwithstanding, GM executives recognized that any move toward production smoothing would entail certain costs. Indeed, Bradley himself went on to say:

Flattening out the rate of production and building up stocks of cars against future heavy demand also has its drawbacks. Such storage requires additional capital with its interest charge, greater insurance expense and similar items. If sales do not come up to expectation the cost of carrying stocks may be unduly increased through prolonging the storage period and further losses may result from the necessity of forced selling of the excess stock.

[Automotive Industries, 18 March 1926, p. 489]

We find these statements significant because they highlight several elements of cost that feature prominently in standard modern-day formulations of the production scheduling problem.

The procedure was kept in place as described above with only minor changes throughout the remainder of the 1920's. However, the auto industry was particularly hard hit during the Great Depression. New-car registrations fell more than 2.7 million units (over 70 percent) between 1929 and 1932 (Survey of Current Business, Annual Supplements, 1932 and 1938), compared with a 28-percent decline in real GNP over the period. GM fared little better than the rest of the industry, suffering a 66-percent reduction in retail deliveries of autos. These developments caused GM to reconsider the design of the control program:

In view of the instability of economic conditions in the early 1930's and the resultant greater difficulty in appraising consumer demand, it was recognized that sudden and considerable changes in forecast might become necessary. [Hayford, 1946 p. 87]

In May, 1932, a new Procedure was issued. In tone, the new Procedure was similar to previous ones, the operating divisions being instructed to set production "giving consideration to the best estimate of deliveries to consumers for the complete model sales year and having regard to the extreme desirability of running at as level a rate of production as practicable" (Hayford, 1946 p. 85). In practice, however, the revised program differed importantly from the ones that had been in force during the 1920's. Under the revised program, the central office no longer transmitted to the divisions a "Preliminary Analysis of Production Requirements" which, under the earlier program, had been a starting point for the divisional decision-making process. Furthermore, in recognition of the greater uncertainty about market conditions, the new Procedure specified that the divisions were required to notify the central office only "whenever a change in the outlook necessitates a change of ten percent or more in the total Production Schedule for the entire Forecast period" (Hayford, 1946 p. 87).
Two other developments during the 1930's also may have influenced the apparent effectiveness of the production control program. First, the amplitude of the seasonal variation in sales declined. In part, this reduction undoubtedly reflected the increasing mechanical reliability of newly manufactured cars, the gradual disappearance of open cars, and the increased extent of paved roads. In addition, it probably also reflected the coordinated shift of the shutdown period from the turn of the year to the late summer. The Automobile Manufacturers Association proposed in 1933 "that the industry as a whole shift its new model announcement dates to the fall of the year for the purpose of attaining a greater regularity of production and employment" (Hayford, 1946 p. 59). The Roosevelt Administration supported the plan, and between 1934 and 1935 the introduction dates were moved forward by several months (see Russell Cooper and John C. Haltiwanger, 1992).

Labor relations became more difficult during the late 1930's. Tensions boiled over in 1937, when a sitdown strike by GM workers effectively closed most GM plants in late January and early February. 3 Collectively, these three changes in the 1930's (the introduction of the new procedure, the decrease in the seasonal amplitude of sales, and the increasing difficulty of labor relations) lead us to investigate whether GM's behavior was different after 1932 than it had been before then.

II. The Basic Model

Our baseline model is similar to one proposed by Charles F. Holt et al. (1960) and subsequently studied by many others. 4 We assume that the firm minimizes expected cost as given by:

$$\text{min } E_{t-1} \sum_{j=0}^{\infty} \beta^j \left[ \alpha_0 (\Delta Q_{t+j})^2 + \alpha_1 (Q_{t+j})^2 + \alpha_2 (H_{t+j} - \alpha_3 S_{t+j+1})^2 \right]$$

subject to $H_{t+j} = H_{t+j-1} + Q_{t+j} - S_{t+j}$, with $H_{t-1}$ given, where $\beta$ is a discount factor, $H_t$ is the end-of-period stock of finished cars, $Q_t$ is production, and $S_t$ is sales. We assume that the firm makes its production decision before current-period sales are known. The three components of the cost function all are standard from the inventory literature and are consistent with the anecdotal evidence provided above.

