Unit load (belt) conveyor operating design and cost

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A conveyor cost estimation methodology is developed which takes into account the two major costs of operating unit load conveyors: maintenance and power. A programmable calculator program (CONVEY) is developed to assist the plant engineer in determining new operating conditions for the belt, such as motor size, belt tension, gear and sprocket ratio. CONVEY also computes power consumption for specified belt operating parameters.

Introduction

The unit load conveyor system is one of the most efficient methods of transporting mass quantity unit loads within a facility, such as a warehouse or manufacturing plant. The evaluation of alternative conveyor systems is primarily based on the initial system cost. Not much attention has been given to actual conveyor system operating costs in the evaluation process, nor to identifying the conveyor system modifications needed to respond to different and changing loading requirements. Consideration of operating design and cost is especially important when motors are changed in the plant or when conveyors are moved and rebuilt.

A conveyor cost estimation methodology is developed which takes into account the two major costs of operating unit load conveyors: maintenance and power. Maintenance cost is the most variable factor in selecting conveyor systems and should be thoroughly analysed. Electrical energy accounts for about half the total manufacturing energy requirements in the United States [1]. Since most unit load conveyor systems use electric motors, conveyor energy consumption must be considered in any economic analysis. Maintenance costs are a function of the conveyor design and labour costs, and are difficult to evaluate. Power costs can be computed by estimating the energy losses inherent to the system. Adding these costs in the system evaluation analysis can change the outcome of a selection. This is often the case when belt replacement is considered.

Designing new or redesigning existing conveyor systems is another major problem associated with conveyor operations. The process usually requires a great deal of time searching through manufacturing catalogues and specifications. A program (CONVEY) is developed to assist the plant engineer in determining new operating conditions for the belt, such as motor size, belt tension, gear and sprocket ratio. CONVEY also computes power consumption for specified belt operating parameters. With this calculator program, the plant manager and conveyor vendor can design the conveyor system and compute operating energy requirements and all component requirements and specifications on site. The program is very useful and can save hours of going through charts and manufacturers' manuals.

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Conveyor energy requirements

Power consumption is a conveyor system operating cost. Most unit handling conveyor systems are driven by an electric motor. The electric power required to drive the system is a function of belt speed, unit load, belt weights, pulleys, drive mechanisms, length of conveyor and other components. The efficiency of the power conversion from electrical power to transporting the unit load is equal to actual belt horsepower divided by electrical horsepower. For standard roller belts, power efficiency is approximately 57% [2]. A rule of thumb some conveyor manufacturers use to estimate horsepower requirements is one horsepower for every load on the conveyor [3]. For instance, loads being conveyed on 20-foot centres would require a 2.5-horsepower motor for a 50-foot conveyor. These methods are useful in estimating motor requirements. However, a more in-depth analysis of the power transfer and drive system and conveyor operation is required to accurately determine power consumption and efficiently design unit handling conveyors.

Each factor affecting energy consumption of the conveyor belt must be examined in order to accurately determine energy consumption. A typical unit handling system is shown in Fig. 1. Each factor affecting energy consumption is presented. Their effects on energy consumption and efficiency are described for each component of the conveyor system, starting from the unit load and ending with the electrical power.

![Conveyor components](image)

Figure 1. Conveyor components.

**Effective belt pull**

The effective belt pull is the force required to move the unit loads on the conveyor, the conveyor belt itself, friction forces created by the conveyor’s pulleys and slider beds, and gravity forces on inclines if applicable [4, 5] (see Fig. 1). The effective belt pull is computed by:

\[
T_e = \left\{ FrL(W_m + 2W_b + R_iC_i + R_p + C_p + R_iC_i) + (W_m)b \right\}/Ft
\]

(1)

\[
T_e = \left\{ FsL(W_m + W_b) + FrL(W_b + R_iC_i) + (W_m)b \right\}/Ft
\]

(2)

where:

