

Real-Time, Wide Area Dispatch of Mobil Tank Trucks

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Mobil Oil Corporation has adopted a completely integrated, highly automated, real-time computer system for centralized control of distribution to customers in the continental United States of light petroleum products — gasolines, diesel, heating oil, and so forth. This system manages all aspects of marketing and distribution, from order entry via an audio response computer through credit checking, delivery, and billing — operations that annually generate \$4 billion in sales on 600,000 customer orders and that use 120 bulk terminals and a fleet of more than 430 vehicles. The heart of this system is computer assisted dispatch (CAD), a collection of integer programming methods used within a real-time, transaction-driven information management system, which allots about one second, on average, per dispatch for optimization. CAD exploits the experience and knowledge of the human dispatchers it assists. Using CAD, Mobil has substantially reduced costs and staff while improving customer service.

In the spring of 1985, a nationwide system for dispatching and processing customer orders for gasoline and distillates began full operation at Mobil Oil

Corporation. The final computer and communications connections marked a historic moment in the marketing and distribution of light petroleum products: a

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TRANSPORTATION — ROUTE SELECTION
PROGRAMMING — INTEGER, APPLICATIONS

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completely integrated, highly automated system now controls the flow of \$4 billion annual sales from initial order entry to final delivery confirmation and billing. The entire complex process is overseen by a handful of people in a small office in Valley Forge, Pennsylvania, but it now operates more efficiently than the old system in all respects: it provides better customer service, greatly improved credit, inventory, and operating cost control, and significantly reduced distribution costs.

We describe here the development and implementation of CAD (computer assisted dispatch), the centerpiece of Mobil's new system. Without this component, an electronic dialog among

Dispatching turns out to be the most crucial time-sensitive central activity in this business.

the other marketing and distribution data systems would not be possible or even sensible. CAD is designed to assist human dispatchers in real time as they determine the means by which ordered product will be safely and efficiently delivered to customers. Dispatching turns out to be the most crucial time-sensitive central activity in this business and perhaps the most influential in terms of total business performance. CAD supports the dispatching work load so well that just a few people are needed to comfortably control operations nationwide. At the same time, CAD uniformly enforces management policy and saves money.

Under the best of conditions, dispatch-

ing is hard work. The dispatcher must attend to myriad details concerning customer, vehicle fleet, and product status. Dispatching petroleum tank trucks involves following intricate rules that govern safe and efficient operation. The costs of distribution are very sensitive to dispatching decisions, and even small errors in judgment can severely disrupt daily operations. Under the time pressure of peak business activity, dispatching is stressful, and manual dispatching can be exhausting. We will describe some of the reasons for this along with CAD's real-time prescriptive cure.

When considering the dispatching problem, one must take into account the following aspects (Figure 1): an area may have several terminals (sources of products). Each terminal may have different products available, and the same product may have a different laid down cost at each terminal. Although over 20 products may be distributed (gasolines, diesel fuel, aviation fuels, heating oil, and so forth), three grades of motor gasoline constitute most of the volume.

The trucks available may be Mobil's own trucks (its private fleet) or hired trucks (either dedicated contract carrier trucks or common carrier trucks). Most terminals are domiciles for some trucks, but certain terminals have no trucks, such as those where the product is available through an exchange agreement with another company. The cost structure for each truck depends on its specific terms of employment: some trucks incur costs on a miles and hours basis, while others are quoted by a common carrier at a specific point-to-point cost. In some cases

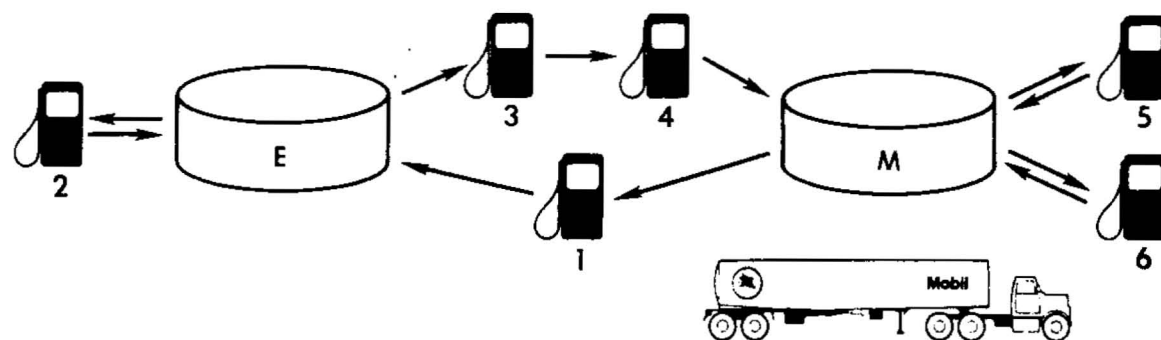


Figure 1: A small area dispatch in which terminal M is a truck domicile, and terminal E is not. Customer 1 is used as a relay load to terminal E so that customer 2's order may be delivered economically from there. Customers 3 and 4 constitute a split load (a multiple stop, route delivery). This simplified illustration ignores limited product availability, one-way streets, weight and load restrictions, bridge and road tolls, truck shift limits, and other realistic features encountered in practice.

