

**AIR CIRCULATION INSIDE REFRIGERATED SEMI-TRAILERS
TRANSPORTING FRESH PRODUCE**

by

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ABSTRACT

AIR CIRCULATION INSIDE REFRIGERATED SEMI-TRAILERS TRANSPORTING FRESH PRODUCE

In North America, refrigerated semi-trailers are commonly used to transport large volume of produce. They are equipped with refrigeration and air circulation systems to provide an optimum transit environment for the produce. Air circulation plays a vital role in maintaining produce temperature during transport. Its performance is greatly affected by the availability of air channels through and around the load.

This study is an attempt to evaluate the performance of the air circulation system. Air temperature data was gathered from 20 mixed loads of produce transported in trailers having a variety of accessories and using different loading patterns. Pearson correlation coefficient was used as an indicator to describe the air distribution inside the semi-trailers. The results showed that the air distribution inside semi-trailers is generally not uniform. In most cases, the areas that received little amount of airflow were the middle section along the length and width, and the middle and bottom sections along the height of trailers. The variability in the results precluded any determination of the effect of trailer accessories and loading patterns on the air distribution.

RÉSUMÉ

LA CIRCULATION D'AIR À L'INTÉRIEUR DES SEMI-REMORQUES REFRIGÉRÉES TRANSPORTANT DES FRUITS ET LÉGUMES FRAIS

En Amérique du Nord, les semi-remorques réfrigérées sont couramment utilisées pour transporter des volumes considérables de fruits et légumes frais. Elles sont équipées avec des systèmes de réfrigération mécanique et de circulation d'air forcée pour fournir un environnement transitoire optimal pour les produits frais. La circulation d'air joue un rôle vital pour maintenir la température des produits lors de leur transport. Sa performance est beaucoup influencée par la disponibilité de conduits d'air à travers et aux alentours de la masse de produit.

Cette étude tente d'évaluer la performance du système de circulation d'air. Les données de température d'air ont été recueillies sur 20 charges mixtes transportées dans les semi-remorques équipées de différents accessoires en utilisant différents modèles de placement de palettes. Le coefficient de corrélation de Pearson a été utilisé comme indicateur pour décrire la distribution d'air à l'intérieur des semi-remorques. Les résultats obtenus indiquent que la distribution d'air dans les semi-remorques était généralement non-uniforme. Dans la plupart des cas, les régions où il y avait moins d'écoulement d'air étaient le milieu sur le sens de la longueur et de la largeur, aussi le milieu et le fond dans le sens de la hauteur des charges. La variabilité sur les résultats ne permettait pas de déterminer l'effet des accessoires et du modèle de placement de palettes sur la distribution d'air.

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NOMENCLATURE

B	bottom
COFC	container-on-flatcar
F	front
FVA	fully braced (on every pair of pallets), vertical air bag
HA	horizontal air bag
L	left
L	London Distribution Center
M	middle
n	number of samples
NA	no air bag
NPLA	National Perishable Logistics Association
P	preliminary test
Q	Vanier Distribution Center
R	rear
R	right
r	Pearson correlation coefficient of variables Y_1 and Y_2
r^2	coefficient of determination
RORO	roll-on/roll-off
RTF	Refrigerated Transportation Foundation
S_1	variance of variable Y_1
S_2	variance of variable Y_2
S_{12}	covariance between the variables Y_1 and Y_2
T	top
TOFC	trailer-on-flatcar
VA	vertical air bag
Y_1	random variable 1
$\overline{Y_1}$	mean of Y_1
Y_2	random variable 2
$\overline{Y_2}$	mean of Y_2

I. INTRODUCTION

1.1 BACKGROUND

In 1992, it was estimated that 208 million tons of fruits and vegetables were produced worldwide (IIR, 1995). Whether they are destined for local consumption or for export, the majority of this produce had to be transported several times before reaching the consumer. Fresh produce can be transported throughout the distribution chain either by road, rail, sea or air.

Transportation of fresh fruits and vegetables is a dynamic industry in North America. Refrigerated semi-trailers are commonly used as the primary means of moving large volumes of fresh produce. Produce is normally shipped from the producers to the wholesalers, then to the distributors and retailers and finally to the consumers. Due to their perishable nature, fruits and vegetables have to be maintained at optimum temperature during transit. A 1996 survey showed that at least 42,149 trailers in the U.S. offered refrigeration or freezer services to provide optimum conditions for the transport of produce or other perishable goods (CHRW, 1999).

Proper air circulation inside refrigerated semi-trailers is one of the main factors that influence produce temperature during transport. Researchers have identified several other important factors that may affect produce temperature such as its initial loading temperature, performance of the refrigeration system and climatic conditions outside the trailer. Various precooling methods have been developed and used to ensure produce is at its optimum temperature before loading. Furthermore, recent developments in electronics made possible microprocessor controlled refrigeration systems offering precise temperature control on various modes of operation. These refrigeration systems also have cooling capacities large enough to maintain produce temperature while traveling in tropical or freezing external environments. The main challenge in ensuring optimum produce temperature during transport lies in achieving uniform distribution of conditioned air inside the semi-trailers.

1.2 STATEMENT OF PROBLEM

The uniformity of air distribution inside a semi-trailer is influenced by the availability of air channels for air movement around and through the load. Current literature pointed out that various trailer accessories and loading arrangements affect the efficiency of the air circulation system. The use of an air duct and bulkhead, various floor configurations, as well as the different loading patterns have been widely discussed. Nevertheless, the effects of these components or loading practices have not been quantified. Research in the past focused mostly on quantifying the fluctuation of produce temperature, which is affected by a wider variety of factors. Little effort was made to study explicitly the performance of the air circulation system.

This study intends to provide an overview of the equipment and practices currently used by the industry. It attempts to examine the individual influences of various trailer accessories and loading patterns on air distribution. Special consideration was placed on the evaluation of centerline loading using vinyl air bags as restraint, since most of the literature reviewed emphasized the need for air channels between the load and the trailer walls to reduce the conduction of outdoor heat.

1.3 OBJECTIVES

The objectives of this study are:

1. Examine the equipment and practices currently used to transport fresh produce.
2. Verify the uniformity of air distribution inside refrigerated semi-trailers.
3. Define the airflow patterns in semi-trailers having different accessories and loads.
4. Evaluate the effect of various loading and bracing patterns on air distribution.

1.4 SCOPE OF THE STUDY

This study describes the transport of mixed loads loaded from a central distribution center situated at Boucherville, Quebec and delivered to satellite centers in London, Ontario and Vanier, Quebec. Data loggers were placed on selected pallets in each load to record air temperature at various locations during transit. These readings

were used to assess the association between temperature of air at a certain point in the load and temperature of air supplied by the refrigeration system. The association between the temperatures was used as an indicator of the performance of the air circulation system. Due to the large variability in field conditions, conclusions drawn out of this study are limited to cases encountered in the field tests.

II. LITERATURE REVIEW

2.1 MODE OF TRANSPORT FOR FRESH PRODUCE

Fresh fruits and vegetables are transported either by road, rail, sea or air. The choice of the mode of transport is usually based on the location and distance of the market, the quantity and value of the produce, its perishability, the transit time and the freight rates. Also considered important is the required transport environment, the climatic conditions at the origin and destination, the availability of infrastructure and the quality of transport service available.

2.1.1 Road Transport

Road transport is the most common method of hauling large volumes of produce across the North American continent. The presence of a well-developed road network, the reliability of transport equipment, the moderate cost of transport, and the flexibility to deliver produce to almost any location make road transport the most widely used method for transporting produce. Road transport can also be combined with other modes of transport to deliver produce over longer distances. Three types of transport equipment can be found on highways, namely: refrigerated semi-trailer, intermodal container and RoadRailer.

Refrigerated semi-trailer, commonly referred to as trailer, is the most common transport equipment on highways. It is normally equipped with mechanical refrigeration system(s) and is usually pulled on the road by a tractor as tractor-trailer (Figure 2.1). It can also be transported on railroad flatcar (piggyback or trailer-on- flatcar (TOFC)) or loaded onto sea vessel (roll-on/roll-off (RORO)). A refrigerated semi-trailer basically consists of an insulated rectangular box supported by a set of wheels at the rear and a pair of adjustable landing gears at the front. Older trailers are equipped with heavy-duty spring suspensions, but the newer ones operate on air-ride suspension systems. The air-ride suspension system provides a smoother ride, consequently reducing vibration and shifting of the load that occur during transport. When a tractor is pulling the semi-trailer, the kingpin of the semi-trailer is hooked up to the fifth wheel of the tractor. This connection allows the trailer to transfer its front weight to the tractor. Refrigerated semi-

trailers are available in nominal lengths of 12 m (40 ft), 13.7 m (45 ft), 14.6 m (48 ft) or 16.2 m (53 ft) (McGregor, 1989). The 14.6-m and 16.2-m long semi-trailers are the most common trailers used by the transport industry.

2.1.2 Rail Transport

Rail transport used to be the dominant method of land transport. With the increased use of road transport, rail transport has steadily declined in North America. However, the recent merger of several rail networks may revitalize this mode of transport. Five different equipment can be used for rail transport: ice-refrigerated railcar, mechanically refrigerated railcar, refrigerated TOFC, intermodal container-on-flatcar (COFC) and RoadRailer.

Ice-refrigerated railcar consists of an insulated wagon with one or more ice compartments to supply cooling for produce. Mechanically refrigerated railcar is similar to ice-refrigerated railcar, except that it is equipped with mechanical refrigeration at one end of the wagon (Figure 2.2). Piggyback or TOFC describes a semi-trailer which is loaded on a wagon that has no sidewalls (flatcar). When an intermodal container is loaded on a flatcar, it is called as COFC. The concept of RoadRailer was introduced in the U.S. around the 70s, but it was only recently introduced in Canada (Truck News, 2000). The RoadRailer is similar to a semi-trailer, but is equipped with both rubber tires and rail wheels (Figure 2.3). It can be pulled by a tractor on highways or by a locomotive on railroad tracks. The refrigerated version of RoadRailer, ReeferRailer, is used for transporting fruits and vegetables.

2.1.3 Marine transport

For overseas transport, produce can be loaded as break-bulk in conventional refrigerated ships or in container ships. Presently, produce is commonly transported in sea containers. These containers are called intermodal containers since they can be easily loaded directly onto sea vessels, on rail flatcars as COFC or on a set of chassis pulled by a tractor on the road (Figure 2.4). Refrigerated intermodal containers are equipped with recessed mechanical refrigeration units with bottom-air delivery systems.

2.1.4 Air transport

Air transport is used mainly to deliver high value and highly perishable produce. It provides very fast, but costly deliveries. Due to the weight limitations in aircraft, containers used to transport produce are not equipped with any cooling system and have very limited insulation (Figure 2.5). Produce temperature can be maintained using dry-ice packages placed inside the aircraft containers.



Figure 2.1: Refrigerated semi-trailer pulled by a tractor.

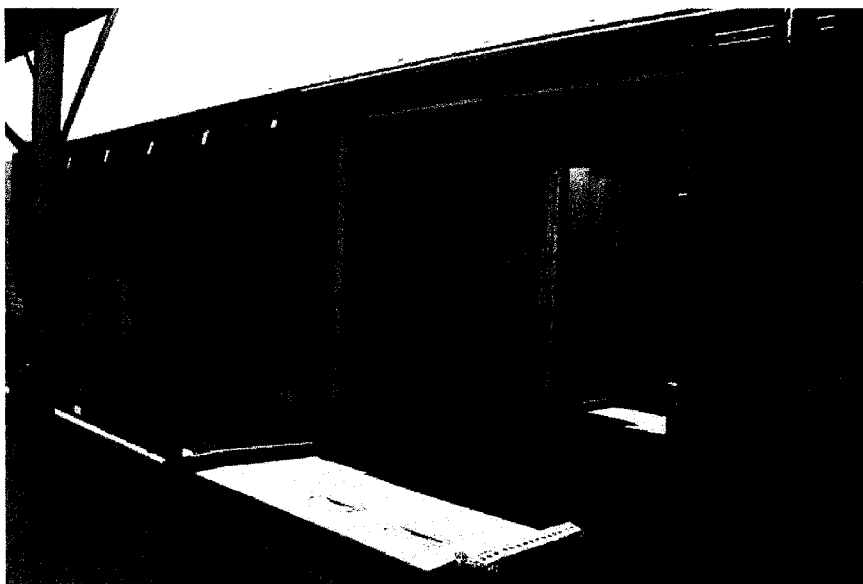


Figure 2.2: Mechanical refrigerated railcar.