- \( T_e \) = effective belt pull (lb)
- \( L \) = conveyor length (ft)
- \( W_m \) = weight of unit load (lb/ft)
- \( W_b \) = weight of belt (lb/ft)
- \( R_i \) = unit weight of carrying roller less shaft (lb)
- \( R_p \) = unit weight of pressure roller less shaft (lb)
- \( R_i \) = unit weight of return roller less shaft (lb)
- \( C_i \) = number of carrying rollers per foot
- \( C_p \) = number of pressure rollers per foot
$C_i =$ number of return rollers per foot
$h =$ net change in elevation (ft)
$P_l =$ terminal loss factors (0.85)
$Pr =$ roller bed friction factor (average condition 0.075)
\hspace{1cm} (excellent condition 0.05)
$Ps =$ slider bed friction factors
\hspace{1cm} (bare duck belt surface 0.30)
\hspace{1cm} (friction belt surface 0.35)
\hspace{1cm} (rubber-covered belt surface 0.45)
\hspace{1cm} (rubber-covered belt surface with water lubrication 0.25)

The unit load weight is determined by the number of loads on the conveyor.

$$W_m = \{\text{number of loads on conveyor} \times \text{weight/load}\}/L \quad (3)$$

Once $T_e$ is specified, the amount of torque required by the drive pulley can be determined.

**Drive pulley forces**

The drive pulley moves the belt by friction between the two. The amount of power loss from the pulley to belt is considered minor (about 5%) because forces $T_1$ and $T_2$ (Fig. 2) are designed to prevent slippage between belt and pulley. Note there is always some minor slippage at start-up. The relationships between $T_1$, $T_2$, and $T_e$ are:

$$T_2 = k_2 T_e$$

$$T_1 = k_1 T_e = (1 + k_2) T_e$$

where:

$$k_1 = \frac{C}{C-1}$$

$$k_2 = \frac{1}{C-1}$$

$$c = \exp \{\pi/180 fa\}$$

$f =$ 0.25 for bare steel pulley, 0.35 for lagged pulley

$a =$ arc of contact between belt and pulley (degree of wrap)

Notice that with lagging and large degrees of wrap, the amount of friction force increases between the drive pulley and belt; thus, less tension is required to prevent slippage.

![Figure 2. Drive pulley.](image-url)
The torque requirement at the drive pulley to move the belt is:

\[ \text{TORQ}_{dp} \text{(in.-lb)} = T_e \times \text{drive pulley OD (in.)} \]

The pulley’s angular velocity is computed by using the design belt speed as follows:

\[ \omega_{dp} \text{(r.p.m.)} = \frac{3.817 \times \text{belt speed (r.p.m.)}}{\text{drive pulley OD (in.)}} \]

Once the pulley’s r.p.m. and torque are computed, the horsepower required at the pulley shaft can be computed.

\[ HP_{dp} = \frac{W_{dp} + \text{TORQ}_{dp}}{63025 \times (0.95)} \]

From the above information, the power requirements are known at the drive pulley’s input shaft.

**Chain drive**

A chain drive transfers power from the gear reducer to the drive pulley. Some drive pulleys are connected directly to the drive pulley by a shaft while others use a belt. The chain drive will be considered in this analysis, since it is generally used for unit load conveyors. The sprocket on the gear reducer output is connected to the sprockets on the drive pulley shaft by a 40 to 80 drive chain. The speed reduction ratio of the chain (CR) can be computed as follows:

\[ \text{CR} = \frac{\text{number of teeth on the drive pulley sprocket}}{\text{number of teeth on the reducer shaft sprocket}} \]

The gear reducer output shaft angular velocity \( \omega_{gr} \) can be computed by:

\[ \omega_{gr} = \text{CR} \omega_{dp} \]

The chain drive is estimated to be 95% efficient [5]. The gear reducer output horsepower requirements \( HP_{gr} \) can be computed by:

\[ HP_{gr} = \frac{1}{0.95} HP_{dp} \]

The output torque required at the output shaft of the gear reducer \( T_{gr} \) is:

\[ T_{gr} = \frac{63025 \times HP_{gr}}{W_{dp}} \]

The gear reducer outputs needed to drive the conveyor system are specified.