minimum charges may also apply. The trucks may have different capacities, and different numbers and sizes of separate bulk cargo compartments. In addition, trucks may carry special delivery equipment, such as meters, couplings, or pumps, and be Mobil-marked or unmarked. Trucks may be loaded up to volume marks welded inside each compartment, or by metered volume, depending on the legal jurisdictions through which they pass. Most trucks deliver products by simply dropping the contents of the compartments into underground tanks.

An order usually consists of several products and may be for a truckload or less. Each order has a requested delivery shift and a delivery location that may require special delivery equipment.

Assigning orders as loads on trucks may require gallonization (adjustment) of the ordered quantities of products so that they fit into the truck compartments. Further, equipment compatibility must be taken into account, and the routes must reflect the various weight jurisdictions

through which the trucks pass, as well as the cost of road and bridge tolls. Finally, the trucks must be safely loaded; for example, double bulkheads are needed between certain products to prevent product contamination, and in partially loaded trucks, the load must be in the forward compartment(s).

The objectives of the dispatching process are to minimize the cost of delivered product, to balance the work load among the company trucks, and to load the maximum weight on a truck while adhering to all laws and proper loading rules. These conflicting objectives must be met within the constraints of maintaining customer service levels.

In order to achieve an acceptable dispatch, the following set of decisions must be made:

- From which terminal to supply each order;
- Assignment of orders to delivery trucks;
- Gallonization of order quantities to fit truck compartments, loading the trucks to their maximal legal weight; and

— Routing the trucks and sequencing deliveries.

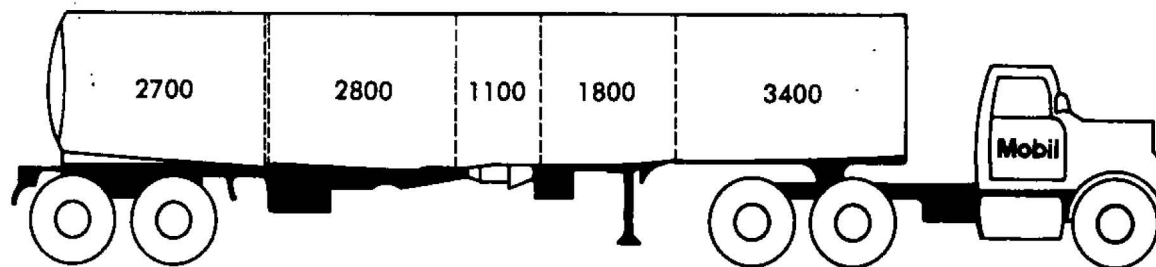
These decisions must take into account truck cost; product cost, availability, specific gravity, and temperature by terminal; equipment compatibility; weight jurisdictions; and delivery policy. Due to the complexity of the decisions and the interaction among them, human dispatchers are usually looking for acceptable feasible solutions. They may be guided by simple decision rules that perform reasonably well on the average but poorly in specific situations. In such an environment, dispatchers cannot be expected to look for very low-cost solutions. In fact, they are not even aware of all the needed data. Dispatching decisions are too complex for "human optimization."

For example, loading the trucks by weight (instead of by volume) allows more gallons to be loaded on the trucks, but it is tedious in detail. Volumetric compartment markers essentially say, "load gasoline up to this point, or diesel up to this lower point, . . . and you will never be over standard weight or overfull." Although this provides an easy loading rule, it is necessarily very conservative in that it allows for the heaviest conceivable gasoline, or diesel, and so forth. Usually, more gallons (than the nominal volume) may be loaded in a compartment without exceeding the legal weight of the truck and without increasing the delivery cost. The density of each light petroleum product varies as a complicated nonlinear function of product temperature and gravity (standard weight per volume); given the temperature and gravity of each product on an order, the maximum shell

capacity and weight for each truck compartment, the tare weight, and some additional restrictions, it is sometimes possible to load five to six percent more product. But no human dispatcher can be expected to manually incorporate these considerations into his dispatching decisions. Convince yourself of this by trying to solve the simple loading problems in Figure 2, and note that a dispatcher must consider thousands of such trial fits every day.

System Development

In 1980, Mobil had four light products control centers where order taking, dispatching, and order entry were performed manually. The fast development of computers and telecommunications presented opportunities for automating that process. First, Mobil automated the order taking process by establishing the Mobil order response center (MORC). To use MORC, the customer dials a toll-free number, available 24 hours a day, seven days a week, from any push-button telephone. That number is connected to an audio response computer which asks the caller for a customer ID number, the products and quantities ordered, and the requested delivery shift. The caller provides the data using the phone's push-buttons. Thus the order is taken and entered by the computer without manual assistance. A "help" function to obtain the assistance of a human dispatcher is also available during business hours. In addition to reducing order entry costs, the introduction of MORC made accurate order data available quickly on a computerized medium for further processing by a dispatching system.