Figure 2.3: Bi-modal RoadRailer.

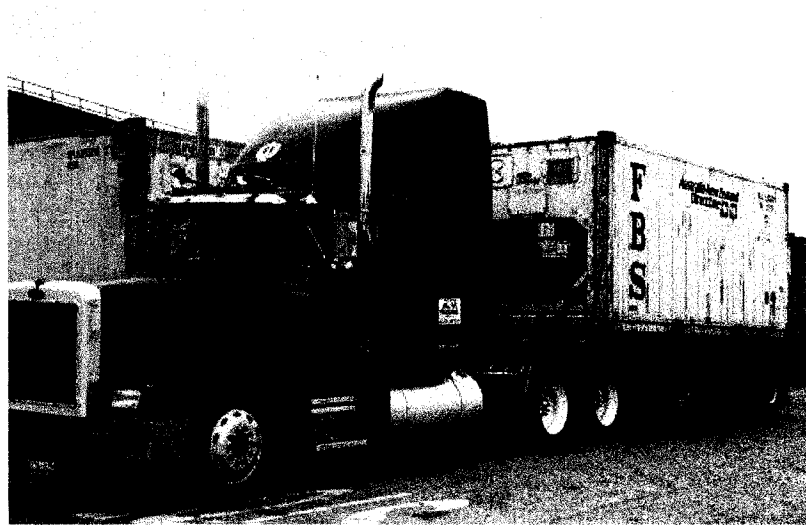


Figure 2.4: Refrigerated intermodal container pulled by a tractor.



Figure 2.5: Lightweight aircraft containers waiting for loading.

2.2 THE IMPORTANCE OF MAINTAINING PRODUCE TEMPERATURE

Produce quality at the point of sale is dependent on a series of physiological processes that are affected by the surrounding environment. Fresh fruits and vegetables are living organisms. They undergo a series of physiological processes that are necessary for the continued growth and development of tissues. While produce is attached to the mother plant, it is supplied with nutrients necessary for its metabolism. These metabolic processes continue even after harvest. However, once the produce is detached from the plant, it uses its own nutrient reserves for the life-sustaining processes and these nutrients are not replenished. These processes lead to the deterioration of produce and the reduction of its quality.

Similar to other bio-chemical processes, temperature affects the rate of produce metabolism. The metabolism rate and the deterioration rate increase with produce pulp temperature. Produce becomes more perishable as its pulp temperature increases. Temperature is considered as “the single most important factor” which influences the quality of horticultural products (Wills et al., 1998). It also affects the rate of growth and development of decay organisms that attack the produce after harvest. Even though deterioration of fruits and vegetables is an inevitable and irreversible process, produce can be preserved longer if its pulp temperature is lowered immediately after harvest and this optimum temperature is maintained throughout the distribution chain.

Produce quality is also a function of time. The effect of improper temperature on fruits and vegetables is cumulative. Quality will be affected even if produce is exposed to adverse temperatures for short and intermittent periods of time (Thompson et al., 1998). Transportation is one of the main steps in the distribution chain where produce can spend anywhere from hours to months. Some highly perishable produce, such as lettuce, can spend almost half of its postharvest life in transport vehicles. Therefore, it is essential to maintain fruits and vegetables at the desired temperature during transport.

2.3 TEMPERATURE MANAGEMENT IN REFRIGERATED SEMI-TRAILERS

To ensure minimal quality losses during transport, produce must be kept in an environment that is favorable for maintaining its quality. This requires the management

of the surrounding environment to the desired level. Since temperature is the most critical factor in maintaining produce quality, semi-trailers are equipped with systems that regulate the temperature of the environment around the produce. Several factors influence the temperature of produce loaded inside a semi-trailer: the heat sources within and outside the trailer, the source of heating and cooling, the amount of air circulation and its distribution, the packaging and loading arrangement of the produce.

2.3.1 Heat sources

There are three sources of heat that have to be controlled in order to maintain produce temperature during transport. They are the residual heat load initially held within the trailer and produce, the external heat load penetrating the vehicle during transport, and the internal heat generated by the produce.

2.3.1.1 Residual heat load

Residual heat load includes any heat initially held within the semi-trailer before loading as well as the field heat contained in the produce and its packaging materials. It comprises sensible heat of warm air initially present inside the trailer, heat contained in the insulation and inner lining of the trailer (Ashby, 1999), heat held by trailer accessories and bracing materials, heat generated by loading equipment, as well as heat contained in warm produce. To be able to maintain produce at its optimum temperature, the semi-trailer and the produce itself has to be at the optimum temperature prior to transport. The cooling unit installed in a trailer is generally designed to remove only the external and internal heat loads in transit. It does not have extra capacity to handle the residual heat load at the same time. Therefore, the semi-trailer and the produce need to be thoroughly cooled prior to loading.

Fruits and vegetables are harvested at ambient temperature and they are usually warm. In order to maintain produce quality, field heat is rapidly removed after harvest. Forced-air cooling, hydrocooling, vacuum cooling or icing can be used to precool produce after harvest. The amount of field heat in the produce is a function of its mass, specific heat, and the difference between its initial and optimum storage temperature. Improperly precooled produce increases the cooling demand from the semi-trailer refrigeration system and affects its performance. Poorly precooled produce also increases

the amount of internal heat load (Hui et al., 2000). Therefore, precooling the produce to its recommended transport temperature before shipment is very important.

Well-precooled produce may also gain heat during handling. Loading and unloading of trailers is sometimes done at ambient temperature in open loading docks. Produce may gain heat from the surroundings if left at ambient temperature even for short periods of time. It is important to keep produce in a refrigerated area and avoid delays in the loading and unloading operation to prevent rewarming of produce.

2.3.1.2 External heat load

External heat load results from the interaction between the trailer and its external environment. It is usually the most significant heat load which influences produce temperature during transport. External heat enters the trailer through conduction, convection, infiltration or radiation.

Conduction and convection heat can be transmitted from the roof, floor, walls and doors into the internal surfaces of a trailer. Whenever a temperature gradient exists between the outside and inside surfaces of the trailer, a certain amount of heat flows across these surfaces. The amount and direction of heat movement is a function of the overall heat-transfer coefficient, the area of the surfaces involved and the temperature gradient between the outside and inside surfaces. The overall heat-transfer coefficient depends on the thermal conductivity of the insulation materials and the R-value of the stagnant air films covering the inside and outside surfaces of the trailer (Hui et al., 2000). To reduce the amount of conduction heat load, insulation materials are used. The insulation materials used in trailers have to be resistant to fire, breakdown at extreme temperatures, cracking, crumbling, shifting, vibration, or any other type of mechanical abrasion (ASHRAE, 1998). It should also have low moisture permeability and water retention, moderate cost, easy to apply and lightweight (ASHRAE, 1998). Physical damage and moisture penetration usually decreases the insulation value of materials. Therefore, damages on trailer surfaces must be immediately repaired and drain holes have to be maintained free of debris to prevent water accumulation. Physical damage normally occurs over time and usage, so the amount of conduction heat load is generally higher in older trailers.

Infiltration is one of the most significant sources of external heat in transport trailers. Warm air usually enters through small holes, cracks, drainage holes and broken door seals of the trailer. The opening and closing of the trailer door for inspection or for multiple stop deliveries also significantly increase the external heat load. ASHRAE (1998) found that the heat gain due to opening and closing of doors in a multiple stop delivery can be five times more than the conduction heat load across the trailer's inner surfaces.

Solar radiation also increases the external heat load in a refrigerated trailer. In a study reported in ASHRAE (1998), it was found that the cooling requirement of stationary vehicles increased by 20 % when exposed to sunlight for several hours. Heat gain through solar radiation is minimized by using highly polished steel, aluminum plates, or reflective paints on the outside surfaces of the trailer (Ashby, 1999). Frequent cleaning is required to maintain the reflective properties of the outer surfaces. Kasmire and Hinsch (1987) suggested road heat may have a greater effect on produce temperature than heat transmitted through walls and roof, since well-compacted and dark colored highway roadbeds tend to act as heat sinks and accumulate tremendous amount of heat. This heat is radiated 24 hours a day from mid-spring through mid-fall into the bottom of trailer (Kasmire and Hinsh, 1987). The heat radiated to the floor is generally less during nighttime than daytime.

2.3.1.3 Internal heat load

Internal heat load in a trailer includes respiration heat generated by the produce during transit. Biological materials respire as part of their metabolic process. Horticultural produce continues to respire even after harvest. As produce respire, CO₂, moisture and heat are released. The respiration rate varies with the type of produce. Produce such as asparagus, corn and strawberries respire more than apples, oranges and potatoes (Ashby, 1999). Since respiration rate increases with produce pulp temperature, produce that is not properly precooled tends to have a higher respiration rate and produce more internal heat (Hui et al., 2000).

2.3.2 Mechanical refrigeration

Several methods are available to maintain optimum temperature inside semi-trailers. Mechanical refrigeration is the most widely used method of temperature control in refrigerated semi-trailers. It operates on the vapor-compression-refrigeration cycle, similar to household refrigerators (Wark, 1988). In such systems, a refrigerant changes phase from liquid to vapor and back to liquid in a closed cycle. As a result of these phase changes, the refrigerant is able to absorb heat from the evaporator located inside the trailer and release it through the condenser outside the trailer.

The main components of a mechanical refrigeration system are the evaporator, compressor, condenser and expansion valve. In the evaporator, liquid refrigerant absorbs heat from air passing through the evaporator coils and changes into vapor. The vaporized refrigerant is then compressed in the compressor to a pressure high enough to allow the refrigerant to release heat and condense at ambient temperature. A regulated amount of liquid refrigerant is released by the expansion valve into the evaporator where it vaporizes at low pressure. The refrigerant absorbs heat from air circulated by the blower through the load, thereby regulating the temperature inside the trailer.

The refrigeration system on a semi-trailer is typically driven by a diesel engine. All components of the refrigeration system are built into a self-contained unit that is mounted on the front wall of a trailer. The system usually has the engine, condenser, and other accessories installed outside of the front wall, with only the evaporator and blower placed inside the semi-trailer (Figure 2.6).

Mechanical refrigeration systems installed on semi-trailers are not only designed for fresh produce, they can also provide lower temperatures for deep-frozen products. The capacity of the refrigeration system varies among the different models. Its performance is affected by the external air temperature and temperature of air returning to the evaporator. For typical units operating at an ambient temperature of 38 °C (100 °F) and a return air temperature of 2 °C (35 °F), the capacity of the refrigeration systems range from 12.7 to 15.8 kW when the engines operate at high-speed (data obtained from product catalogues of Thermo King Corporation and Carrier Transicold).

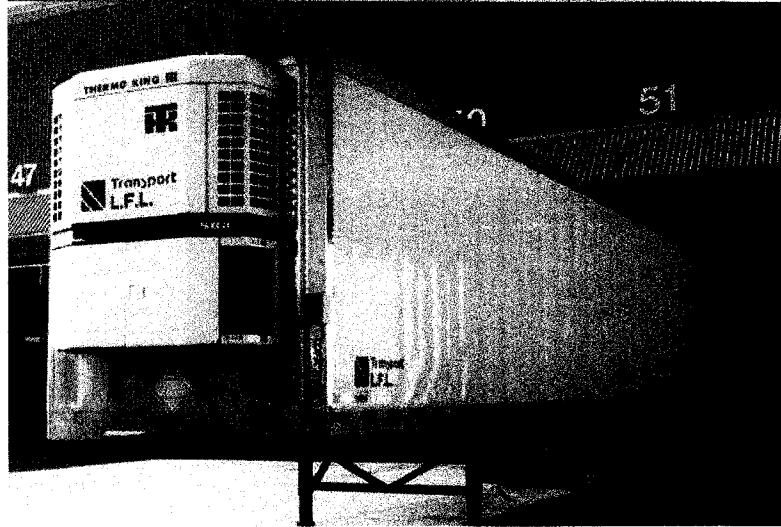


Figure 2.6: Nosemounted mechanical refrigeration system on a semi-trailer.

The mechanical refrigeration system can be operated at continuous or automatic (start/stop) mode. In continuous mode, the compressor and the blower operate continuously and temperature is maintained very close to the setpoint. In the automatic mode, the compressor works intermittently, but the blower that circulates air inside the trailer operates continuously. The use of automatic mode results in fuel savings, but creates a wider temperature fluctuation around the setpoint compared to the continuous mode.