**Gear reducer**

The gear reducer reduces the motor’s output and increases the torque transmitted to the conveyor. The reducer is usually kept as close as possible to the drive pulley to reduce overhang load. The ratio of the gear reducer is usually printed on the casing. The ratio can also be computed by dividing the motor actual r.p.m. by the required output r.p.m. The efficiency transfer of gear reducers is difficult to estimate and varies according to bearings, gear arrangement, and other factors pertaining to the gear design. For the range in which most conveyors operate (i.e., a belt speed of
40 to 60 f.p.m., and 0.75- to 5-horsepower motors), efficiency is 75 to 85% with a 1725-r.p.m. motor. Using this information, both input torque and horsepower requirements can be computed.

\[ HP_m = \frac{HP_{gr}}{\text{reducer efficiency}} \]

**Motor**

The drive motors in almost every unit load conveyor system are a.c. squirrel cage types. This electric motor type requires little maintenance and produces moderate torque. The efficiency may vary 75 to 84%, depending on the motor. The squirrel cage motors for unit load conveyors have a nominal output of 1800 r.p.m. and an actual output of 1750 r.p.m. [6]. Starting torque is 200 to 300% greater than running torque. The motors are directly coupled to the gear reducer and can incorporate a soft clutch or brake to control loads during conveyor operations. The motors are most efficient when at full load. When at less than full load, efficiency drops rapidly. The power consumption of the motor in \( P_m \) watts is calculated:

\[ P_m = \frac{HP_m + 0.7574 \times \text{(load efficiency factor)}}{\text{motor efficiency}} \]

The load efficiency factor is a function of the load and is obtained from the motor's torque power curves. Thus, the amount of power consumed in watts is computed for a given system.

**Maintenance of conveyors**

Like all other machinery with moving components, the unit load conveyor requires maintenance. Maintenance costs for conveyor equipment are difficult to generalize because of the many different conveyor systems and approaches taken in performing the maintenance. Some conveyor belt operators have their own in-house maintenance personnel specifically assigned to the conveyors, while others use general plant maintenance personnel, such as electricians and mechanics, to maintain specific components of the conveyor system (e.g., pulleys, motors, and belts). Still others have their conveyor maintenance work contracted to specialized repair firms. Costs of a maintenance contract are fairly easy to estimate, since there is usually an annual service agreement contract with no cost-plus arrangements. Conveyor maintenance costs are difficult to estimate when the plant does its own maintenance. Since a majority of the plants perform their own maintenance, a methodology has to be developed to analyse and estimate annual maintenance costs for a given conveyor system.

There are two general categories [7] of maintenance: scheduled and nonscheduled. Scheduled maintenance covers routine inspections, lubrications, and expected system component replacements. Nonscheduled maintenance includes the repair of unexpected failures, accidents, and breakdowns. Nonscheduled maintenance costs [7]: exponential increase in costs, constant increase in costs, power installing a new system, it is sometimes impossible to accurately determine even scheduled maintenance costs. Basic guidelines are presented for computing conveyor maintenance costs.
Scheduled maintenance

The three major types of scheduled maintenance are: (1) inspection, (2) prevention, and (3) replacement. Inspection costs are small, but important; for example, a small undetected crack in the belt can lead to major system failure. The cost of inspection ($C_i$) is computed by:

$$C_i = \text{(time to inspect a unit length of homogeneous bed)} \times \text{(inspector's wage rate)} \times \text{(entire conveyor bed length)} \times \text{(number of inspections per year)}$$

Each different belt type must be computed separately because different times are required for roller and slider beds.

The cost of preventive maintenance ($C_p$) is computed in a similar manner. This maintenance usually includes lubrication and belt treatment. Homogeneous conveyor systems must be considered in estimating the costs.

$$C_p = \{\text{(time to perform a unit length of maintenance} \times \text{total length of particular bed} \times \text{wage rate)} + \text{supplies and equipment}) \times \text{(maintenance frequency)}$$

Scheduled replacement costs include belts, pulleys, and motors. In most conveyor systems, the belt is the major replacement item. Pulleys and motors are expected to last the life of the system. Belt life is a function of belt tension, service factor, load, and system configuration. This information must be obtained from the manufacturer. Annual belt material costs ($C_b$) can be estimated by:

$$C_b = \text{(number of replacements per year)} \times \text{(cost to replace belt)}$$

As a general rule, unit load belts on roller beds last longer than belts on slider beds [8], due to greater friction on the slider bed.