<u>Product</u>	<u>Order 1 (Easy to fit)</u>	<u>Order 2 (Not so easy)</u>	<u>Order 3 (Hard)</u>
Super	2900	3500	2900
Regular	3400	1100	4000
Unleaded	5500	7200	4900

Figure 2: A simplified example of tank truck loading. The simplified rules are to fill the compartments, gallonizing each total loaded product volume by no more than ± 400 gallons. For this example the truck capacity and the total volume of each order are 11,800 gallons. The double bulkhead between the two aft compartments is not necessary for this specific set of products. Product temperatures and gravities, special equipment on the trucks, tare weight and gross weight limits are ignored.

Next, Mobil moved to automate the dispatching process by contracting for the development of the computer assisted dispatching (CAD) system. The CAD system is functionally an extension of earlier work by Brown and Graves [1981] for dispatching refined petroleum products from a single terminal to customers; however, CAD has a wider perspective and a completely different solution technology. The CAD extensions are in several areas: dispatching an entire area that includes several terminals at once (for example, the Los Angeles basin), consideration of product laid-down costs, loading tank trucks to maximum weight, allowing for split loads (multiple-stop routes), provision for terminals without trucks, and much faster computer performance.

The CAD system makes the following major business decisions:

(1) *Own versus hired transportation:* By con-

sidering the availability and cost of proprietary, dedicated contract carrier, and common carrier trucks, the system reduces costs and balances work load among trucks. The cost of overtime and undertime of trucks and drivers is also a consideration.

(2) *Sourcing:* The inclusion of all terminals in the area results in dynamic sourcing of orders, which allows differences in laid-down product costs at the various terminals to be considered in concert with transportation costs to further reduce costs.

(3) *Vehicle Loading:* Fitting the orders well on the trucks keeps customers happy. Loading to maximize product weight increases the delivered quantities per load while adhering to weight limits and safe loading rules.

(4) *Routing:* Delivery time and mileage trip standards are maintained for

frequently used routes between terminals and customer locations. A georeference system estimates trip time and mileage for other routes and, incidentally, provides an independent means of auditing trip standards. Routing takes into account weight jurisdictions under way and road and bridge tolls, thus assuring good sequencing of loads for each truck.

As a result of these decisions a truck may load at a source other than its home base and may end the shift(s) at any required location (for example, for maintenance purposes).

CAD applies a set of highly specialized optimization methods in real time. The overall objectives of the system are to minimize all costs, maintain service levels, and remain safe and legal. A more detailed description of the CAD processing steps is provided in Appendix A.

CAD cannot completely replace the human dispatcher because many crucial aspects of the dispatching process are not quantifiable. To achieve ideal results, CAD must support human judgment. By relieving human dispatchers of the routine dispatching tasks, CAD allows them to concentrate on the qualitative aspects of the specific dispatching situation and to quickly see the economic impact of manually overriding CAD's recommended solutions. Accordingly, CAD provides for trial-and-error dispatching, inviting experimentation and digression with user-friendly on-line model support. CAD also automatically logs off-line every version of every dispatch for later use in evaluating new ideas and alternatives and gaug-

ing individual dispatcher performance.

The CAD system consists of an optimizer and support programs residing within Mobil's marketing operations system (MOS) implemented in IMS on an IBM host computer complex in Princeton, New Jersey. The dispatching operation

Usually, more gallons (than the nominal volume) may be loaded in a compartment without exceeding the legal weight.

and MORC are located in Valley Forge, Pennsylvania, and dispatchers use color CRT's connected through communication lines to the host in Princeton (Figure 3). The final dispatches are communicated to the terminals through Mobil's automated terminal system (MATS). CAD is an interactive system that must respond within a second or so. Two shifts are dispatched daily for 23 areas. CAD may be invoked several times for each area dispatch and must share the host computer with numerous other on-line business systems.