Thermostats are used to regulate the air temperature inside the trailer. Modern refrigeration units measure both the supply and return air temperatures. Sophisticated microprocessor-based control systems are used to maintain temperature very close to the setpoint. For example, one of the commercially available temperature-control systems claims to be able to maintain the supply and the return air temperatures to within ± 1.1 °C (± 2 °F) of setpoint when the setpoint is above -12 °C (10 °F) (Carrier Transicold, 1995). This system reduces the fluctuation in temperature across the evaporator coil and eliminates the heat-cool cycling that occurs in conventional systems.

The choice of setpoint temperature is a function of the type(s) of produce present in the load. Different products have different optimum holding temperatures. For example, highly perishable produce such as lettuce and strawberry should be maintained at 0 °C (32 °F), while mature green tomato has to be kept at 12.8 °C (55 °F) to 21.1 °C (70 °F) (Thompson et al., 1998). If the load contains only one type of product, the

setpoint is usually adjusted for the specific produce. If different products are transported together in a mixed load, the transit temperature has to be carefully selected. For mixed load, the setpoint is usually adjusted for the produce requiring the highest holding temperature. Although this temperature is not ideal for other produce requiring lower temperatures, compromises have to be made to avoid chilling or freezing injury. This problem of temperature incompatibility is commonly found at the distribution level, where produce at different temperatures is loaded in the same trailer.

2.3.3 Air circulation

Air circulation plays a critical role in maintaining produce temperature during transport of fruits and vegetables. Conditioned air has to be circulated uniformly through and around the load to absorb internal and external heat loads. Internal heat load usually consists of respiration heat generated by the produce. This respiration heat must be removed to prevent the rapid increase in pulp temperature. By circulating conditioned air through and around the load, heat build up is prevented allowing produce temperature to be maintained at optimum levels.

External heat continuously penetrates the semi-trailer during transport. The insulation of the trailer can slow down but not totally stop the flow of heat. Over a period of time, these surfaces would absorb heat from the exterior and carry it across the internal surfaces of the trailer. By circulating conditioned air between the load and the trailer surfaces, heat movement through this space is retarded. The conducted heat is absorbed by the air and removed by the refrigeration unit. Heywood (1998) emphasized that an air jacket at the optimum temperature is the “best insulation” around the load. The temperature of the trailer surfaces becomes unimportant if produce is not touching these surfaces due to the presence of the air envelope (Heywood, 1998). Air can also be heated and circulated around the load to prevent chilling or freezing of produce in winter (Ashby, 1999). On the whole, circulating air around the load removes external heat, retard heat flow and isolate the load from warm/cold surfaces within the trailer.

Good air circulation allows air to remove heat faster from around and within the load to the refrigeration unit. This not only allows faster heat removal, but also reduces the temperature gradient across the evaporator and prevents frequent defrosting of the refrigeration unit. The capacity of the refrigeration system is irrelevant if conditioned air

is not circulated properly (Ashby, 1999). Although most refrigeration systems have excess cooling capacity, air circulation is frequently inadequate in removing excess heat inside the trailer (Kasmire and Hinsh, 1987). Aside from a high airflow rate, a uniform air distribution is needed to maintain the desired produce temperature throughout the entire load. Uneven air distribution results in over-warming or over-cooling at different parts of the load that could lead to shorter shelf life and eventual spoilage. Inefficient air distribution is more likely to be the main reason for improper cooling of the load during transport (ASHRAE, 1998).

2.3.3.1 Air delivery system

The bottom-air delivery system extensively used in intermodal containers has a very limited use in refrigerated semi-trailers (Ashby, 1999). Containers that use this type of delivery system are generally equipped with horizontal T-beam floor, vertically ribbed rear doors and vertically ribbed sidewalls. Air movement in bottom-air delivery system is mostly vertical. It requires that the floor area be entirely covered by the load. The refrigeration system forces conditioned air underneath the T-beam floor of the container. The pressurized air flows from the front to rear of the container and is forced upward through the load and the ribbed sidewalls. When air reaches the ceiling of the container, it flows toward the front wall and returns to the evaporator of the refrigeration unit (Figure 2.7).

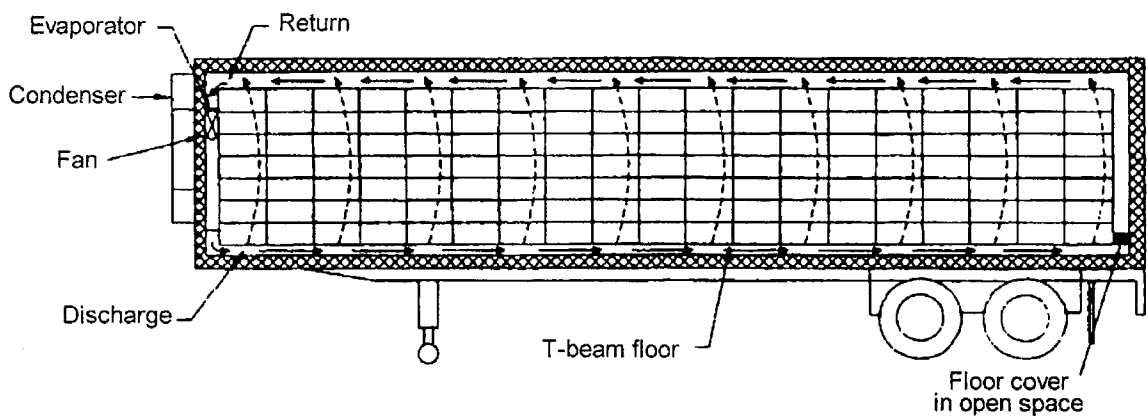


Figure 2.7: Airflow pattern in the bottom-air delivery system (Ashby, 1999).

Although this system provides an efficient method for circulating the air, it has some disadvantages which limit its use in refrigerated semi-trailers. The ribbed sidewalls and deep T-beam floors can be easily damaged by forklifts during loading and unloading. Air can easily get short circuited when the trailer floor is not fully covered, especially when the trailer is transporting a mixed load that consist of different sizes of package containers. In addition, the extra weight of the accessories reduces the amount of produce that can be loaded in the trailer since highways have gross vehicle weight limits. Consequently, bottom-air delivery systems are normally used only in intermodal containers for long distance transport where cycle times are infrequent and no weight restrictions exist.

The overhead or top-air delivery system is the most widely used method of air circulation in refrigerated semi-trailers. This system delivers high velocity, low-pressure airflow longitudinally inside the trailer. Air travels above the load from the front to the rear of the trailer. Along the way, some of the air flows down between the sidewalls and the load. As the air reaches the rear end of the trailer, it flows downward between the rear door and the load. Air then moves underneath the load from the rear to the front along the floor when it reaches the front wall, air flows upward behind the load and returns to the evaporator (Figure 2.8). As air circulates along the surfaces of the trailer and through the load, it picks up heat coming into the trailer and heat generated by the produce.

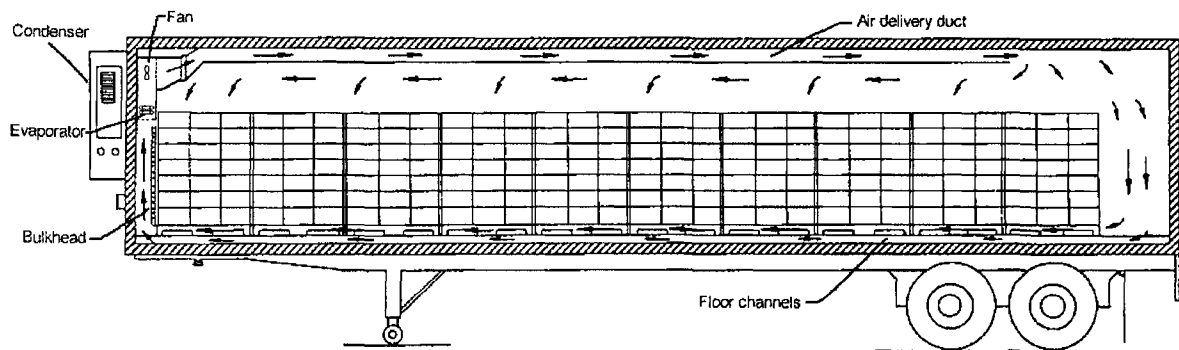


Figure 2.8: Airflow pattern in the top-air delivery system.

Several features are available which assist air circulation within refrigerated semi-trailers. Semi-trailers can be equipped with an air-delivery duct, a deep-channel floor and a pressure return-air bulkhead (Figure 2.8 and 2.9). These features help to maintain air pathways above and below the load, as well as at the front and rear of the semi-trailer. The use of these features enhances air circulation and consequently improves control of load temperature during transport (Ashby, 1999).

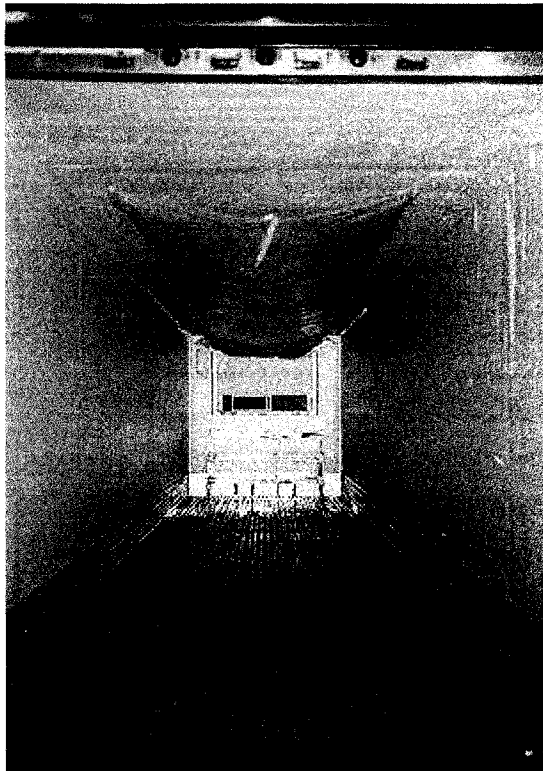


Figure 2.9: The air-delivery duct, deep-channel floor and return-air bulkhead inside a refrigerated semi-trailer.

2.3.3.1 Air-delivery duct

The air-delivery duct helps to distribute air from the outlet of the refrigeration unit to the rear and both sides of the load. The duct is usually made of canvas or vinyl (Kasmire et al., 1996) and it is connected to the blower discharge through an adapter. It is mounted on the middle or slightly off to the side to the ceiling using Velcro, grommets or nylon twist fasteners (Aero Industries, 1999). Quick release fasteners can be used as

connectors to the refrigeration unit or bulkhead adapter to ensure accessibility of the evaporator coils for sanitary inspection and maintenance.

In terms of the air duct design, the National Perishable Logistics Association /Refrigerated Transportation Foundation (NPLA/RTF) recommends a minimum cross-sectional area of 0.15 m^2 (240 in^2) (Ashby, 1999). The duct covers the discharge of the fan near the front wall and extends to at least 3 to 5 m (10 to 15 ft) from the rear doors (Craig, 1990). Progressive air spills are placed along the length of the duct, except at the first 3 m (10 ft) near the refrigeration system (Ashby, 1999). The air spills are used to divert the airflow and allow some air to flow sideways. For the first 3 m, the edges of the duct are fastened tightly to the ceiling (Craig, 1990). If the connection is not tight, air can short circuit to the bulkhead, thus affects the thermostat reading and causes poor regulation of temperature. Beyond this point, spacers of 6.4 to 7.9 mm (0.25 to 0.31 in) are used with fasteners to create the side air spills (Craig, 1990). The size of the air duct is normally matched to the type of refrigeration unit used and the ceiling area of the trailer. Information on the proper size of the air duct is usually available through the manufacturer of the trailer refrigeration system.

One of the disadvantages of the air duct is that it can obstruct the movement of the forklift during loading or unloading operations. To prevent damage, the duct has to be hanged no more than 0.15 m (6 in) below the ceiling and the middle of the rear opening has to be secured to prevent getting caught up in the pallet (Craig, 1990). Securing the rear opening also pressurizes air inside the duct and improves the spilling of air sideways.