The first-order condition necessary for cost minimization is given by:

$$E_{t-1} \left[ \alpha_0 (2\beta^2 \Delta Q_{t+2} - 2\beta \Delta Q_{t+1} + \Delta Q_t) + \alpha_1 (-\beta Q_{t+1} + Q_t) + \alpha_2 (H_t - \alpha_3 S_{t+1}) \right] = 0.$$ 

A similar equation holds for all periods "$t$" in this baseline model. 6

A. Identification

The parameters $\{\alpha_0, \alpha_1, \alpha_2\}$ in equation (2) are not separately identified. In our baseline set of estimates, we achieve identification by imposing the following restriction on these three parameters:

$$\alpha_0 (1 + 4\beta + \beta^2) + \alpha_1 (1 + \beta) + \alpha_2 = 1.$$ 

Students of control theory will recognize that equation (3) is motivated by the strong

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3Aside from these labor disputes, we found no mention (either in Hayford's report or elsewhere) of transitory fluctuations in costs.


5For expository convenience, here we suppress linear terms in the cost function. In the empirical work, we allow for such terms by including an intercept in the Euler equation.

6Equation (2) is derived by using the accumulation identity to substitute out all occurrences of $Q_{t+j}$ in the objective function, differentiating with respect to $E_{t-1} H_t$, and then simplifying again using the accumulation identity.
form of the Legendre-Clebsch condition (Robert F. Stengel, 1986). We should emphasize, however, that any linear restriction across \( \{\alpha_0, \alpha_1, \alpha_2\} \) would yield equivalent results asymptotically, so long as the restricted linear combination did not in fact equal zero in the population.\(^7\)

We also impose a priori the value of the discount factor \( \beta \) following a long tradition in this literature, and in line with the suggestion made by Allan W. Gregory et al. (1989), who discuss the difficulty in identifying \( \beta \) in this class of models.

B. Multicointegration and the Importance of Allowing \( \alpha_3 \) To Be Nonzero

Equation (2) can be rewritten as follows:

\[
(2') \quad E_{t-1} \left\{ \alpha_0 (\beta^2 \Delta Q_{t+2} - 2\beta \Delta Q_{t+1} + \Delta Q_t) \right. \\
- \alpha_1 \beta (\Delta H_{t+1} + \Delta S_{t+1}) \\
+ \alpha_1 \Delta H_t - \alpha_2 \alpha_3 \Delta S_{t+1} \\
+ \alpha_2 \left[ H_t - \left( \frac{\alpha_3 (1-\beta)}{\alpha_2} \right) S_t \right] \right\} = 0.
\]

This form of the equation highlights that as long as \( S_t \) is integrated of order 1, \( I(1) \), \( H_t \) must be \( I(1) \) also, and \( H_t \) and \( S_t \) must be cointegrated. Furthermore, if \( H_t \) is \( I(1) \), \( \Delta H_t \) must be \( I(0) \); but since \( \Delta H_t = Q_t - S_t \), \( Q_t \) and \( S_t \) must be cointegrated. Hence, our analytical model predicts that \( H_t, Q_t, \) and \( S_t \) should exhibit the type of long-run inter-relationships labeled “multicointegration” by Clive W. J. Granger and Tae-Hwy Lee (1989, 1990).

Equation (2') also highlights the importance of allowing \( \alpha_3 \) to differ from zero. As West (1986) noted, some authors have argued that \( \alpha_3 \) should be set equal to zero. Equation (2') makes clear, however, that the parameter describing the cointegrating relationship between \( H_t \) and \( S_t \) would be negative if \( \alpha_3 \) were set equal to zero (provided \( \alpha_1 \) and \( \alpha_2 \) are positive), in which case a permanent increase in sales would induce a permanent decrease in inventories.\(^8\) In fact, a common feature of actual data is that inventories and sales covary positively in the long run as well as in the short run.

C. Inference

We have shown that if \( Q_t, S_t \), and \( H_t \) are integrated, they are also cointegrated. The results of West (1988) and Christopher A. Sims et al. (1990) therefore suggest that inference in our model can be carried out using standard asymptotic distributions.\(^9\) If the stochastic process followed by sales is the only source of nonstationarity, there is no need to include time trends in the specification of the model, regardless of whether sales are trend- or difference-stationary. However, if there is some other source of a deterministic trend in the data—say, a deterministic trend in costs unrelated to production—then deterministic trends should be included in the specification of the Euler equation. We carry out our estimation and hypothesis-testing under the assumption

\(^7\)Ramey (1991) provides the citation to Stengel (1986). She imposes \( \alpha_2 = 1 \) as an identifying assumption and then tests whether the Legendre-Clebsch condition is satisfied.