CAD data are organized as follows:

- (1) *Area Data*: Georeference system, weight limits, loading rules, default area-specific policy parameters.
- (2) *Terminal Data*: Location, product availability, laid-down cost, temperature, gravity, type of loading meters, and supply management data.
- (3) *Truck Data*: Compartment sizes, markers, and weight limitations; tare weight; special equipment; vehicle hours available and penalties for over

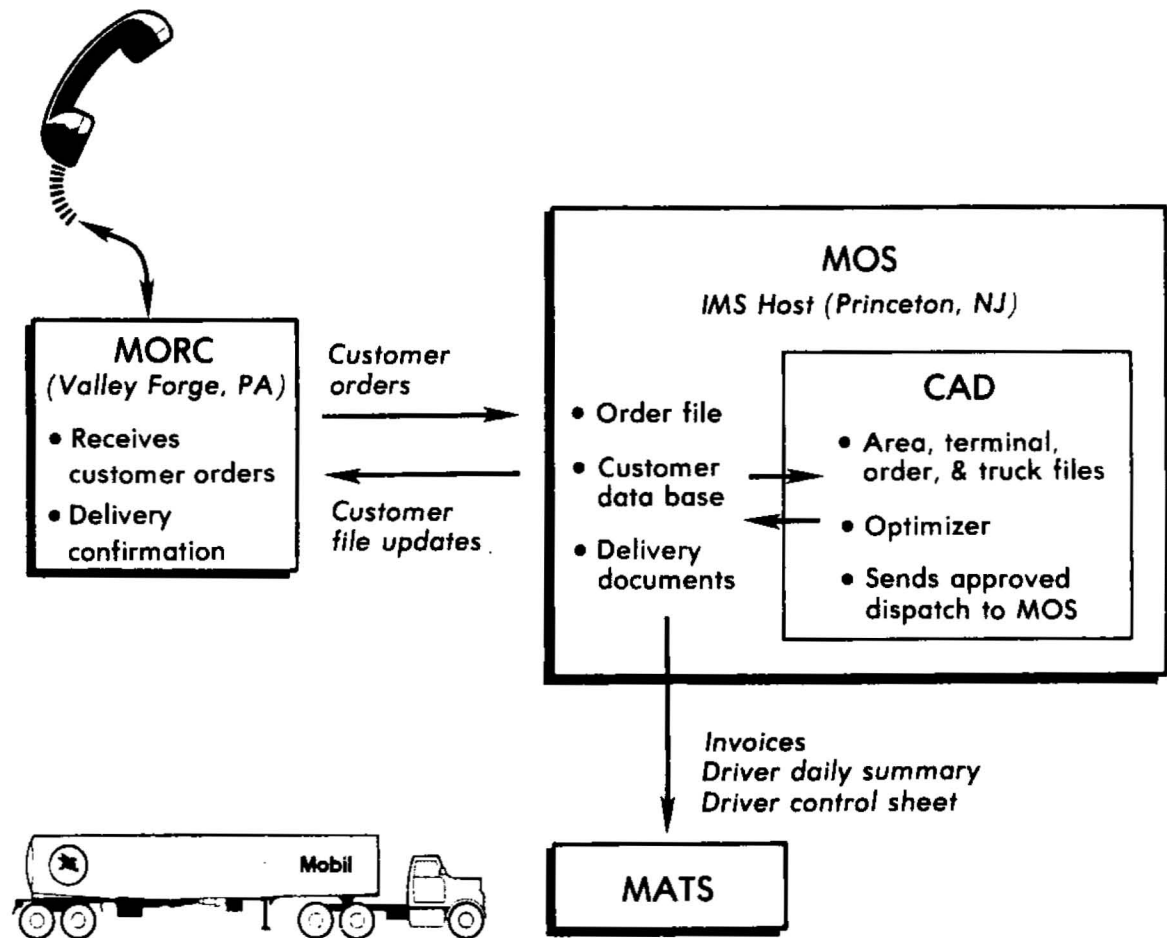


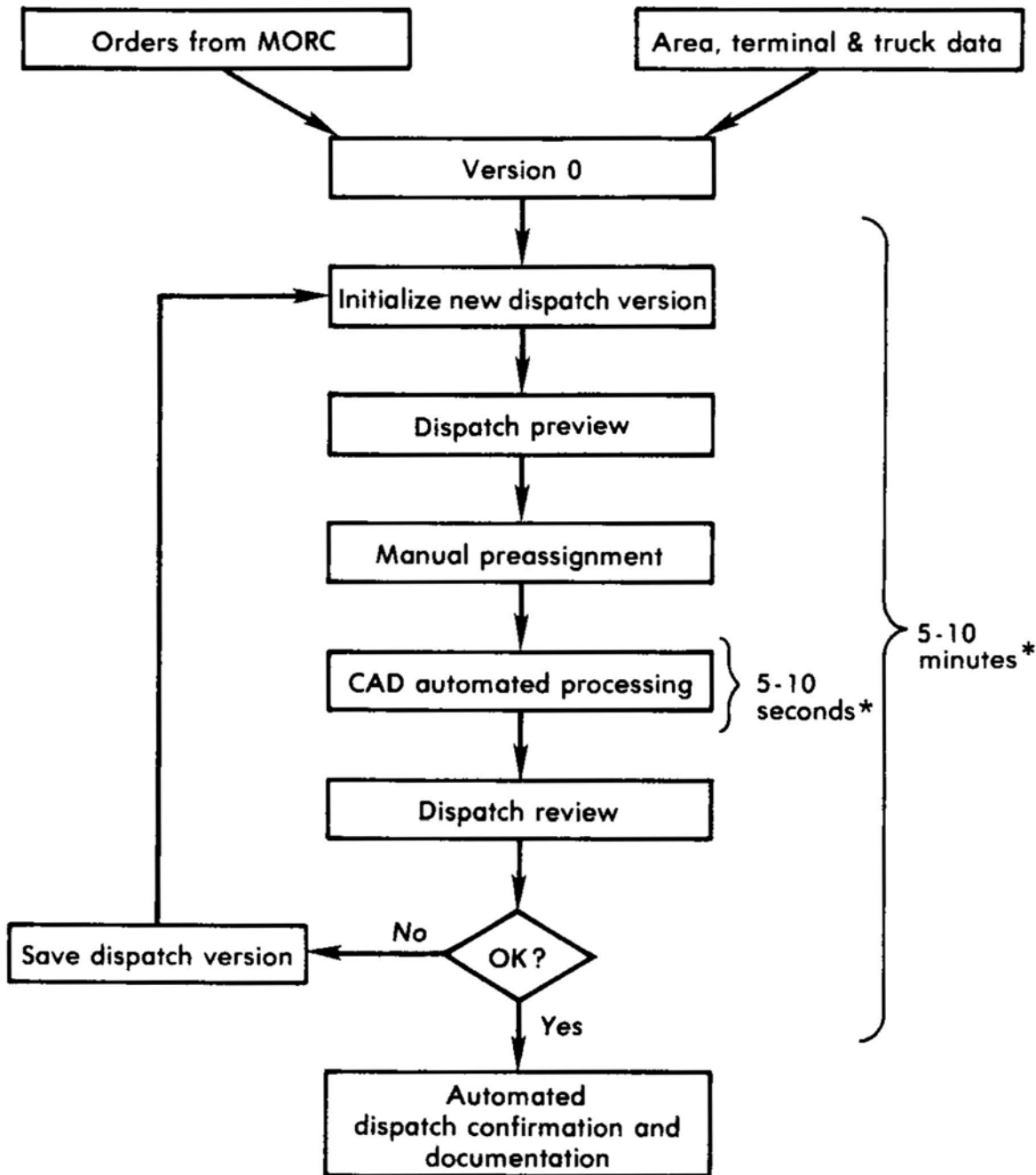
Figure 3: Mobil light products order and dispatch information flow. Customers call an audio response computer system named MORC (Mobil order response center) to place orders or confirm delivery schedules. MORC sends customer order data to another computer system called MOS (marketing operating system). MOS maintains data bases, supports CAD (computer assisted dispatch) and communicates with other business systems such as MATS (Mobil's automated terminal system) which produces control documents at the sites where product is actually loaded on trucks. MOS also tells MORC when each order is scheduled to be delivered.

and undertime; start and end location; and operating cost.

- (4) *Order Data:* Delivery location, trip standards, delivery notes, special equipment requirements; requested shift and date; product quantities and restrictions on gallonization.

CAD supports many features unique to the problems at hand. If the product in a customer's tank is nearly exhausted or if little excess storage space remains in the

tank, the dispatcher may specify restrictions on gallonization (limits on increasing or reducing the ordered quantities to fit truck compartments) that are strictly honored by CAD. Weight jurisdictions and loading rules vary within and between cities and states. Sometimes these rules can change daily: frost laws in some northern states reduce the gross weight limits on short notice to minimize road damage in thawing conditions. Ice and