To prevent the air duct from collapsing against the ceiling and blocking air movement, produce has to be loaded below the level of the air duct. Blockage of the air duct can be avoided by painting a line on the sidewalls below the level of the air duct indicating the maximum allowable loading height (Ashby, 1999).

The air duct has to be inspected for damage and cleanliness prior to each trip. Torn ducts create an uneven air distribution inside trailers (Craig, 1990). Dirt accumulated inside the air duct will be blown by air and contaminate the load. The air duct has to be removed and cleaned at regular intervals using cleaning agents approved by governmental agencies (Craig, 1990).

2.3.3.2 Floor

In a top-air delivery system, the space between the load and the floor of the trailer acts as a plenum for return air to the evaporator. If there is insufficient amount of return-air space between the floor and the load, airflow will be throttled and the fan will rotate without discharging any conditioned air to the load. Ashby (1999) stated that around 0.15 m^2 (240 in^2) of return air space is required for the fan of an average trailer to operate at 100 percent capacity. Kasmire et al. (1996) suggested that about 0.19 m^2 (290 in^2) of unrestricted return air passage is needed by a fan to achieve maximum capacity.

The most common types of floor found in refrigerated semi-trailers are flat floor (without any channels), duct board floor, duct-T floor and T-beam floor (Figure 2.10). Each design offers a different cross-sectional area for return air passage. Flat floor provides no return air space. In a trailer with an internal width of 2.46 m (97 in), 31.8 mm (1.25 in) deep duct board floor provides approximately 0.03 m^2 (47 in^2) of return air channels, which is considered inadequate (Kasmire et al., 1996). Duct-T floors with heights of 25.4 mm (1 in) and 38.1 mm (1.5 in) supply around 0.05 m^2 (73 in^2) and 0.07 m^2 (102 in^2) of return air space respectively, which meet about 26 to 37% of the required opening (Kasmire et al., 1996). A 57.2 mm (2.25 in) deep T-beam floor provides about 0.13 m^2 (200 in^2) of return air channels (Kasmire et al., 1996). None of these floor designs provide sufficient air passage for return air, therefore, it is recommended to load produce on pallets (Figure 2.10) or wood racks when these types of floor are used (Kasmire et al., 1996).

T-beam floor provides more return air passage than any other design, but it has several disadvantages. It is more susceptible to forklift damage during loading and unloading operations as compared to other types of floor. Debris can easily accumulate in the deep channels, make the floor very difficult to be cleaned and reduce the effectiveness of the floor design. Furthermore, forklift is more susceptible to slippage during loading and unloading due to the reduced contact area between the floor and tires.

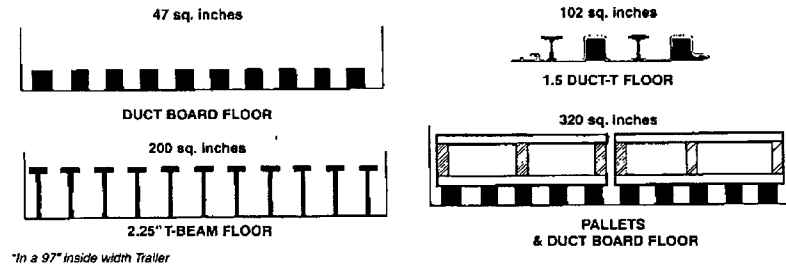


Figure 2.10: Different floor designs used in semi-trailers (Kasmire et al., 1996).

2.3.3.3 Return-air bulkhead

A return-air bulkhead is basically a false wall that provides a clear pathway for air to return to the evaporator. It serves to isolate the load from the front wall, to prevent the load from blocking the air return to the evaporator and to force air to go around and under the load without short-circuiting (Kasmire et al., 1996). The bulkhead can cover the full width and half the height of the front wall. Frame and solid/pressure bulkheads are commonly used. In terms of temperature management, solid/pressure bulkhead is better than frame bulkhead since the later may allow some air to by-pass the load. A frame bulkhead is simply a rectangular lattice made of aluminum or wooden beams (Figure 2.11a). Solid or pressure bulkhead generates a pressure difference across the outlet and inlet of the fan (Kasmire and Hinsh, 1987). This causes air to circulate through, around and underneath the load before returning to the refrigeration unit.

Various designs of solid or pressure bulkhead are available. They can be classified as standard solid bulkheads or molded bulkheads. The standard pressure bulkhead is usually made of fiberglass-reinforced plywood and aluminum. They can be a single solid wall or a composite of solid and frame walls (Figure 2.11b). The one-piece molded bulkhead is a newer design made of polyethylene (Figure 2.11c). This design takes into account the air intake area, the air movement and the impact strength (Aero Industries, 1999). For example, one model has built-in directional airflow bridges allowing cross circulation to optimize the air movement. This model has more than 0.23 m^2 (350 in^2) of cross-sectional area for air return and it has built-in pallet stops to prevent air blockage at the inlet (Aero Industries, 1999). Compared to other types of bulkhead, the molded bulkhead comes in as a one-piece unit that requires no assembly.

The air return at the bottom of solid/pressure bulkheads is usually covered with screens to prevent debris from entering the bulkhead.

The NPLA/RTF recommends a space of at least 76 mm (3 in) between the bulkhead and the front wall and a minimum open space of 152 mm (6 in) between the bottom edge of the bulkhead and the trailer floor (Ashby, 1999). Bumpers or pallet stops may be installed at the bottom opening to prevent blockage due to load shifting. The airflow may be blocked at the bottom due to improper loading or load shifting. The top of the bulkhead must have an open area of 0.02 m² to 0.03 m² (30 to 50 in²) to allow mixing of top and bottom-air, as well as allowing some air flows to the thermostat in case of blockage at the bottom of the bulkhead (Ashby, 1999).

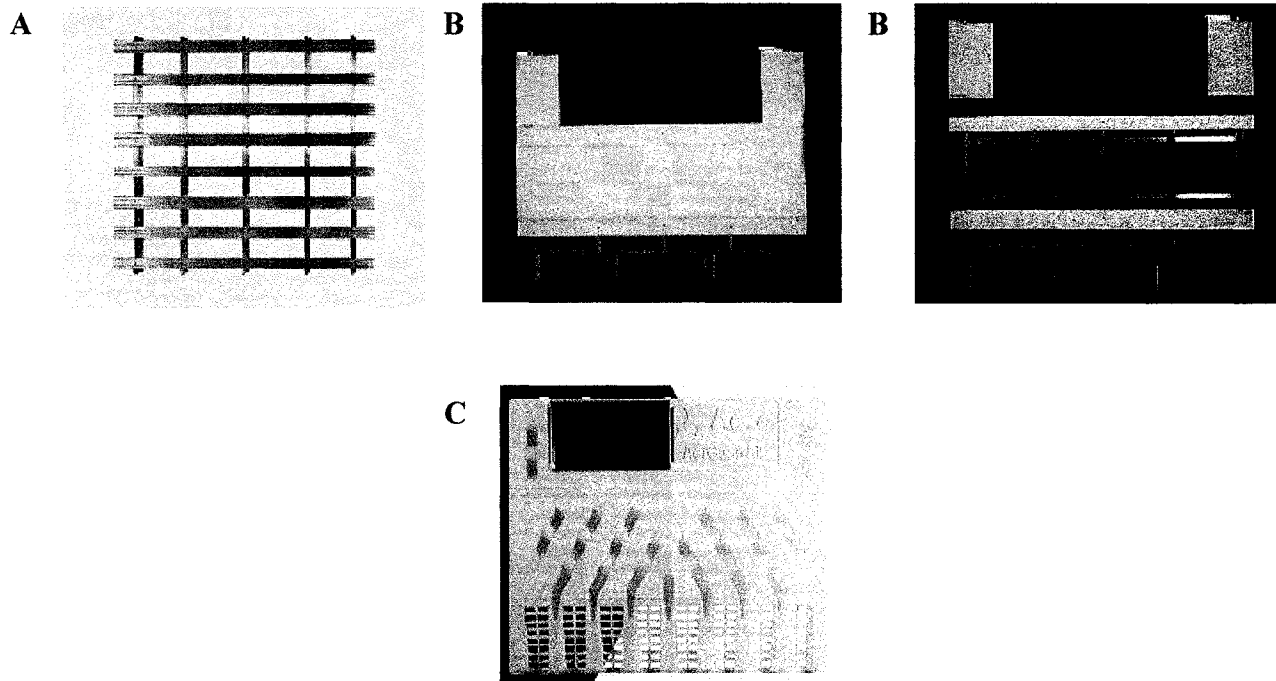


Figure 2.11: Different types of bulkheads: a) frame bulkhead, b) solid bulkheads and c) molded bulkhead (Aero Industries, 1999).

2.3.3.4 Other features

Several other features can be added to improve air circulation aside from the use of air duct, deep-channel floor and pressure bulkhead. Kasmire et al. (1996) recommended curving the bottom edge of the bulkhead, installing wind deflectors on the

front wall and installing standoff on the rear doors to enhance air movement around these areas.

2.3.4 Load characteristics

The load inside a trailer is not only a source of heat but also an impediment to airflow. The packaging of produce and the subsequent arrangement of these packages inside the trailer significantly affect the circulation of air, consequently affecting the efficiency of heat removal from the inside of the trailer. The availability of air channels and the airflow pattern change with the design of produce packaging, the package arrangement, the type of external wrapping, the pallet loading pattern, the use of bracing materials or a combination of these factors. The choice of packaging, the package arrangement and the choice of external wrapping material affect the efficiency of air circulation across the load, while the loading pattern affects the air movement around the load. Bracing is commonly used to prevent the blockage of air channels around the load due to load shifting.

Packages are loaded inside a semi-trailer in two ways: either as a unitized load or a palletized load. In a unitized load, packages of produce are individually hand-stacked inside a semi-trailer, usually from floor to ceiling to optimize space. In a palletized load, packages are first arranged on pallets and the pallets are then loaded inside the trailer by forklifts. Although a larger quantity of produce can be transported in a unitized load, palletized load is preferred due to the ease of handling, the reduced loading and unloading time, and the reduced labor requirements.

Produce is usually loaded on a 1.02-m wide by 1.22-m long pallet (40 in x 48 in). Different configurations of pallets are available. Two types of pallets are commonly used: the 4-way-double-deck-solid-beam pallet with large openings along the width and the 4-way-double-deck-cube-beam pallet with large openings on all four sides (Figure 2.12). A palletized load may be composed of one single type of commodity (straight load) or several types of commodities (mixed load) in one trailer. At the wholesale and distribution level, produce is mostly palletized and mixed loads are common. Straight loads are usually found at the producer level. The following discussion will focus on palletized loads of fruits and vegetables.



Figure 2.12: Produce loaded on a 4-way-double-deck-cube-beam pallet placed on top of a 4-way-double-deck-solid-beam pallet.

2.3.4.1 Package container

The choice of package container is usually based on the characteristics of the produce, the precooling method, packaging method, strength, cost, availability, buyer specifications and freight rates (McGregor, 1989). The most common package containers are the corrugated fiberboard boxes and bins, wooden bin and wire-bound crates, plastic boxes and bin, paper and mesh bags, Styrofoam boxes, and baskets. Among all the containers available, corrugated fiberboard boxes are the most commonly used packaging material in the industry. They come in assorted styles, sizes, shapes, weights, thickness, strength and coatings.

Most of the fiberboard boxes are made of double-faced corrugated fiberboard. The double-faced fiberboard consists of a layer of corrugated paper sandwiched between two flat liners of paperboard (Figure 2.13). The capacity of this material to handle produce is measured by its burst strength and crush strength. For boxes intended for export, a fiberboard with a minimum of 1896 kPa (275 psi) burst strength is recommended (McGregor, 1989). When layers of packaged produce are stacked on a pallet, the edge crush strength is used as an indicator of load capacity of the packaging material rather than the burst strength. Certificates printed on the bottom of the boxes usually indicate the strength characteristics and limitations of the boxes. One major

limitation of corrugated fiberboard is moisture absorption from the surrounding environment or from the produce. The absorption of moisture can reduce the strength of the boxes by up to 75% (Boyette et al., 1996). Therefore, for fiberboard boxes that are subjected to water, ice, or high humidity, they have to be treated with anti-moisture coatings such as wax or plastic.