\(^8\)In the new steady state after a positive innovation in permanent sales, the firm will choose to incur a higher marginal stock-out cost because it will be experiencing a higher marginal production cost (associated with \( \alpha_1 \)). Unless the target level of inventories is a positive function of sales, the higher marginal stock-out cost will entail a lower level of inventories.

\(^9\)We are grateful to one of the anonymous referees for considerable assistance on the issue of inference in this model when the variables are difference-stationary.
that deterministic trends need not be included in the equation.

We assume that production in period \( t \) is chosen before the level of sales (or any other random variable) in period \( t \) is known; therefore, the expectational error that results from dropping the expectations operator from equation (2) is \( MA(1) \). We estimate the coefficients and their standard errors using the generalized method of moments with a covariance matrix calculated according to the method of Whitney K. Newey and West (1987).\(^{10}\) Our computer code and a complete data set are available (from the authors) upon request.

III. The Model With Annual Shutdown

Thus far, we have followed earlier authors in assuming that the manufacturer produces output every period. We view this assumption as particularly unsatisfactory for the automobile industry. After all, even during the 1920's and 1930's GM closed its assembly plants each year for inventory-taking and retooling. We take a small step toward reality in our theoretical model by assuming that the manufacturing plant shuts down once a year. We treat this shutdown period as exogenous to the model, as if it were, say, constitutionally imposed upon the company as a condition of incorporation.\(^{11}\) We maintain the assumption that sales are made throughout the year, including during the shutdown period. We further assume that the manufacturer pays a fixed cost to open or shut a plant and does not, in opening one up or shutting one down, bear the cost usually associated with changing production.

In most months, equation (2) remains the relevant first-order condition despite the explicit introduction of annual shutdown into the problem. When shutdown has just occurred or is imminent, however, a modified first-order condition is relevant. For example, in the first period following a shutdown, the relevant first-order condition is given by

\[
E_{t-1}\{\alpha_0(\beta^2\Delta Q_{t+2} - 2\beta \Delta Q_{t+1}) \\
+ \alpha_1(-\beta Q_{t+1} + Q_t) \\
+ \alpha_2(H_t - \alpha_3 S_{t+1})\} = 0
\]

where the absence of the term in \( \Delta Q_t \) reflects our assumption about the cost of reopening a plant.

In the last period of operation before a one-month shutdown period, the following first-order condition obtains:

\[
E_{t-1}\{\alpha_0(\beta^3\Delta Q_{t+3} + \Delta Q_t) \\
+ \alpha_1(-\beta^2 Q_{t+2} + Q_t) \\
+ \alpha_2\{H_t - \alpha_3 S_{t+1}\} \\
+ \beta(H_{t+1} - \alpha_3 S_{t+2})\} = 0.
\]

In the penultimate month of production before shutdown the following first-order condition is relevant (regardless of how long the shutdown is expected to last):

\[
E_{t-1}\{\alpha_0(-2\beta \Delta Q_{t+1} + \Delta Q_t) \\
+ \alpha_1(-\beta Q_{t+1} + Q_t) \\
+ \alpha_2(H_t - \alpha_3 S_{t+1})\} = 0.
\]

Modifications of equation (5) relevant for two- and three-month shutdowns are easily

\(^{10}\)In the first step, we estimate the \( \alpha 's \) using nonlinear two-stage least squares. (The equation is nonlinear in the parameters when identification is achieved using equation (3), but not when identification is achieved by setting \( \alpha_2 = 1 \).) Next, we form the cross products of the residuals from the first stage with the instruments, using the lags = 3 and damp = 1 options in RATS. Then we reestimate the \( \alpha 's \) using the inverse of the cross-products matrix as a weighting matrix, again invoking the lags = 3 and damp = 1 options. Results obtained by setting lags = 2 were very similar to those shown in Tables 1 and 2.

\(^{11}\)A more complete treatment of the problem would include an explanation for the choice of a technology that requires shutdown to occur (see Cooper and Haltiwanger [1993] for a serious consideration of the machine-replacement problem).
derived. Of course, we recover the condition \( Q_s = 0 \) for months in which the plant is not operating.