* approximate wall clock intervals

Figure 4: Steps in a computer assisted dispatch. Area dispatch data are extracted from the host information management system and assembled as a complete version of the dispatch. The dispatcher previews the version under consideration and pre-assigns any exceptional conditions. CAD is invoked and requires only a second or so to complete the dispatch. This may require five to ten seconds of wall-clock time before the dispatcher can review the result, accept it for actual use, or repeat the process with any prior version used as the next version. In this way, it is possible for several alternate scenarios to be investigated in parallel. The dispatcher is expected to complete this process in five to ten minutes.

slush clinging to trucks can increase their weight significantly. CAD accommodates such details with minimal direction.

The dispatching process with CAD is shown in Figure 4. The orders are received from MORC continually and may be previewed on the CRT screen by the dispatcher. Several hours before a delivery shift, the dispatcher closes the set of orders for that shift (or he may dispatch that shift together with the following shift). During the dispatch preview stage the dispatcher updates product and truck availability for the specific shift(s) and area being dispatched, as well as product temperature and gravity. The dispatcher gets this data by telephone from the supervisors in the terminals and then approximately balances the work load with truck availability by hiring carrier trucks, delaying delivery of orders to a following shift, or delivering orders a shift early, all within customer service limitations. (Expected work load summary displays assist the dispatcher in making these decisions within management policy.) The dispatcher may manually pre-assign unusual or problem orders to a specific truck and part of the shift.