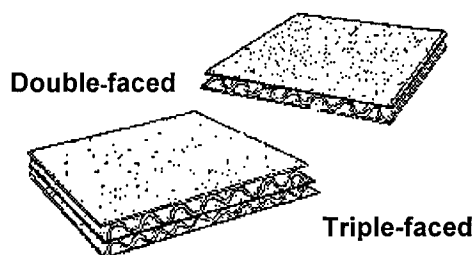


Figure 2.13: Configurations of corrugated fiberboard (Boyette et al., 1996).

The presence of ventilation holes on the sidewalls of the packaging container affects the amount of airflow across the produce. Adequate amount of openings is needed in containers for the removal of respiration heat. For corrugated fiberboard boxes, the design of hand holes and ventilation slots is primarily optimized for forced-air cooling. These designs also ensure sufficient openings to allow air flows through packages during transport. Corrugated fiberboard containers can have vent holes up to 5% of the total side panel area without sacrificing its strength (Thompson et al., 1998). A few large vent holes are better than many small ones for the same total opening surface. Also, vertical slots perform well, but they have to be kept at least 51 mm (2 in) away from the corners of corrugated boxes since the stacking strength is concentrated mostly in the corners of the container (Mitchell, 1992).

Besides having enough vent holes, the shipping container also needs to be rigid. A strong shipping container does not only protect produce from physical damage, it also preserves the integrity of the palletized load and prevents the collapse of boxes that may obstruct air passages. Therefore the container must be able to withstand rough handling, compression from other containers, impact and vibration during transport. As well, it should be able to resist high humidity during precooling, transport and storage (McGregor, 1989).

A family of reusable and recyclable plastic containers has been developed to address the need for strong, vented containers. The containers were also optimized for various precooling methods and can provide 20% to 30% vent holes on the side panels (Goyette and Vigneault, 1999).

Internal packaging materials such as liners, trays, wraps, dividers or pads can be used within the package containers as long as they do not obstruct the vent openings. When produce such as grapes is covered by a plastic liner or packed in bags, it is usually packed in a box slightly higher than the grape bags to allow air flows over the top of the packaging materials (Thompson et al., 1998).

2.3.4.2 Package arrangement and wrapping

Packages of produce boxes are commonly stacked in layers on a pallet. Two important factors have to be considered when stacking produce boxes on pallets. First is the alignment of vent holes on the boxes along the direction of airflow; and second, the stability of packages piled in layers. The effectiveness of the ventilation holes in allowing air to remove respiration heat depends on how much air flows uniformly across the box of produce. The alignment of vent holes and stability of the column of boxes is easily achieved in straight loads since the package containers are of the same dimension and configuration. However, it is much more difficult to achieve this condition in mixed loads where a pallet can be loaded with produce using one or several types of containers. For the latter, it is difficult to align vent holes of the various styles of containers in one direction. Compounding this problem is the wrapping of produce pallets with plastic film for stabilization. The use of plastic film severely restricts air circulation across the packages. The stability of the pallet is a more dominant issue than air circulation in mixed loads.

Properly stacked pallets do not only provide good air circulation and protect produce from physical injury, but also ensure the safety of loading personnel by preventing packages from falling off the stacked pallets. Furthermore, unstable containers on a pallet may fall while in transit and block air circulation channels. To ensure the stability of the column, packages have to be stacked in a manner that make the best use of their inherent strength (Ashby, 1999). Most containers are designed to support pressure on specific area(s) without damaging the contents. For corrugated fiberboard boxes, they

are designed to support weight on the four side panels (Ashby, 1999). Their strongest points are the corners. Consequently, corrugated fiberboard boxes should be stacked upright, one on top of the other. The bottom corners of the upper box should be aligned to the top corners of the lower one. This corner alignment allows the transmission of pressure from the top layer all the way down to the pallet.

When palletizing a straight or mixed load, it is important to arrange the packages within the confined area of the pallet. Overhanging the boxes beyond the edge of pallets will reduce the load bearing capacity of the package containers making the load unstable. For example, overhanging a fiberboard box reduces its strength by one-third (McGregor, 1989). Similarly, if boxes are covering less than 90% of the pallet surface area and are not aligned with the edges of the pallet, the load will tend to shift during transport (McGregor, 1989).

For a mix-loaded pallet, it is common to have various types and sizes of corrugated fiberboard boxes loaded one on top of the other. Sometimes these fiberboard boxes are mixed with plastic boxes, Styrofoam boxes, wire-bound crates, paper bags, mesh bags or plastic bags on the same pallet. In some cases, half a pallet of produce (with the pallet) would be loaded directly on top of another half pallet of produce (Figure 2.14). For mix-loaded pallets, similar size containers can be loaded on the same pallet to increase stability. Produce weight has to be normally distributed, with heavier produce at the bottom and lighter produce at the top. Bagged commodities that are highly susceptible to physical injuries can be placed at the top.

In the industry, it is common to interlock (cross-stacked) corrugated fiberboard boxes to increase the stability of the whole pallet of produce. Cross-stacking places the corners of one box on the walls of the one below it, thus reducing the stacking strength of the lower box (Boyette et al., 1996). It is not recommended to use cross-stacking at bottom layers since a tremendous amount of vertical pressure is exerted on them. When palletizing the boxes, the first few layers of packages are supposed to be column stacked while the upper layers can be cross-stacked. (Boyette et al., 1996) (Figure 2.15). The reusable plastic containers mentioned in the previous section have more stacking strength than corrugated fiberboard boxes. They have pre-cut edges that allow the upper container to interlock with the lower one. This results in a more solid and straight column of

produce. The walls of this container are stronger; therefore they can be cross-stacked all the way from the bottom to the top layer of the stack. These newly designed containers are now gaining popularity in North America.



Figure 2.14: Mix-loaded pallets waiting at the loading dock.

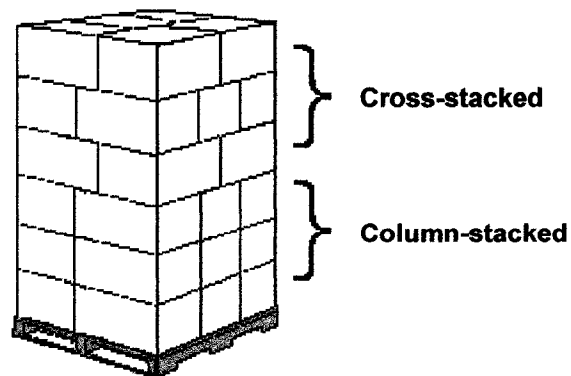


Figure 2.15: Cross-stacking versus column-stacking (Boyette et al., 1996).

2.3.4.3 Package restraint

In addition to proper stacking, different restraining materials are used to increase the stability of packages on pallets. These materials help to maintain the integrity of the column and prevent produce packages from falling or shifting. Plastic or paper corner tabs are applied along the corners of the palletized load to protect the edge of packages and keep the load straight (Figure 2.12). Plastic straps and tapes are commonly applied around the palletized load (Figure 2.12). A special glue applied on top of each package is also used to secure packages together during stacking (McGregor, 1989). Tarpaulin covers can be used for produce which are susceptible to moisture loss (Peleg, 1985).

Plastic stretch film is also widely used to secure palletized load. It may be used to cover the entire palletized load or used as partial straps. Plastic film wrap helps to reduce moisture loss and provides stability at the same time. Due to its elasticity, this film can be applied to any size or shape of load. It can be applied manually or by semi-automatic systems. The biggest disadvantage of plastic film wrap is that it seriously restricts air circulation through the palletized load (Boyette et al., 1996). It greatly reduces the amount of respiration heat that can be removed by air, so such wrap should be not applied on produce that needs ventilation (McGregor, 1989). An alternative to plastic film wrap is plastic netting. It provides good stability and allows free air circulation across the load. Nevertheless, for mix-loaded pallets, plastic film wrap remains the most widely used restraining material in the industry.

2.3.4.4 Pallet loading pattern

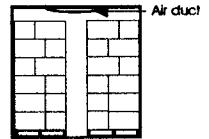
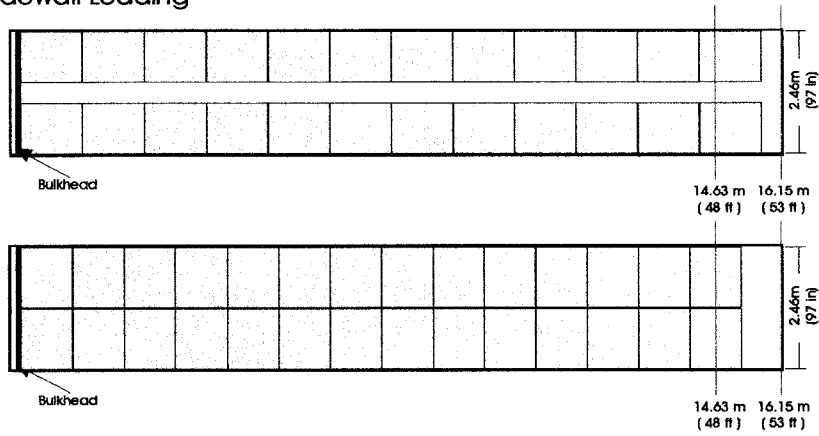
After stacking produce packages on pallets and applying the restraint materials, pallets are loaded into the refrigerated semi-trailer. Various loading patterns are used in the industry. The loading pattern affects air circulation, the amount of contact between the load and the inner walls, the stability of the load, and the volume of payload. The way in which pallets are loaded influence air circulation and the consequent removal of all heat loads on the trailer. The availability and direction of air channels is dependent on the loading pattern, which affect the airflow pattern around and across the load. The loading pattern also determines the amount of contact between produce and the trailer surfaces, thus affecting the amount of produce warming or freezing due to conduction.

Furthermore, the stability of a load is affected by how well produce pallets are interlocked with each other. Finally, the loading pattern influences the number of produce pallets that can be transported in a given length of trailer. Various loading patterns are used by the industry; produce pallets can be sidewall loaded, offset loaded, pinwheel loaded or centerline loaded by a forklift or pallet truck (Figure 2.16).

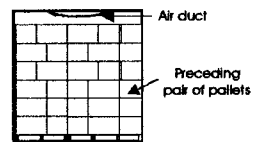
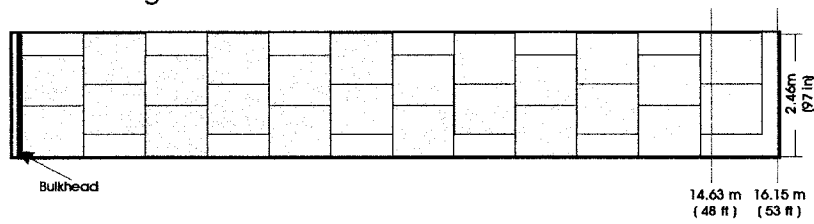
In sidewall loading, produce pallets are aligned into two rows, loaded closely against the left and right sidewalls of the trailer. With standard pallets measuring 1.02 m in width by 1.22 m in length (40 in x 48 in), the pallets can be arranged with either their width or length facing the rear of the trailer. For a typical trailer having an internal width of 2.46 m (97 in), loading the pallets straightway with their width facing the rear will create an empty space of 0.43 m (17 in) between the two rows of pallets (Table 2.1). This longitudinal channel allows air to circulate freely between the rows. However, if the load is not braced in the middle, the pallet may collapse and block this air channel. This passage also provides access for loaders to verify the content or status of the load, which is very practical for mixed load shipments. When pallets are all turned around with their length facing the rear, there is an increase in the number of pallets that can be loaded into the trailer (Table 2.2). However, no air channel will be left in between the two rows of produce. For this type of load arrangement, significant contact between the produce and trailer walls is unavoidable. As a result, sidewall loading considerably increases the chance of produce warming or freezing during transport (Kasmire and Hinsh, 1987).

In offset loading, all pallets are loaded “straight” with their width facing the rear doors. They are arranged in pairs with one pallet touching the other. The first pair is loaded against the one side of the trailer wall, and the second pair is loaded against the opposite side of the wall. The rest of the load is arranged in this staggered or zigzag fashion. This loading pattern increase the stability of the load as pairs of produce pallets are inter-locked with each other and do not need any sideward bracing. Compared to sidewall loading, offset loading reduces the amount of produce-sidewall contacts in half. It also provides a better air circulation around the load by creating some alternating vertical channels around the load. This loading pattern is considered as a compromise between sidewall and centerline loading (Kasmire et al., 1996).