Thus, the augmented model predicts that the specification of the first-order condition for any given month will depend on the orientation of that month with respect to shutdown periods, both preceding and following. Many strategies for dealing with this situation are possible; we pursue two of them here. The first involves simply dropping the shutdown-contaminated observations from our sample and estimating the cost parameters using the remaining observations. The second involves retaining all non-shutdown observations in the sample, and applying to each observation the appropriate form of the Euler equation, enforcing that \( \alpha_0, \alpha_1, \alpha_2, \) and \( \alpha_3 \) are the same in all specifications.\(^{12}\) The advantage of the second approach is that it attempts to exploit the information in the observations coming just after and just before shutdown periods and therefore holds out the possibility of a gain in statistical efficiency. The risk in this approach, however, is that we will not be able to incorporate that additional information into our model in a valid fashion, and in expanding the sample, we may primarily be increasing the specification error in the equation, rather than augmenting its statistical efficiency. One troubling indicator in this regard is that we never observe production to be zero in any month in our sample, contrary to the key assumption in our shutdown-augmented model.\(^{13}\) On balance, therefore, we favor the first approach, but we implement both of them in the next section.

\section*{IV. Empirical Results}

We begin with five charts that highlight the main features of the data.\(^{14}\) First, monthly sales during the 1920's and 1930's were much more variable than they are today. Especially during the 1920's and early 1930's, the bulk of this variation was accounted for by regular seasonable fluctuations. Figure 1 demonstrates these points by showing monthly domestic unit sales by all GM divisions as a percentage of a 12-month centered moving average for the periods 1924–1940 (top panel) and 1971–1987 (bottom panel). In the 1920's, the pace of sales during the busiest month of the year (generally March or April) frequently was more than three times as great as the sales pace during the slowest month (generally November or December). In the mid and late 1930's, the amplitude of the variation in sales declined somewhat, and the seasonal pattern became less regular. Even in that later period, however, the amplitude of the variation in sales was enormous compared with more recent experience: Since 1971, sales in the busiest months have rarely been even twice as great as sales in the slowest months (bottom panel).

Second, the long-run comovements of inventories, sales, and production conform to the predictions of the model. Figure 2 abstracts from short-run (especially seasonal) fluctuations by plotting 12-month centered

\(^{12}\)When we are estimating under this approach, we make room for other differences across the periods by allowing the intercept to take on a different value depending on whether the observation in question is (i) a normal operating month, (ii) a month immediately following a shutdown period, (iii) a month immediately preceding a shutdown period, or (iv) a month preceding a shutdown period by two months.

\(^{13}\)We suspect that our failure to observe zero production mainly reflects the fact that GM did not perfectly align its shutdown periods, either across divisions or with the calendar months, and so was always operating at least one of its plants during at least part of a “shutdown” month. Since our model views each period as a point in time, it is silent on the issue of how production should behave during a month when GM was operating only part of its capacity part of the time.

\(^{14}\)The data were kindly provided to us by a member of GM's staff. The data are monthly and cover the corporation as a whole. Data at the divisional level are not available. The data for 1925 include Chevrolet trucks; data for the other years do not include Chevrolet trucks. In 1925, Chevy trucks accounted for about 5 percent of total sales and production of the corporation as a whole. We made a simple adjustment to the level of sales and production in 1925, which preserved the inventory accounting identity between 1924 and 1926. Details of this adjustment will be provided along with the data upon request. The GM staff member cautioned that the data from the early years may be less reliable than those from the later years.
Figure 1. Monthly Sales as a Percentage of a Centered 12-Month Moving Average
Figure 2. Long-Run Relationships Among Production, Inventories, and Sales
(Centered 12-Month Moving Averages)
moving averages. The top panel shows sales and production and strongly suggests that those two variables are cointegrated and that the cointegrating parameter equals 1. The bottom panel shows sales against a linear transformation of inventories (where the linear transformation was chosen in line with one of our preferred sets of estimates reported below) and shows that inventories and sales also appear to have moved together over the long term. The relationship between these two variables was not as tight as the one between production and sales. However, our confidence in the validity of the underlying relationship is bolstered by the fact that all of the important deviations from the equilibrium relationship between inventories and sales have obvious economic interpretations. On the upside, inventories were unusually high during 1924 (the very episode that caused GM to institute the new program of production control), the first three years of the Great Depression, and the recession of 1938. On the downside, inventories were unusually low during 1928 (at the peak of the expansion) and in the winter of 1936–1937, when labor strife culminated in the sitdown strike of 1937.