The first two annual scheduled maintenance costs are dependent on the conveyor system, wage rate, and lubrication costs over time. Belt replacement costs are dependent on belt life, conveyor system configuration, and material cost over time.

Nonscheduled cost

Nonscheduled maintenance costs result from the need to perform major repair or replace system components, such as pulleys, belts, and motors, which fail before their expected life. These costs are extremely difficult to predict and must be estimated from experience with the existing system. The probability of component failure usually increases as cumulative operating time increases. In addition, there are more parts which could fail in the more complex system. A roller bed has many more moving parts than a slider bed.

Several different methods can be used to estimate yearly nonscheduled maintenance costs [7]: exponential increase in costs, constant increase in costs, power function increase in costs, and constant costs. All but the method using constant annual maintenance costs assume that nonscheduled maintenance costs will increase with time as the equipment becomes older.

The reduction and accurate evaluations of maintenance are extremely important when determining operational costs. These costs become critical when evaluating conveyors on their operating costs. For example, a slider bed belt might have to be changed four times a year compared to no changes for a similar roller bed belt system. However, the preventive maintenance and nonscheduled maintenance costs might be greater because of the more complex roller bed system. Thus, the slider bed might be more economical to operate. This example is extreme, but illustrates the
many variances in maintenance costs. The use of general assumptions in computing maintenance costs might mask the variances in individual maintenance costs.

**Conveyor energy and design program**

A computer program, CONVEY, is designed for a programmable calculator to compute the unit load conveyor energy requirements and design criteria. The program was put on a programmable calculator to enable on-site conveyor system analysis. This program allows sales personnel and plant engineers to develop design criteria in the plant, eliminating the need to search through manuals and tables and calling information into main offices to obtain design results. CONVEY is especially useful to the plant engineer when replacing conveyor drive motors or changing belt speeds and unit loads, since it calculates the correct gear ratios and belt tension required.

Another advantage of the calculator program is that the user can go back to any point in the program and start. For example, the user can go back to the gear reduction calculations while skipping the input conveyor belt data. This enables the user to compare many alternatives without reentering the data.

The basic flowchart for CONVEY is shown in Fig. 3. The program was developed on a Hewlett-Packard 41CV 2-2 kilobyte programmable calculator. The program is listed in the Appendix. The program executes simultaneously while prompting the user for the data required for interim calculations. The program executes and first prompts the user for information about the conveyor system including belt weight per foot, pulley weights per foot, conveyor length, diameter of pulley, conveyor speed, angle of wrap, lag, and service factor. The pulley weights can be obtained from conveyor manufacturers or weighed directly. A service factor of 1.0 is usually employed for unit load conveyors with continuous use, while a factor of 1.1 is used for frequent stopping and starting. The friction factors (eqn. 1) assume the system is in good operating condition.

**Load information**

The rate of loading and the length and weight of the unit load are prompted. The program has a built-in check to see if the loading rate is feasible. If not, an error flashes. The program will compute the most efficient speed for the specified carton length and spacing. The user can use the indicated conveyor speed or input a new conveyor speed.

**Belt drive information**

The program uses the conveyor operating characteristics and load information in eqns. (1) and (2) to compute the effective pull $T_e$ and slack tension $T_s$. Drive pulley power torque and angular velocity requirements are also displayed. Energy losses are assumed to be 5% but can be changed within the program.

**Chain drive**

The program prompts the user for the number of teeth on the drive pulley and gear reducer sprockets. If a chain drive is not used, enter a 1 for each prompt. The program will assume a one-to-one ratio and not include the 5% energy loss in the power transfer.
SEQ CONVEY

COMPUTE: \( R = 0.06 \times (\text{DSS WS}) \times (\text{D FULL P}) \)

COMPUTE: \( \text{MAX V} = (\text{D SS P}) \times (\text{DSS PATEL/12}) \)

MAX = CONV SPEED

COMPUTE: \( \text{MAX} = 0.05 \)

COMPUTE: \( \text{MAX} = \text{CONV SPEED} \)