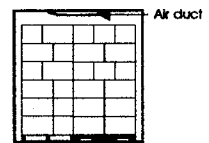
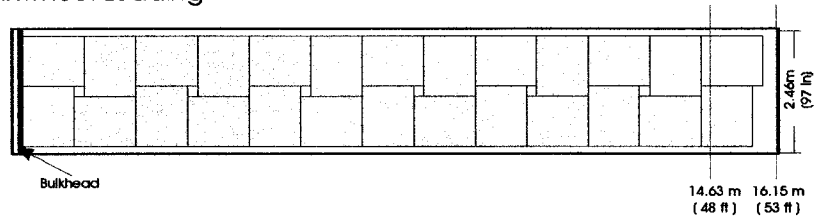
A) Sidewall Loading



B) Offset Loading



C) Pinwheel Loading



D) Centerline Loading

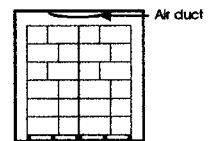
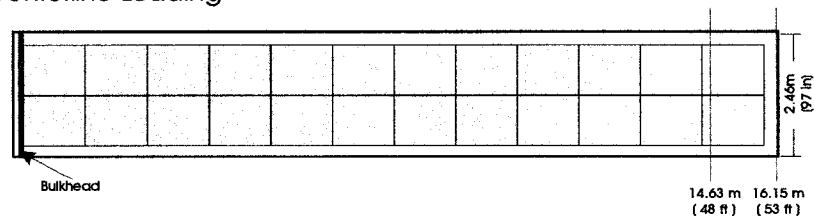


Figure 2.16: Various patterns of loading produce pallets inside refrigerated semi-trailers (top and rear views).

In pinwheel loading, pallets are loaded in a set of four. For the first pair of pallets, one pallet is left straight and the other pallet is turned. In the next pair of pallets, the pallet behind the straight pallet (of the first pair) is turned and the other one is left straight. Due to the difference between the width and the length of pallets, a pinwheel is generated. Subsequent pairs of pallets are loaded in the same fashion creating a series of pinwheels (Figure 2.16). Pinwheel loading provides more stability than offset loading. The chimney in the middle of each pinwheel provides an air channel surrounding the packages. However, this vertical air circulation may not be uniform from the front to the rear of the trailer (Kasmire et al., 1996). If the set of pallets are loaded tightly against each other and all pinwheels are centered in the trailer, a maximum of 0.11m (4.5in) of space is available on each side of the load (Table 2.2). This provides a limited space for air circulation.

In centerline loading, all pallets are loaded straight. The pairs of pallets are loaded closely together and placed in the middle of the trailer. This loading pattern results in a single row of paired pallets centered right in the middle of the trailer. Bracing is required on both sides to prevent shifting. Wide air circulation channels are created on both sides of the load and across the space near the rear doors, creating an air jacket around the entire load. Centerline loading eliminates all contact between the produce and the sidewalls. It enhances the removal of external heat, respiration heat from produce packages, and eliminate the risk of warming or freezing. The use of centerline loading is recommended to protect highly perishable commodity such as strawberry, mushrooms and cut flowers during transport (Kasmire et al., 1996).

Table 2.1: Maximum number of pallets that can be loaded inside a semi-trailer.

Loading patterns	Nominal length of semi-trailer	
	14.63 m (48 ft)	16.15 m (53 ft)
Sidewall (pallet width facing the rear)	22	24
Sidewall (pallet length facing the rear)	26	28
Off-set	22	24
Pinwheel	24	26
Centerline	22	24

Table 2.2: Sideward space available in a 2.46 m (97 in) wide semi-trailer.

Loading patterns	Free space available for air circulation
Sidewall (pallet width facing the rear)	0.43 m (17 in)
Sidewall (pallet length facing the rear)	0.03 m (1 in)
Offset	0.43 m (17 in)
Pinwheel	0.23 m (9 in)
Centerline	0.43 m (17 in)

2.3.4.5 Load bracing

To maintain the space between the pallets and sidewalls, and at the rear, palletized loads can be secured in place by using aluminum or wood load locks, fiberboard honeycomb fillers, inflatable vinyl or Kraft paper air bags or cargo nets and straps. Some of these bracing materials, such as aluminum load locks, are placed at the rear of load to prevent backward shifting. Inflatable vinyl or Kraft paper air bags are used in between the produce pallets or between the pallet and the sidewall. Such positioning prevents the load from shifting sideward.



Figure 2.17: The use of lock bars to prevent produce from shifting backward.

III. MATERIALS AND METHODS

A series of field tests were carried to evaluate the performance of air circulation system in semi-trailers. The study was conducted with the collaboration of McGill University, Agriculture and Agri-Food Canada, Provigo Inc. and Centerload Shipping Technologies. McGill University provided assistance in developing the tools needed in the experiment as well as the overall conduct of the study. Agriculture and Agri-Food Canada supplied the necessary instrumentation, assisted in developing the experimental protocol and in data analysis. Provigo Inc. provided access to their distribution centers, supplied produce and semi-trailers as well as personnel in both the shipping and receiving centers to facilitate the research. Centerload Shipping Technologies supplied the vinyl air bags needed for bracing the load in some of the tests.

Provigo Inc., one of the largest grocery retailers in the Province of Quebec, owns a network of supermarkets and a number of distribution centers in Quebec and Ontario. It has two principal distribution centers located in the suburbs of Montreal Island. The center located in Laval, north of Montreal, handles mostly dry goods. The other center located in Boucherville, south of Montreal, delivers fresh produce to retailers and other distribution centers. Loeb Inc., located in London (Ontario), is the first satellite distribution center involved in the study. London is located southwest of Boucherville. The transit time from Boucherville to the London Distribution Center is around 8 hours using mostly the highways. Three preliminary tests were carried out between May to June 1999. The data gathered from these tests were used to define the critical parameters and refine the experimental procedure for the study. After the preliminary tests, six field tests were conducted on the Boucherville-London route between June and July 1999.

Due to a reduction in the volume of fresh produce handled between Boucherville and London, the research was redirected to another Provigo distribution center in Vanier, which is located northeast of Boucherville. The transit time between Boucherville and Vanier is around 3 hours using mostly the highways. Eleven tests were conducted on the Boucherville-Vanier route in September 1999.

3.1 MATERIALS

3.1.1 Temperature data loggers

Two types of data loggers were used in the experiment: the HOBO[®] H8 Temp/External Logger and the HOBO[®] H8 Pro RH/Temp Logger (Onset Computer Corporation, Bourne, Mass., U.S.A.). These portable data loggers are battery-powered. Each device is equipped with sensor(s), microprocessor and data storage. Once activated, it measures and stores data automatically over time. When connected to a personal computer, the logger can be programmed, activated and data can be downloaded through a software.

The HOBO[®] H8 Temp/External logger is capable of recording two temperature readings simultaneously. Inside the plastic case, a thermistor mounted on the circuit board is served as a temperature sensor. An external thermistor can be connected to the circuit board through a miniature RCA connector. This external sensor provides a second temperature reading for the unit.

The HOBO[®] H8 Pro RH/Temp Logger is capable of recording temperature and relative humidity data simultaneously. It has a built-in thermistor for temperature measurement and a capacitive sensor for relative humidity measurement.

3.1.2 Produce

Mixed loads were examined in the field tests. They consisted of a large variety of fruits and vegetables such as celery, carrot, green onion, pepper, lettuce, cauliflower, cabbage, potato, tomato, pear, orange, apple and fresh-cut produce. Some loads contained a small amount of cut flowers. A small amount of canned food, nuts and dairy products were also loaded in some Vanier shipments. All of the produce was palletized and some pallet loads were wrapped in plastic film. A single pallet load might contain one or several types of produce. In some cases, half a pallet of produce was placed on top of another half pallet. In general, the height of produce pallets varied considerably.

3.1.3 Semi-trailer

The trailers investigated used top-air delivery systems. These trailers were equipped with an air duct. Some of the air ducts were slightly offset to the right. The

trailers were usually equipped with frame or solid bulkheads, except for two trailers which did not have any. The floor of the trailers was either duct or flat, and the trailers had a nominal length of 14.63 m (48 ft) or 16.15 m (53 ft). The model of the refrigeration system varied from trailer to trailer. External carriers provided these trailers on contract with the distribution center.

A multi-temperature trailer was used in two of the tests. The division panels inside the trailer were removed during the tests. This particular trailer had no air duct, it had a solid bulkhead and a flat floor. It has a nominal length of 16.15 m (53 ft) with roll-up doors at the rear (regular trailers have sideward swinging doors). The refrigeration system of this trailer can supply conditioned air through two outlets at the front wall, but only the outlet at the right was activated during the tests.

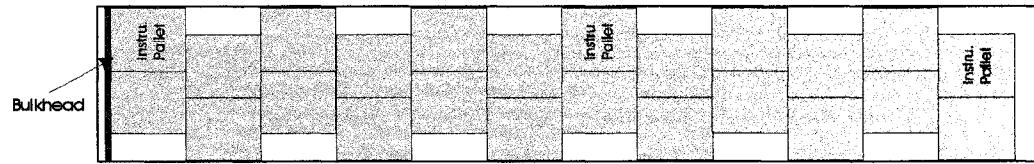
3.1.4 Loading pattern

The volume of produce to be shipped and the length of the trailer usually determine the pallet arrangement inside the trailer. In the study, the distance between the last two pallets to the rear door varied from load to load. The number of produce pallets in a truckload varied from 18 to 26. The most common loading patterns used by the packers were offset and pinwheel (Figure 3.1). Centerline loading was not a standard arrangement for the packers at this distribution center. During the experiment, a number of loads were centered in the trailer to study the effect of centerline loading. In those shipments, produce pallets were either centerline loaded or arranged as pinwheel with spaces on both sides of the load (Figure 3.1). These centerline-loaded shipments were braced with vinyl air bags on the two sides.

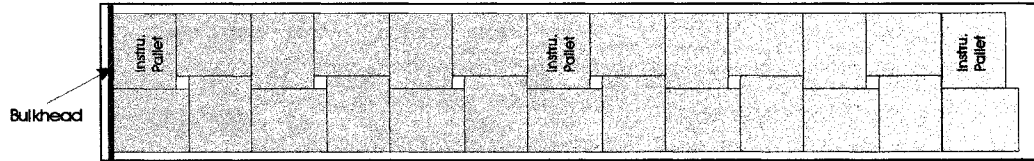
3.1.5 Air bags

Centerload Shipping Technologies (San Leandro, Calif., U.S.A) supplied the air bags used in the study. Each air bag measures 0.46 m in width and 1.37 m in length (18 in x 54 in). It is made of 0.25 mm (0.01 in) thick vinyl and has a plastic valve for filling and releasing air. The elasticity of vinyl allows the bag to conform to the shape of palletized produce packages and fill up the void between the load and the sidewall. A portable inflation device was used to inflate the air bags.

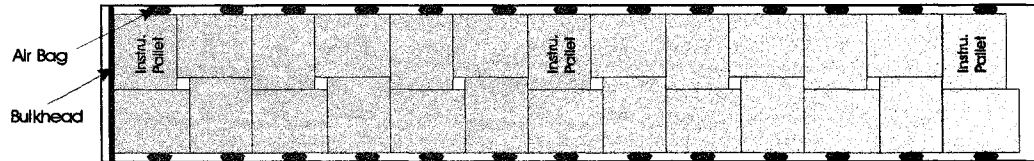
Offset NA



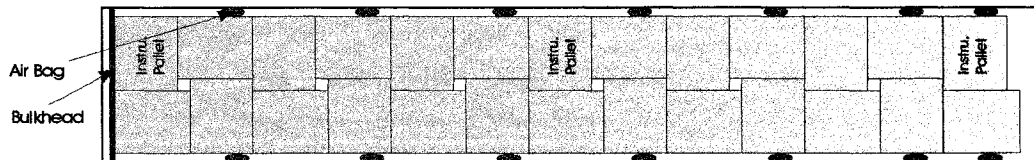
Pinwheel NA



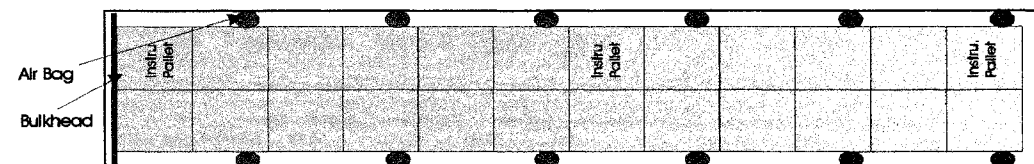
Pinwheel FVA



Pinwheel VA



Centerline VA



Centerline HA

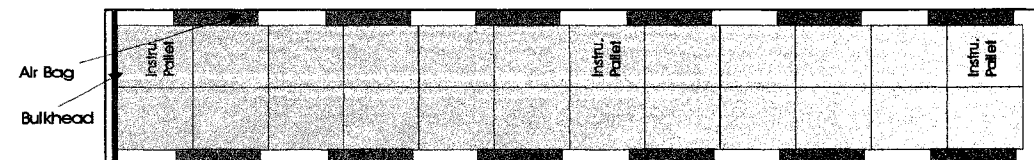


Figure 3.1: The loading and bracing pattern used in the field tests. The actual locations of the instrumented pallet may vary depending on the number of produce pallets in the load and the length of the trailer.