Third, the behavior of production during months we identify as "operating" months differed markedly from the behavior of production during the year as a whole. Figure 3 compares the variance of production with the variance of sales for each model year on two different bases: first using data from all months of each model year (the dashed line), and second using data from only the operating months of each model year (the solid line). In more than half the years

15We were unable to develop conclusive information on the exact timing of the annual shutdowns at the individual plant level. We inferred approximate shutdown dates from Hayford and various issues of Automotive Industries, a contemporary trade journal. Whenever we had substantial doubt about whether GM was fully operational during a given month, we erred on the side of caution and flagged that month as a shutdown month. The months we identified as shutdown months are listed in the notes to Table 1.
Figure 4. Production, sales, and the level of inventories
between 1925 and 1940, the variance ratio calculated over operating months was at least 30-percent lower than the variance ratio calculated over all months. Only once (in 1938) was the variance ratio for operating months higher than the variance ratio for all months.\(^{16}\)

Fourth, contrary to the anecdotesal evidence presented above, GM appears to have arranged its production chiefly to maintain a reasonable short-run correspondence between the level of inventories and expected sales. At the margin, production appears to have been a bit smoother than it would have been if GM had aimed to hold the inventory-sales ratio fixed to the exclusion of all other factors. Figure 4 provides evidence in support of the first part of this proposition. It plots the unfiltered levels of production and sales in the top panel and inventories and sales in the bottom panel. The bottom panel shows that inventories tracked sales not only at business-cycle frequencies, as was evident in Figure 2, but also at seasonal frequencies, suggesting that one of GM's objectives was to tie the level of inventories to the volume of sales within each model year as well as between model years. Figure 5, which shows the inventory-sales ratio \(\frac{H_t}{\bar{S}_{t+1}}\) as the solid line and production as the dotted line, supports the second part of the proposition. In every year between 1925 and 1932, the inventory-sales ratio hit its seasonal low when production was at or near its high, consistent with the conclusion that production was smoother than it would have been if GM had been aiming to hold the inventory-sales ratio constant at some fixed level year-round.

\(^{16}\)The spike in 1938 appears to reflect a colossal forecasting error. GM opened the 1938 model year with two months of extremely aggressive production, even as the economy was turning into a sharp nosedive. They then spent the rest of the model year slashing production not only in line with the weakness in sales, but also to shed the inventories that had piled up in the first few months of the model year.
Finally, the behavior of production was different after 1932 than it had been before 1932. This difference is evident in Figure 5: in some years after 1932, the correlation between the inventory-sales ratio and production appears to have been about zero; in other years (such as 1939 and 1940), it appears to have been strongly positive. Overall, it is much more difficult to make the case on the basis of this chart that production after 1932 was smoother than it would have been under a policy of fixing the inventory-sales ratio. Figure 3 provides another perspective on the change in the behavior of production in 1932: in the eight years after 1932, the variance ratio measured over operating months exceeded 1 four times; by contrast, in the eight years up to and including 1932, the variance ratio exceeded 1 only once (in 1932). We view both of these pieces of evidence as suggesting that some factor or factors inhibited the apparent effectiveness of the production control program after 1932. Such factors could have been either internal or external to the firm. Two obvious candidates in this regard are the 1932 modification in the production-control program and the increased difficulty of labor relations.

We now report the results of estimating the parameters appearing in the first-order conditions for cost minimization. Our goal in conducting the formal statistical work is to develop additional evidence either corroborating or contradicting the graphical evidence already presented. Table 1 summarizes nine sets of results, reflecting three different methods of handling shutdown periods and three different sample periods. With regard to the treatment of shutdown periods, the first method involves simply ignoring any special considerations related to the handling of the shutdown periods and applying the basic first-order condition [equation (2)] to all observations in the sample. The second method is our preferred one; it involves dropping all shutdown-contaminated observations from the sample and applying equation (2) to the remaining observations. In line with the results from our theoretical model, we treat an observation as "shutdown-contaminated" if it was (a) a shutdown month; (b) a month that immediately followed a shutdown period; or (c) a month that preceded a shutdown period by either one or two months. The third method involves dropping only the shutdown months themselves and selecting for each of the remaining observations in the sample the appropriate specification of the first-order condition from among equations (2), (4), (5), (6), and the modification of (5) for two- and three-month shutdowns. As for sample periods, we implement each of these three methods over: the full sample period (January 1925–December 1940), the period before any major changes were made in the original program (January 1925–May 1932), and the remainder of the sample period (June 1932–December 1940). All nine sets of results shown in Table 1 were derived using the Legendre-Clebsch condition [i.e., equation (3)] as the identifying assumption.  

The most important feature of the results in Table 1 is that the estimated slope of the marginal-cost curve, given by \( \hat{\beta} + \hat{\alpha} \), is positive in all specifications. We interpret this result as tautologous to the claim that GM was a production-smoother. We note, however, that the implications of the positive slope of the marginal-cost curve for the dynamics of production depend crucially on the process followed by sales.