Once finished with the preview, the dispatcher invokes the CAD optimizer. Results are presented almost immediately on a color CRT that highlights special instructions, warnings, or outright unacceptable situations that require intervention. He or she reviews the results, and if they are satisfactory, a single key-stroke approves the dispatch and transmits it for automated preparation of shipping and billing documents. If the results are unsatisfactory, the dispatcher returns

Dispatch:	7 Terminals, supplying 25 Metered product sources, for 30 Trucks, delivering 116 Orders, with 329 Product orders;
Activity:	1,031,715 Gallons delivered, 6,600 Miles driven, 282 Truck hours used, 30 Dispatcher minutes expended.

Table 1: The dispatch resources and activity for the Los Angeles basin area during the day shift on Tuesday, April 15, 1986.

to the preview stage for any prior version of the dispatch, makes desired changes and invokes the CAD optimizer again. Before approving CAD results, the dispatcher may resequence the loads for each truck shift while taking into account requested delivery time windows, rush-hour traffic congestion, road and weather conditions and other relevant factors. An actual dispatch shift is abstracted in Table 1.

The approved dispatch is also fed back to MORC so that customers may call the toll-free number and by telephone push-button get confirmation of a scheduled delivery.

Accomplishments

The development of CAD took over two years. It involved a large effort to make the system user friendly and to create interfaces with existing corporate systems and data bases. The computerization of the manual dispatching process required management to formalize many delivery policy decisions. Different dispatchers have different attitudes about dispatching and different methods. Computerizing the system compelled management to standardize its delivery policy, and the system automatically enforces that policy.

For example, uniform gallonization rules are now enforced. The dispatchers have had to gain experience with using computerized CAD features such as penalties for exceeding preset limits. The idea of penalties, their function and values, has had to be explained and experimented with in order to properly calibrate the model to achieve the desired results.

The CAD system was fully implemented during the first half of 1985, and with its implementation, Mobil has finished consolidating three manual centers

CAD also automatically logs off-line every version of every dispatch for later use in evaluating new ideas and alternatives.

into one automated center dispatching about 50,000 orders for light products per month.

The productivity of dispatching personnel has increased more than twofold, on the basis of the number of orders delivered per person.

The costs of communications and computer operation have been higher than originally forecasted, but so have the savings. Annual net cost savings for product distribution of well over \$2 million have been realized. As dispatchers become better acquainted with their new tools, ever greater benefits are expected.

The wide area perspective is new and has necessitated a large investment in research and development. However, just the influence of laid-down product costs on dispatch economics has more than re-

paid this effort. In fact, it is most gratifying to see such marked improvement in an industry already so efficient.

The centralized computerized dispatching simplifies operational management, assures uniform enforcement of delivery policies, and allows evaluation of the economic consequences of the dispatching decisions. In addition, it cuts dispatching lead time, improves customer service, and assures safe and legal operations.

CAD is also used off-line as an identity simulation to evaluate strategic decisions such as exchange agreements, proprietary fleet size, fleet mix, and fleet location. Complete historical data from daily dispatch operations is automatically logged by the on-line IMS system. An off-line modeling support system is used to assemble and suitably modify extracts from this database. This allows evaluation of various scenarios based on exhaustive actual historical data and thus provides answers to "what if" questions.

CAD assists, but does not replace the human dispatcher. CAD relieves the dispatcher of extremely detailed decisions and simultaneously exploits the economics of the dispatch to reduce costs. The dispatcher uses CAD to work with a large geographic area containing several bulk terminals as a single transaction. Non-quantified conditions are expressed to CAD as restrictions, and results from CAD are always reviewed before final acceptance. CAD must quickly identify and try to correct oversights, must operate very swiftly and robustly within a congested real-time information management system, and must effectively communicate the reasons for unexpected actions.

Ken Clark, manager of the light products staff services, says, "More than 10,000 light products orders come in each week, and CAD analyzes each one of them with this kind of broad perspective. No other company in the world has a system this sophisticated" [Burke 1985].

Note: This work was performed when D. Ronen was at the University of Missouri-St. Louis.

APPENDIX A — CAD Processing Steps

CAD generates a dispatch for one or more future shifts in six sequential processing steps. These are shown in Figure 5 and described in more detail below.