COMPUTE: \( \text{MAX} = \text{CONV SPEED} \)

EQ 1, 2, and 3

DISPLAY \( \text{MAX} \)

COMPUTE: \( \text{FULL TORQ} \)

\( \text{FNL HP}, \text{FNL RPM} \)

EQ 4, 5, and 6

COMPUTE: \( \text{L SMAT} \)

COMPUTE: \( \text{D SMAT} \)

COMPUTE: \( \text{RPO RPM} \)

\( \text{RPO RPM} \)

DISPLAY: \( \text{RPO RPM} \)

COMPUTE: \( \text{RPO RPM} \)

\( \text{RPO RPM} \)

DISPLAY: \( \text{RPO RPM} \)

COMPUTE: \( \text{RPO RPM} \)

\( \text{RPO RPM} \)

DISPLAY: \( \text{RPO RPM} \)

COMPUTE: \( \text{MOTOR HP} \)

\( \text{FSS HP} \times \text{FSS TRQ} \)

COMPUTE: \( \text{MOTOR HP} \)

\( \text{FSS HP} \times \text{FSS TRQ} \)

COMPUTE: \( \text{MOTOR HP} \)

\( \text{FSS HP} \times \text{FSS TRQ} \)

COMPUTE: \( \text{MOTOR HP} \times 0.051 \)

MOTOR RPM
**Unit load (belt) conveyor design**

*Figure 3. CONVEY flowchart.*

**Gear reducer**

The output ratio and horsepower and torque requirements are calculated and the gear reducer output horsepower requirements are displayed. Next the user is prompted for the actual motor r.p.m. The program then calculates the required gear reduction ratio. At this point the designer could specify the gear unit. The drive pulley and gear reducer output teeth would have to be changed if the gear ratio were different from the one of the existing system. The program then will prompt for the gear reducer efficiency. If unknown, an efficiency of 0.8 should be entered.

*Figure 4. CONVEY input/output.*
Motor

The actual motor horsepower requirements are computed and displayed for the given system. The motor operating efficiency is prompted and the kilowatt hours are displayed.

The advantage of the calculator program is that the user can go back to any point in the program and start. An example of the program input and output is presented in Fig. 4.

Example problem

An example of the economic analyses and their effect on evaluation of different conveyor system alternatives is illustrated in the table using the example problem developed by Tanchoco et al. [9]. Using conveyor selection methodology, they found the optimal system for moving 1000 parts per minute on a conveyor 100 feet long in various size containers. The comparison is made between the 'base' 14-inch slider bed belt and the 18-inch roller bed systems.

Using the operation cost methodology and program, the number of kilowatt hours is computed for each alternative. Assuming the belts are in operation 10 hours per day for 220 days a year, the annual costs are computed using 5 cents per kilowatt hour. The conveyor systems are compared on an annual basis. The total cost is given. Notice that the slider bed has much greater power consumption.

The scheduled maintenance cost of the slider bed system is assumed to be 7.5% of the initial system cost. The belt is replaced every 3 years of operation. Roller bed maintenance costs are assumed to be 12% of the initial system cost. This higher maintenance cost is due to the number of rollers in the system. The belt, however,

| Conveyor |  |
|----------|  |
| Belt width | 12 inches | 18 inches |
| Support bed | 14-gauge steel slider | 4 inch C roller |
| Drive motor | 1.5 h.p. | 0.75 h.p. |
| Drive unit | Logan 650 | Logan 350 |
| Drive pulley | Lagged, 200° angle of wrap | Lagged, 200° angle of wrap |
| Operations |  |
| Belt speed | 50 ft/min | 33.3 ft/min |
| Unit load weight | 80 pounds | 53.3 pounds |
| Load weight | 2000 pounds | 3000 pounds |
| Belt weight | 246 pounds | 396.6 pounds |
| \( T_e \) | 562 pounds | 337 pounds |
| \( T_1 \) | 996 pounds | 579.6 pounds |
| Minimum horsepower | 1.31 h.p. | 0.62 h.p. |
| Power | 1.49 kW | 0.60 kW |
| Power consumption/yr (10 hours/day) | 2618.00 kW-hr/yr | 1100 kW-hr/yr |
| Initial system cost | $3870.80 | $4467.29 |
| Maintenance cost ($/yr) | 5 belt replacements | 1 belt replacement |
| | $275.00 | $536.07 |
| Electric cost ($/yr) | $143.99 | $60.50 |
| Present worth (12%) | $6590.22 | $4354.20 |