In response to a transitory (white-noise) increase in sales, the estimates shown in

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17 The estimates in Tables 1 and 2 were obtained using an instrument set that included the following 10 variables: the contemporaneous value and the first two lags of the change in production; the first two lags each of the change in sales, the change in the log of industrial production, and the change in the log of the composite Standard and Poor's stock index; and the first lag of the difference between production and sales. In addition, the instrument set included as many seasonal dummy variables as possible (a dummy variable for December could not be included, for example, if no December observations were included in the particular sample being estimated). This instrument set reflects our assumption that GM did not know current-period sales when it chose production. We included the contemporaneous value of production in the instrument set because it was the choice variable of the firm.
Table 1—Estimated Cost Parameters: The Baseline Estimates

<table>
<thead>
<tr>
<th>Sample</th>
<th>(a_0)</th>
<th>(a_1)</th>
<th>(a_2)</th>
<th>(a_3)</th>
<th>(J) statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. All months:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. January 1925–December 1940</td>
<td>0.210</td>
<td>-0.142</td>
<td>0.032</td>
<td>1.28</td>
<td>24.8</td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
<td>(0.035)</td>
<td>(0.019)</td>
<td>(0.65)</td>
<td>[0.13]</td>
</tr>
<tr>
<td>b. January 1925–May 1932</td>
<td>0.195</td>
<td>-0.101</td>
<td>0.036</td>
<td>0.81</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>(0.010)</td>
<td>(0.025)</td>
<td>(0.024)</td>
<td>(0.38)</td>
<td>[0.43]</td>
</tr>
<tr>
<td>c. June 1932–December 1940</td>
<td>0.259</td>
<td>-0.334</td>
<td>0.121</td>
<td>0.61</td>
<td>19.9</td>
</tr>
<tr>
<td></td>
<td>(0.010)</td>
<td>(0.039)</td>
<td>(0.030)</td>
<td>(0.13)</td>
<td>[0.34]</td>
</tr>
<tr>
<td>2. Non-shutdown-contaminated months:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. January 1925–December 1940</td>
<td>0.194</td>
<td>-0.103</td>
<td>0.046</td>
<td>1.22</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>(0.018)</td>
<td>(0.054)</td>
<td>(0.020)</td>
<td>(0.47)</td>
<td>[0.29]</td>
</tr>
<tr>
<td>b. January 1925–May 1932</td>
<td>0.177</td>
<td>-0.052</td>
<td>0.045</td>
<td>0.71</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>(0.010)</td>
<td>(0.032)</td>
<td>(0.022)</td>
<td>(0.25)</td>
<td>[0.48]</td>
</tr>
<tr>
<td>c. June 1932–December 1940</td>
<td>0.223</td>
<td>-0.196</td>
<td>0.057</td>
<td>0.33</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>(0.023)</td>
<td>(0.075)</td>
<td>(0.022)</td>
<td>(0.35)</td>
<td>[0.68]</td>
</tr>
<tr>
<td>3. All operating months:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. January 1925–December 1940</td>
<td>0.216</td>
<td>-0.148</td>
<td>0.007</td>
<td>-2.75</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>(0.017)</td>
<td>(0.054)</td>
<td>(0.019)</td>
<td>(9.43)</td>
<td>[0.58]</td>
</tr>
<tr>
<td>b. January 1925–May 1932</td>
<td>0.206</td>
<td>-0.122</td>
<td>0.012</td>
<td>2.06</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>(0.010)</td>
<td>(0.031)</td>
<td>(0.012)</td>
<td>(1.78)</td>
<td>[0.32]</td>
</tr>
<tr>
<td>c. June 1932–December 1940</td>
<td>0.203</td>
<td>-0.131</td>
<td>0.046</td>
<td>-0.60</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>(0.023)</td>
<td>(0.073)</td>
<td>(0.022)</td>
<td>(0.74)</td>
<td>[0.42]</td>
</tr>
</tbody>
</table>

Notes: Estimates of constant terms are not reported. We assumed that the shutdown months were as follows: 12/25, 12/26, 11/27, 12/27, 11/28, 12/28, 11/29, 12/29, 10/30, 11/30, 10/31, 11/31, 10/32, 11/32, 11/33, 12/33, 10/34, 11/34, 12/34, 9/35, 9/36, 9/37, 8/38, 9/38, 7/39, 8/39, 9/39, 8/40, and 9/40. Standard errors are in parentheses; \(p\) values are in square brackets.