Three air bag bracing patterns were used in the study, namely HA, VA and FVA. In HA and VA patterns, air bags were used to brace every second pair of pallets (Figure 3.1). Two air bags were used for each pair of pallets and they were placed either horizontally (HA) or vertically (VA) between the pallet and the sidewall (Figure 3.2 and 3.3). In FVA shipments, air bags were placed vertically to brace every pair of pallets (Figure 3.1). Since the upper part of the load has a higher tendency to shift during transit, the air bags were inserted to support the upper section of the produce pallets. The symbol NA (no air bag) was used to identify shipments that had no bracing.

Air bags may slip if the load shifts sideways during transit. To ensure the air bags stay in place, each pair of pallets was held closely against each other at the center. The air bags on both sides of the load were then inflated fully to prevent shifting of the pallets.

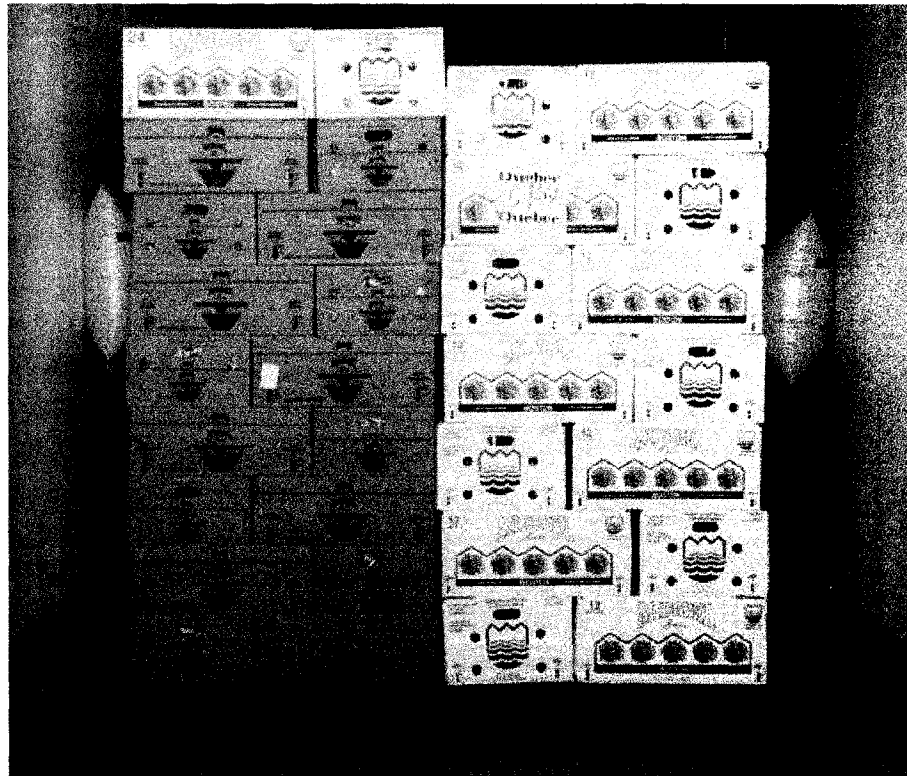


Figure 3.2: Produce pallets braced by vinyl air bags placed horizontally.

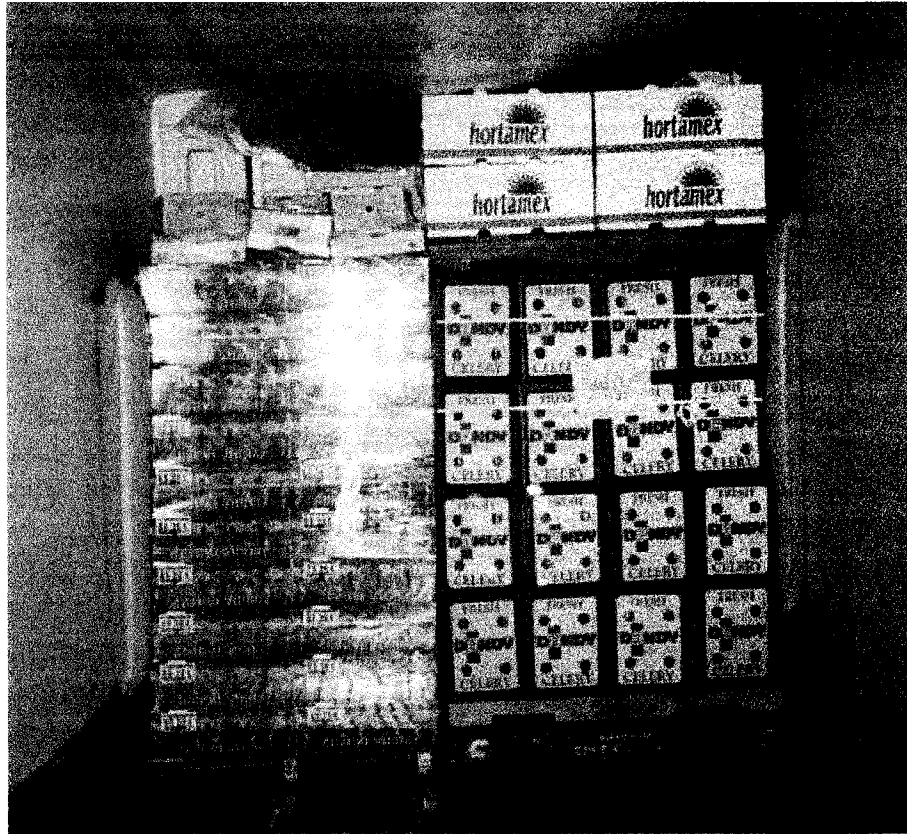


Figure 3.3: Produce pallets braced by vinyl air bags placed vertically.

3.2 EXPERIMENTAL PROCEDURE

The study comprised a total of 3 preliminary tests and 17 main tests. In each test, data loggers were installed at the indoor shipping dock of the Boucherville Distribution Center. They were then retrieved at the indoor receiving dock of the London or Vanier Distribution Center. Each test is coded according to its destination (L-London, Q-Vanier), test number (1, 2, 3, P2 (P-preliminary), P3, etc.), the use and positioning of air bags (NA, HA, VA, FVA). For example, test L4VA is the fourth test destined for London, and the load was braced with vertical air bags. Test Q10NA was the tenth test destined for Vanier and no air bag was used to restraint the load. The experimental procedure for the field tests can be summarized as follows.

3.2.1 Initial set-up

Prior to each test, data loggers were programmed and activated using a personal computer. The internal sensors of the HOBO[®] H8 Temp/External Loggers were used to record air temperatures at different positions in a load. A HOBO[®] H8 Pro RH/Temp Logger was used to record the temperature and relative humidity of the supply air. Each HOBO[®] H8 Temp/External Logger was placed inside a Ziploc bag to prevent damage by moisture or condensation. A one-minute sampling interval was set for all data loggers and they were programmed to collect data simultaneously.

3.2.2 At the shipping dock

At the shipping dock, several pallets were selected for instrumentation. Six pallets were chosen from each load for the preliminary tests, while three pallets were selected for the main tests. In each test, identical pallets with only one type of produce (straight pallets) were selected when available. Otherwise, different produce in straight pallets or mix-loaded pallets were chosen for instrumentation. Each selected pallet was labeled and marked with the location of data loggers.

In the preliminary tests, a total of 27 HOBO[®] H8 Temp/External Loggers and one HOBO[®] H8 Pro RH/Temp Loggers were installed in each load. In each test, three pairs of pallets were instrumented. On each pair, data loggers were installed as a grid of 3 x 3 (Figure 3.4). They were installed on left, middle and right surfaces of each pair of pallets. On each of the surfaces, data loggers were placed on the top, middle and bottom layers. With the pallets facing toward the front wall of the trailer, all data loggers were installed at a distance of 0.64 m (25 in) away from the front surfaces of the pallets. The top data loggers were 0.15 m (6 in) below the top surfaces of the boxes and the bottom data loggers were 0.15 m (6 in) above the surfaces of the wooden pallets. The middle data loggers were installed halfway between the top and bottom data loggers (Figure 3.4).

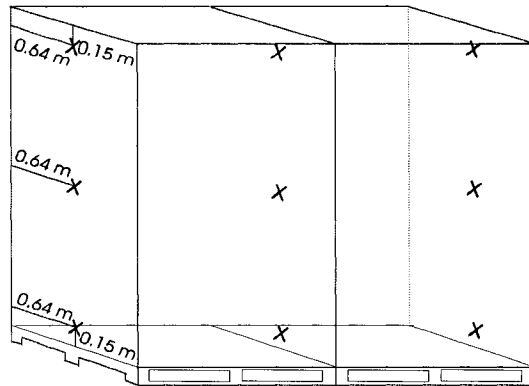


Figure 3.4: Location of data loggers on produce pallets in preliminary tests.

In the main tests, a total of 15 HOBO[®] H8 Temp/External Loggers and one HOBO[®] H8 Pro RH/Temp Loggers were installed in each load. The sampling interval and the location of data loggers remained the same as in the preliminary tests, except only the middle and the right side of the load were monitored (Figure 3.5). In each test, three pallets were instrumented and five data loggers were installed on each pallet. All these instrumented pallets were loaded on the right side of the load.

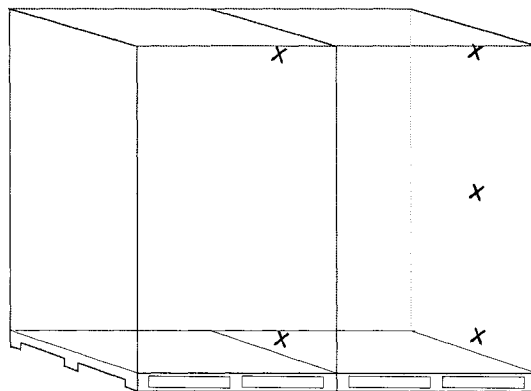


Figure 3.5: Location of data loggers on produce pallets in main tests.

A coding system was developed to describe the position of data loggers with respect to the entire load. The code is composed of three letters: the first letter specifies the location along the length of the load (F-front, M-middle, R-rear); the second letter specifies the elevation (T-top, M-middle, B-bottom); and the third letter specifies the

location along the width of the load (L-left, M-middle, R-right). For example, the FTR data logger was located in the Front pallet, at the Top layer and on the Right surface.

After marking the location of each data logger on the boxes, a HOBO® H8 Temp/External Logger was taped at each location (Figure 3.6). Upon the arrival of the trailer, a HOBO® H8 Pro RH/Temp Logger was installed to monitor the supply air temperature. If the trailer is equipped with an air duct, the data logger was installed in the middle of the duct (Figure 3.7), if not, the data logger was placed near the blower discharge on the front wall (Figure 3.8). After installing the data logger, the trailer was inspected. Its identification number, internal dimensions, the presence of accessories and their physical condition were recorded. Precooling of the trailer was also verified.

During loading, one instrumented pallet (or a pair in case of preliminary tests) was placed at the front row of the load. The second instrumented pallet was placed at the middle and the third one was placed at the rear of the load (Figure 3.1). The loading pattern, the location of instrumented pallets and the varieties of produce in the load were also recorded during the loading process.

For those tests that require bracing, air bags were installed as the pallets were being loaded. After centerline loading a pair of pallets, an air bag was inserted between the produce and the sidewall. The air bag was then inflated using a portable inflation device. The location of air bags with respect to the load was also recorded.