Input Edit and Analysis

Before the actual dispatch optimization process can begin, the input data must be

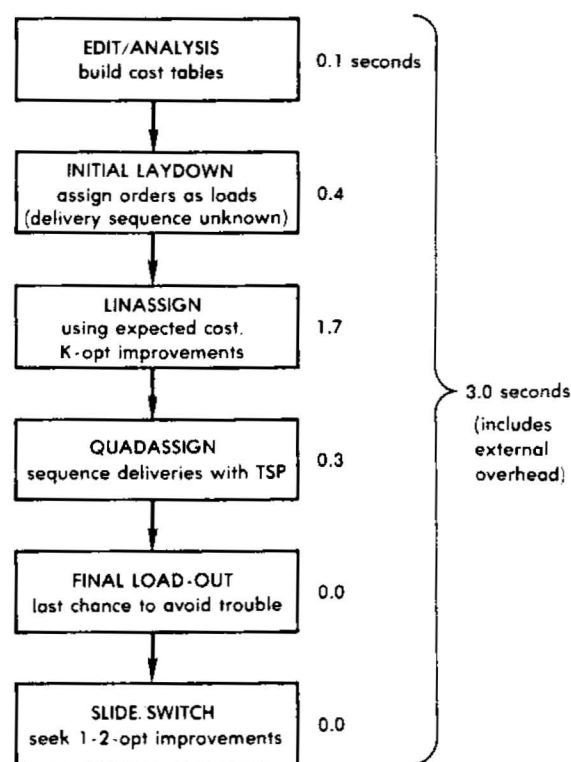


Figure 5: The CAD optimization sequence. IBM 3033 interval time seconds are shown for the dispatch in Table 1, which required 261 kilobytes. A high-accuracy costing routine was applied 29,318 times.

screened for exceptional conditions, and certain preliminary analyses must be accomplished to create the necessary information for subsequent processing steps.

First, a global review of all orders is performed to be sure that the work load can be accomplished with the equipment available and in the time allowed. During this process, three data tables are constructed for subsequent reference:

- (1) *Customer-to-supply-site table*: For each supply-site-customer combination, the following data are stored: the estimated carrier charge in dollars per gallon, the estimated laid-down cost of product at the supply site, the proprietary or dedicated truck time cost, the proprietary or dedicated truck distance cost, the outbound tolls, and the inbound tolls.
- (2) *Customer-to-customer table*: To facilitate building multistop loads, information is entered into this table concerning which customers' orders would fit well or poorly together on the available trucks and the proximity of these customers to each other.
- (3) *Customer-to-truck table*: Orders and customer delivery requirements are matched against the truck data to determine which trucks could handle which orders and estimate how well the orders would fit as loads.

Next, all manual preassignments by the dispatcher are fixed.

Finally, using all previous analyses, table entries, and preassignments, an initial laydown, or preliminary dispatch, is generated. This initial laydown is the starting point for the optimization process. The initial laydown may not be equitably balanced, with some trucks having too much work load and others not enough. Further, the issues of multiple-sourcing and multiple-stop deliveries and how those deliveries should be sequenced has not been addressed at this stage. Rather, their costs are estimated by conditioned

expectations. Nonetheless, each order has been assigned somewhere, and there is an expected cost associated with actually making the initial laydown dispatch.

Order-to-Truck Assignment

Using the expected cost of the initial laydown, the three data tables, and a higher-accuracy costing routine, LINASSIGN determines which orders should be assigned to which trucks to reduce the conditioned expected cost of the total dispatch. This step consumes about half the computer processing time required to complete a typical dispatch. LINASSIGN records the starting solution provided to it as an incumbent and enumerates the total expected dispatch cost for exchanges of single loads, pairs of loads, and so forth for all higher-order exchanges among trucks. In practice, exchanges are usually limited to second order; higher-order enumeration does not justify its expense with improvements in solution quality.

At this stage, it has been determined which trucks will most probably carry which loads, but neither the supply sites that will provide the product for each order nor the sequence in which deliveries will be made is known.

Load Sequencing

Once it is known which loads are to be on which trucks, where each truck starts and ends each shift, and the product cost and availabilities at each supply site, QUADASSIGN determines the best route, or loading and delivery sequence, for the trucks to follow in delivering the orders. QUADASSIGN solves, with the method of Graves and Whinston [1970], a traveling salesman problem (TSP) for each truck. (See Brown, Colmenares, Graves and Ronen [1986].) The high-accuracy costing routine is used in lieu of pairwise cost approximations for sequencing multiple-stop deliveries.

Final Order Load-Out

At this stage of the dispatching pro-

cess, all loads have been built and assigned to trucks, the loading sites have been designated, and the sequence of deliveries is known. All that remains to complete the dispatch is to specify exactly how much product is to be loaded in each compartment of each truck. LOADOUT determines the optimal assignment of products to compartments. Upward and downward adjustment penalties are computed for each product on each order in the load; these reflect the size of the order and the restrictions given for its gallonization. An optimal load sequence is then determined to assign product, volume, and weight to each truck compartment. A mathematical model describing most of the detail in this step is provided in Appendix B.

Slide/Switch

Remaining computer time permitting, the final solution is tested for possible improvement by moving any load to an alternate truck or by exchanging any pair of loads. At this point, sourcing and sequencing costs are known and not estimated.