Table 1 imply that GM would have spread its production response over several periods, building back its lost inventory over time but never allowing the increment to production in any single period to exceed the size of the original shock to sales. This result follows because a white-noise shock to sales does not disturb the desired level of inventories (which is calculated as a ratio to expected future sales) and, hence, does not induce an accelerator-like response in production.

In contrast, in response to a permanent (random-walk) increase in sales, the estimates imply that, during the transition period, GM would have to have boosted its production by more than the increase in sales, on average. This "excessive" response during the transition period—seemingly contradictory to the notion of production-smoothing—would have been required not only to offset the initial drawdown of inventories in the period of the sales surprise, but also to build inventories up to a higher level, given the (permanently) higher level of sales. In the new steady state, the increment in production over the old steady-state level would have been the same as the increment in sales. This intuition implies that even a stationary, but seasonal, sales process would have induced similar accelerator-like behavior in production, again via the adjustment of inventories to keep them in line with expected sales. We conclude that the close comovement of sales and production so overwhelmingly evident in the top
panel of Figure 4 in no way contradicts the assertion that the marginal-cost curve is upward-sloping.\textsuperscript{18}

Another feature of the results in Table 1 worth mentioning is that the estimated cost of deviating from the target level of inventory is positive in all specifications, though not significantly different from zero in all sample periods except when we exclude shutdown-contaminated months. By contrast, the estimated target inventory--sales ratio is surprisingly poorly determined; indeed, the point estimate is negative in lines 3a and 3c, though not significantly so.

Overall, the parameter estimates and equation diagnostics are fairly robust to the method of handling shutdown. Indeed, the only distinction of any note that we can detect is the just-mentioned sensitivity of the estimate of the target inventory--sales ratio. Likewise, the parameter estimates and equation diagnostics are relatively robust to the choice of sample period. The most suggestive hint from the Euler equations of a regime shift in about 1932 comes from the autocorrelation structure of the disturbances. The autocorrelation function of the residuals underlying line 2b (estimated from the pre-1932 sample) is given by:

\begin{tabular}{ccccccc}
\text{lag:} & 1 & 2 & 3 & 4 & 5 & 6 \\
\text{correlation:} & 0.39 & 0.09 & 0.12 & -0.04 & 0.04 & -0.04 \\
\end{tabular}

The autocorrelation function of the residuals underlying line 2c (estimated from the post-1932 sample) is:

\begin{tabular}{ccccccc}
\text{lag:} & 1 & 2 & 3 & 4 & 5 & 6 \\
\text{correlation:} & -0.43 & -0.13 & 0.19 & 0.02 & 0.02 & -0.19 \\
\end{tabular}

In both cases the asymptotic standard error is 0.13. Over the early sample period, the disturbances appear to follow the hypothesized MA(1) process. However, over the late sample period there is greater evidence of correlation at longer lags, consistent with the view that cost shocks may have become more important after 1932 (see Eichenbaum [1989], among others, on the implications of cost shocks for models of the type we study). On the whole, however, we are frankly surprised by the model's apparent inability to discriminate between methods of treating shutdown periods or between sample periods.

Table 2 provides additional results based on alternative assumptions about various features of the model. The first three sets of estimates reported there were derived using our preferred method of handling the shutdown periods. Lines 1 and 2 examine the ability of the data to distinguish between costs of changing production and direct costs of producing as sources of production smoothing. We find that the model is about equally happy with either alternative: in both cases, the estimated slope of the marginal-cost curve remains positive and highly significant. Line 3 shows the results of fixing $\beta$ at 0.99 rather than 0.995; not surprisingly, this perturbation makes hardly any difference.

The last three lines in Table 2 report the results of using $\alpha_2 = 1$ as the identifying assumption rather than equation (3) and handling shutdown periods by the first method (i.e., ignoring their presence).\textsuperscript{19} Recall that, asymptotically, the specification of the identifying assumption should have no effect on either the nature of the decision rule implied by the parameter estimates, or the overall statistical adequacy of the model. In our sample, however, the choice of the identifying assumption turns out to matter a good deal. As shown on line 4b, $\alpha_0$ is estimated to be negative in the early sample period under the alternative identifying assumption, and the estimated slope of the marginal cost curve is negative in all three

\textsuperscript{18}Previous authors have noted the importance of the accelerator mechanism in the standard linear-quadratic model of inventories. For example, absent the accelerator, West (1986) would have been able to reject the linear-quadratic model as an adequate representation of his data simply from the observation that production was more variable than sales. Krane (1993) traces the role of the accelerator in transmitting seasonality in sales into seasonality in production.