Conveyor initial and operation costs.
needs replacing every 8 years. Thus, over a 15-year period, the operating cost of the slider bed system is 1.5 times that of operating the roller bed system. The present worth of the two systems is shown assuming 12% investment rate and 15-year system life. Thus, selection of the slider bed belt on an initial cost basis would be erroneous, because the operating costs are much greater.

Conclusions

The methodology developed should be used when evaluating alternative conveyor systems. With the operation costs considered in an economic analysis of conveyor systems, the lowest initial cost conveyor may not always be the best alternative. These operating costs are extremely important since they are based on labour and energy. Both are subject to inflation.

The programmable calculator routine developed to evaluate conveyor energy consumption can be used for designing and changing conveyor system configuration. The program enables plant engineers to make on-site decisions regarding conveyor operations and equipment.

The unit load conveyor is probably one of the most efficient methods of moving material through a plant. Proper conveyor system analysis with respect to both operating and purchase costs will result in the most cost-effective system.

APPENDIX
CONVEY program listing

01 LBL "CONVEY"
02 "BELT WT"
03 PROMPT
04 STO 01
05 "FULLY WT?"
06 PROMPT
07 STO 02
08 "CONV LT WT?"
09 PROMPT
10 STO 03
11 "D PUL D"
12 PROMPT
13 STO 04
14 "CONV SP"
15 PROMPT
16 STO 05
17 "D PUL"
18 PROMPT
19 "DEG WRK"
20 PROMPT
21 =
22 .0075
23 =
24 10TX
25 STO 06
26 "SER FRC"
27 PROMPT
28 STO 07
29 "F.R."
30 PROMPT
31 STO 09
32 "F.T.?
33 PROMPT
34 STO 10
35 "CRT RA"
36 PROMPT
37 STO 20
39 RCL 05
39 "CRT+CL"
40 PROMPT
41 +
42 12
43 /
44 XXX?
45 STO 05
46 RCL 20
47 "CRT WT?"
48 PROMPT
49 +
50 RCL 05
51 /
52 RCL 01
53 2
54 +
55 56 RCL 07
57 +
58 RCL 03
59 =
60 RCL 09
61 =
62 RCL 10
63 /
64 "=FC="
65 ACR CL X
66 AVIEW
67 STO 20
68 RCL 06
69 RCL 06
70 1
71 -
72 /
73 "TI="
74 ACR CL X
75 AVIEW
76 RCL 06
77 1
78 1
79 /
80 /
81 /
82 RCL 20
83 /
84 "T2="
85 ACR CL X
86 AVIEW
87 AND
88 RCL 05
89 .262
90 /
91 RCL 04
92 /
Une méthode d'évaluation des coûts de transporteur tenant compte des deux principaux postes de coûts dans l'exploitation des transporteurs à charges unitaires (entretien et énergie) est mise au point.

Un programme (CONVEY) sur calculatrice programmable est mis au point pour aider l'ingénieur de production à déterminer les nouvelles conditions d'exploitation des transporteurs à bande (taille de moteur, tension de la bande, rapport de démultiplication). CONVEY détermine également la consommation électrique en fonction des paramètres d'exploitation spécifiés des bandes.

Es wird eine Bewertungsmethode für Förderkosten entwickelt, bei der die beiden wichtigsten Betriebskosten berücksichtigt werden: Wartung und Antrieb.

Ein programmierbares Rechnerprogramm (CONVEY) wird entwickelt, mit der der Anlagentechniker neue Betriebsbedingungen für das Förderband bestimmen kann, wie zum Beispiel Motorgröße, Bandspannung, Übersetzungsverhältnis. CONVEY erlaubt außerdem die Berechnung der Leistungsaufnahme bei gegebenen Betriebsparametern.

References