APPENDIX B — LOADOUT: Order-Truck Fit Model

Indices

- p = Product (in the order).
- c = Compartment (of the truck).

Data

- v_p = Ordered volume of product p (gallons).
- V_c = Volumetric capacity of compartment c (gallons).
- W_c = Weight capacity of compartment c (pounds).
- d_p = Density of product p (pounds per gallon).
- $\underline{Z}_p, \bar{Z}_p$ = Product volume adjustment penalty for quantity reduction or increase.
- $\underline{M}_p, \bar{M}_p$ = Product volume excess adjustment penalty for reduction or increase.
- $\underline{U}_p, \bar{U}_p$ = Product volume adjustment

limit for quantity reduction or increase.

$$\underline{M}_p > \underline{Z}_p; \bar{M}_p > \bar{Z}_p.$$

Decision Variables

$$X_{pc} = \begin{cases} 1 & \text{if product } p \text{ is assigned} \\ & \text{to compartment } c, \\ 0 & \text{otherwise} \end{cases}$$

$\underline{a}_p, \bar{a}_p$ = Reduction or increase in ordered product volume (gallons).

$\underline{e}_p, \bar{e}_p$ = Excess reduction or increase in ordered product volume (gallons).

G_{pc} = Volume of product p to load in compartment c (gallons).

Model

Minimize

$$\sum_p (\underline{Z}_p \underline{a}_p + \bar{Z}_p \bar{a}_p + \underline{M}_p \underline{e}_p + \bar{M}_p \bar{e}_p)$$

Subject to

$$\sum_p X_{pc} \leq 1 \quad \forall c \quad (1)$$

$$\sum_c X_{pc} \geq 1 \quad \forall p \quad (2)$$

$$\sum_c G_{pc} + \underline{a}_p - \bar{a}_p + \underline{e}_p - \bar{e}_p = v_p \quad \forall p \quad (3)$$

$$\underline{a}_p \leq \underline{U}_p, \bar{a}_p \leq \bar{U}_p \quad \forall p \quad (4)$$

$$\sum_p G_{pc} \leq V_c \quad \forall c \quad (5)$$

$$d_p G_{pc} \leq W_c X_{pc} \quad \forall c, p \quad (6)$$

$$X_{pc} \in \{0,1\}; G_{pc}, \underline{a}_p, \bar{a}_p, \underline{e}_p, \bar{e}_p \geq 0.$$

The objective function minimizes the policy penalties due to changes in the ordered quantities of the various products. Quantity adjustments beyond the specified limits (determined by managerial policy) carry much larger penalties than adjustments within these limits. Constraints of type (1) assure no more than one product per compartment. Type (2) assure that each product is assigned at least to one compartment. Constraints of type (3) tie together the quantity adjustments. (4) define the adjustments within the specified limits. (5) assure that com-

partment volume is not exceeded, and (6) assure that compartment weight is not exceeded as well as relate the X and G variables (that is, G may be positive only when the corresponding X is 1).

This model is modified slightly to accommodate product adjacency restrictions and empty compartment limitations. (These modifications can be manifested in some additional linear constraints on the X variables.)

The model is solved by a highly specialized enumeration.

References

- Brown, Gerald G.; Colmenares, Octavio G.; Graves, Glenn W.; and Ronen, David 1986, *Vehicle Routing Using A Quadratic Assignment Approach*, working paper.
- Brown, Gerald G. and Graves, Glenn W. 1981, "Real-time dispatch of petroleum tank trucks," *Management Science*, Vol. 27, No. 1 (January), pp. 19-32.
- Burke, David K. 1985, "CAD/MATS spells new era in light products," *Mobil World*, (May), pp. 4-5.
- Graves, Glenn W. and Whinston, Andrew B. 1970, "An algorithm for the quadratic assignment problem," *Management Science*, Vol. 17, No. 7 (March), pp. 453-471.

H. L. Schwartz, Manager, Operations Services, Mobil Oil Corporation, 3225 Gallows Road, Fairfax, Virginia 22037-0001, writes: "Since CAD's implementation a couple of years ago significant benefits have accrued to Mobil in the dispatching of refined light products (gasoline of various grades and diesel fuel). Among the more important benefits are the following:

1. Savings of about \$3,000,000 per year in operating expenses associated with delivering light products.
2. Centralization of all dispatching operations at one Light Products Control Center (LPCC) in Valley Forge, PA.

Prior to CAD there were three such centers.

3. Greater control over dispatching operations because of one LPCC and a fully integrated operating system.
4. Better service to our customers through improved utilization of assets and resources and consistency of performance.
5. Assurance that all of our shipments are within legal weight limits, regardless of volume differences due to local temperatures or specific gravities.
6. Greater capability than ever before to evaluate fleet productivity.

We at Mobil believe that CAD, in conjunction with our Mobil Order Response Center (MORC), has given Mobil a lead position in the petroleum industry in delivering refined products."