\textsuperscript{19}We obtain similar results using the second method of handling the shutdown periods.
samples. Clearly, the economic implications of the alternative estimates differ dramatically from those of the baseline estimates.

In our view, however, the estimates based on setting \( \alpha_2 = 1 \) should be discounted for three reasons. First, the estimated residuals associated with those estimates are so highly autocorrelated as to suggest that the variables in the model are not cointegrated. (For example, the Durbin-Watson statistic for the residuals from line 4b is 0.23.) Second, the results based on the alternative normalization seem inconsistent with the graphical evidence presented earlier, which pointed toward production smoothing at least before 1932. Finally, we note that others who have experimented with the \( \alpha_2 = 1 \) normalization have also found it to deliver peculiar results. For example, Krane and Braun (1991) report that the Legendre-Clebsch condition was violated in about a third of the industries they studied when they used \( \alpha_2 = 1 \) as their identifying assumption; they found no such violations when they achieved identification by setting \( \alpha_0(1 + \beta) + \alpha_1 = 1 \). West and Wilcox (1992) conduct simulation exercises and find that the Legendre-Clebsch normalization seems to outperform the \( \alpha_2 = 1 \) normalization when applied to data that were generated using cost parameters similar to those shown in Table 1. Thus, we view the alternative results as more of a puzzle with regard to their econometric implications (that the asymptotic approximations of the statistical distributions are very poor) than with regard to their economic implications.

V. Conclusion

In 1924, General Motors implemented a new production control procedure that was intended to "regularize" production and employment. In a report to the Executive and Operations Committees of the corporation, Donaldson Brown described the pro-
program as "permit[ing] an accumulation of stock during the period of the year when sales to consumers are below the average rate, and requir[ing] a liquidation of stock during the period of the year when sales to consumers are above the average rate" (Hayford, 1946 p. 42). A simple plot of monthly inventories and sales suggests that, measured against Brown's yardstick, the program was a failure: during the period we study, GM usually accumulated inventory in the spring, when sales were on their seasonal upswing, and decreased inventory in the late summer and fall, when sales were tailing off.

Further examination of the data, however, reveals considerable success in smoothing production relative to a different yardstick. A plot of production and the inventory--sales ratio shows that, during the early years of the production control program, GM drove its inventory--sales ratio down during the time of the year when production was at its highest and allowed its inventory--sales ratio to spike when production was at its lowest. Moreover (and to our surprise), the data contain some hints of smoothing of this type even at business-cycle frequencies: inventories were taken down to unusually low levels relative to sales at the peak of the expansion at the end of the 1920's and were allowed to accumulate to unusually high levels, relative to sales, during the Great Depression. Formal statistical evidence, based on a modified linear-quadratic model of production behavior, largely corroborates the graphical evidence. We conclude that GM did succeed, during the 1920's and early 1930's, in making production smoother than it would have been if the corporation had only sought to stabilize the inventory--sales ratio.

In 1932, however, the corporation revised the structure of the program. We also deduce indirect evidence that cost shocks became more important. In the second half of our sample, the evidence of production smoothing is more tenuous, even by our more expansive definition. For example, we find that the correlation between the inventory--sales ratio and the level of production—strongly negative before 1932—declines markedly in absolute value after 1932.

We close with two summary points. First, the fact that production tracked sales does not, by itself, imply that GM faced a flat or downward-sloping marginal-cost curve. Indeed, our preferred parameter estimates imply that GM faced an upward-sloping marginal-cost curve and yet still chose to make production mimic sales closely. Our interpretation of the evidence relies heavily on the importance of the inventory--sales target as a determinant of GM's behavior and reinforces the importance of research such as that of James A. Kahn (1992) which seeks to provide a firmer micro foundation for the observed inventory--sales targeting. Second, for certain issues, the phenomenon of annual shutdown is important. As Cooper and Haltiwanger (1993) note, the type of machine replacement that often motivates annual shutdown is common to many industries. Further study of the machine-replacement problem may provide additional insights as to when the explicit treatment of shutdown is essential.

REFERENCES


Eichenbaum, Martin, “Some Empirical Evidence on the Production Level and Production Cost Smoothing Models of Inventory Investment,” American Economic