After all produce pallets were loaded inside the trailer, the presence of bracing at the rear of the load was verified and recorded. The model number of the refrigeration system, the setpoint and the control mode were also recorded.

3.2.3 At the receiving dock

As soon as an instrumented pallet was unloaded at the receiving dock, data loggers were retrieved from the pallet. The HOBO® H8 Pro RH/Temp Logger was collected after the trailer was unloaded. Data was then downloaded into a personal computer from the data loggers. The data retrieved in ASCII format was imported and analyzed using Microsoft® Excel 2000 (Microsoft Corporation) and the SAS system for Windows, Release 6.12 (SAS Institute, Inc., Cary, N.C., U.S.A.).



Figure 3.6: Instrumented pallets in main tests.



Figure 3.7: Data logger at the exit of the air duct.

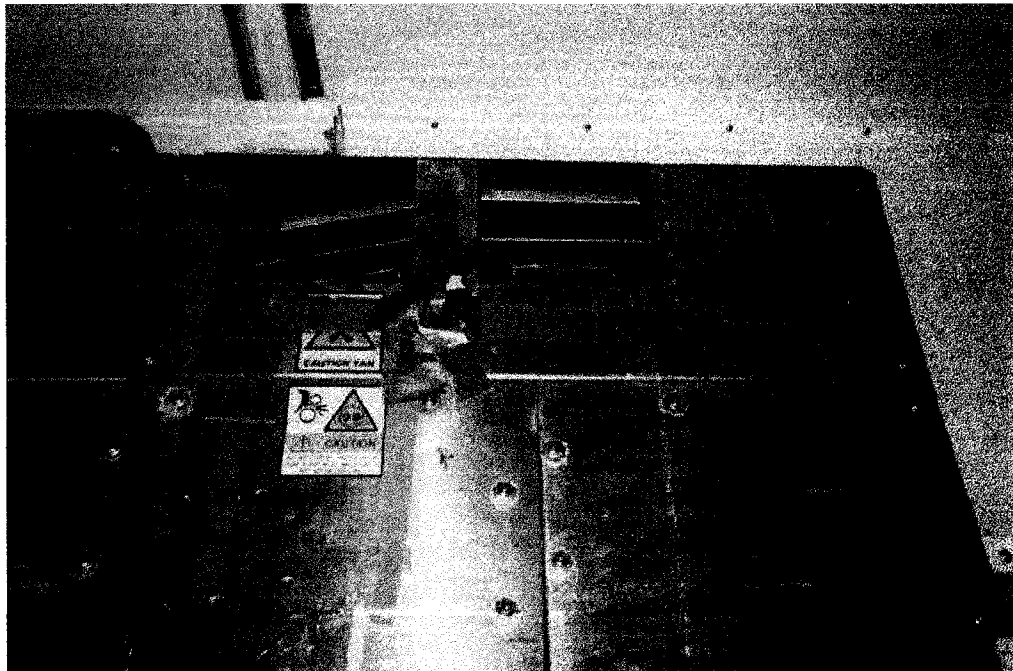


Figure 3.8: Data logger near the exit of blower for trailers not equipped with air duct.

IV. RESULTS AND DISCUSSION

Produce temperature during transport is affected by the efficiency of the air circulation system, performance of the refrigeration system, produce loading temperature, outdoor climatic conditions, trailer physical conditions, produce respiration rate, and packaging. In addition, local practices carried out at the loading and unloading docks also influence produce temperature. Although the study focuses on the air circulation system, a good understanding of the commercial distribution procedure will help to identify some of the limitations encountered in conducting the study. This chapter is divided into two sections. The distribution procedure is described in section one and the results of the study on the performance of the air circulation system are presented in section two.

4.1 COMMERCIAL PRODUCE DISTRIBUTION

4.1.1 Shipping dock

In general, the shipments from Boucherville to London or Vanier Distribution Center followed a similar procedure. For each truckload, the receiving center places an order through a buyer at the shipping center. A Preparation Order is issued through the computer system. This Preparation Order indicates the varieties and quantities of produce which are to be included in the shipment. The order is then given to the packer for stacking the pallets. Working alone or as a team of two, the packer goes around the various storage rooms and places produce on a pallet carried by a pallet truck. After stacking a pallet, sometimes the packer wraps the pallet with a layer of plastic film using an automatic wrapping machine. The packer then lines up the pallet in front of a pre-assigned loading dock.

The trailer may arrive any moment during the preparation of pallets. The driver opens up the rear doors of the trailer and backs it up at a loading dock. The driver normally does not wait at the shipping center, he usually comes back with the tractor when the load is ready to be moved. When the trailer arrives at the dock, the packer may open the loading dock door. This allows air from the loading area flows into the trailer and cool it off.

When pallets on the order are prepared, the packer verifies whether there is any last minute order added to the load. When all orders are prepared, a supervisor sometimes double-checks the list of produce with the packer and confirms that everything is in good order. The packer then starts to load pallets inside the trailer in a timely manner. Once the packer finishes loading, he closes the loading dock door. The rear doors of the trailer are left open until the driver arrives, except for the multi-temperature trailer where the roll-up door is closed before closing the loading dock door.

The packer returns to the shipping department and fills out several documents including the Straight Bill of Lading for the load. The date of shipment, name of carrier, coordinates of the destination, trailer number, load description, setpoint of the refrigeration system and other information concerning the shipment are listed in this Straight Bill of Lading.

When the driver arrives with the tractor, he signs the Straight Bill of Lading and other documents. He then goes out to the parking area and verifies the settings of the refrigeration system. The driver would switch on the system if it was off. He then programs the setpoint and the control mode. After setting up the refrigeration system, the driver backs up the tractor, hooks it up with the trailer, pulls the trailer slightly forward to close the rear doors.

4.1.2 Receiving dock

Upon arrival at the destination, the driver checks into the reception desk. If the center is not open or not ready to for unloading, the driver would park the trailer and wait. The refrigeration system is normally left running during this period. When the trailer is about to be unloaded, its doors will be opened and produce is exposed to outside air. The refrigeration system may be switched off at the same time or at a later time. The trailer is then backed up to the unloading dock. There may be a delay between the opening of rear doors and backing up of the trailer. Once the trailer is at the unloading dock, an operator unloads the pallets using a forklift or pallet truck. Plastic film is removed from wrapped pallets, and the quality of the load is verified. Depending on the height of the storage racks, the operator may unpack the pallets and restack them to fit the storage racks. Before placing the pallets into storage rooms, a label is placed onto each pallet. The label indicates the location of storage, the date of receipt and the number of

boxes on each pallet. There may be a delay between each step of the operation and the duration of this delay may vary from load to load.

4.2 AIR CIRCULATION SYSTEM

An efficient air circulation system distributes air uniformly throughout a loaded semi-trailer. The air circulation system is a closed loop that starts at the discharge of the blower, through and around the load, and returns to evaporator for conditioning. The uniformity of air distribution is affected by the availability of air channels around and between the pallets. If sufficient air channels are available for air movement, any variation in the supply air temperature will result in a similar variation in air temperature everywhere throughout the entire load. Performance of the air circulation system is independent of the refrigeration system setpoint and return air temperature. Its performance can be measured ultimately by the uniformity of air temperature surrounding and through out the load.

4.2.1 Method of evaluation

4.2.1.1 Pearson product-moment correlation coefficient

The semi-trailers investigated in the field tests had top-air delivery systems. They were equipped with different refrigeration systems programmed at a range of setpoint and operation modes. Although these differences do not relate directly to the performance of the air circulation system, they do affect the magnitude and mode of variation in the supply air temperature. This in turn influences the temperature of air circulating inside the trailer. With various setpoint and modes of operation, air temperature values obtained in one test cannot be compared directly to values obtained in other tests. To eliminate the differences caused by the refrigeration systems, a relative index that describes the performance of the air circulation system is needed in order to compare results among tests.

To compare the results among tests, data obtained from the experiments can be analyzed using correlation or regression analysis. Although these two methods of analyses are closely related, they are used for specific circumstances. Correlation is designed to estimate the degree of association between two variables, whereas regression

is generally used to predict the value of one variable based on its relationship with another variable (Sokal and Rohlf, 1969). Since the purpose of this study was to examine the performance of the air circulation system in different trailer loads without going into temperature prediction or modeling, a correlation analysis is deemed more appropriate than regression analysis.

In the analysis, the Pearson product-moment correlation coefficient is used for comparing results among tests. This measure assesses the relationship between temperatures of supply air and of air present at different locations inside the trailer. It describes how closely air temperature at various points in the load varies with the supply air temperature. When airflow is uniformly distributed inside the trailer, air temperature at any location within the trailer would vary and remain close to the supply air temperature and a positive correlation would be obtained. The Pearson correlation coefficient can be used as an index for comparing air circulation among tests subjected to different conditions.

The Pearson correlation coefficient, denoted by r , is based on the covariance of the two temperatures (the level that they vary together) and the variances of each individual temperature. The sample correlation coefficient, can be calculated using any of the following equations (Sokal and Rohlf, 1969; Steel and Torrie, 1980):

$$r = \frac{S_{12}}{\sqrt{S_1^2 S_2^2}} \quad (1)$$

$$= \frac{\sum (Y_1 - \bar{Y}_1)(Y_2 - \bar{Y}_2)/(n-1)}{\sqrt{\sum (Y_1 - \bar{Y}_1)^2/(n-1)} \sqrt{\sum (Y_2 - \bar{Y}_2)^2/(n-1)}} \quad (2)$$

$$= \frac{\Sigma(Y_1 - \bar{Y}_1)(Y_2 - \bar{Y}_2)}{\sqrt{\Sigma(Y_1 - \bar{Y}_1)^2 \Sigma(Y_2 - \bar{Y}_2)^2}} \quad (3)$$

where,

r = Pearson correlation coefficient of variables Y_1 and Y_2

S_{12} = covariance between the variables Y_1 and Y_2

S_1 = variance of variable Y_1

S_2 = variance of variable Y_2

Y_1 = random variable 1

$\overline{Y_1}$ = mean of Y_1

Y_2 = random variable 2

$\overline{Y_2}$ = mean of Y_2

n = number of samples

The magnitude of r varies from -1 to 1 . A value of 1 indicates a perfect positive association between the two temperatures, i.e. air temperature at a point inside the trailer increases linearly with the supply air temperature. A value of 0 indicates there is no association. A value of -1 indicates a perfectly negative association between the two temperatures, i.e. air temperature at a point decreases linearly with an increase in supply air temperature.

In cases where the two variables are jointly affected by external influences, such as temperature in a trailer traveling in changing climatic conditions, the use of correlation is considered as the most logical approach in analyzing a set of data (Steel and Torrie, 1980). The Pearson correlation coefficient is calculated directly from the original temperature data. It is dimensionless such that it is independent of the units of measure of the data (Steel and Torrie, 1980). The correlation coefficient is a symmetrical measure of association, therefore correlating the supply air temperature to air temperature at certain positions, or vice versa, would yield the same value (Walizer and Wienir, 1978). The values of the Pearson correlation coefficient and the levels of significance were calculated using the SAS system for Windows, Release 6.12 (SAS Institute, Inc., Cary, N.C., U.S.A.).

4.2.1.2 Coefficient of determination

The coefficient of determination (r^2) is a useful measure for comparing correlation of different magnitudes (Sokal and Rohlf, 1969). For an association consisting of two random variables, the coefficient of determination is equal to the square of the Pearson correlation coefficient (Steel and Torrie, 1980). The value of r^2 varies from 0 to 1 . When expressed in percentage points, it indicates the proportion of the total variation

in the dependent variable explained or caused by the variation in the independent variable.

4.2.2 Raw data

In general, after closing the trailer doors and switching on the refrigeration system, air temperature inside the trailer dropped. The temperature then became relatively more stable over a period of time. It increased only when the trailer doors were opened at the destination. The actual pattern of the temperature drop, the variations at the middle and the increase in temperature at the end of the trip differed from test to test. However, results from the preliminary and main tests all followed a general trend. Raw data from test LP2NA (London, preliminary test 2, no air bags) and Q6HA (Quebec, test 6, horizontal air bags) illustrated in Figure 4.1 and 4.2 are typical examples of this trend.

Since the study focuses on the performance of the air circulation system during transport, the initial cooling of air inside the trailer and the increase in temperature at the end of the trip were not analyzed. The range of data used in evaluating air circulation covers the middle section of the transit temperature recorded.

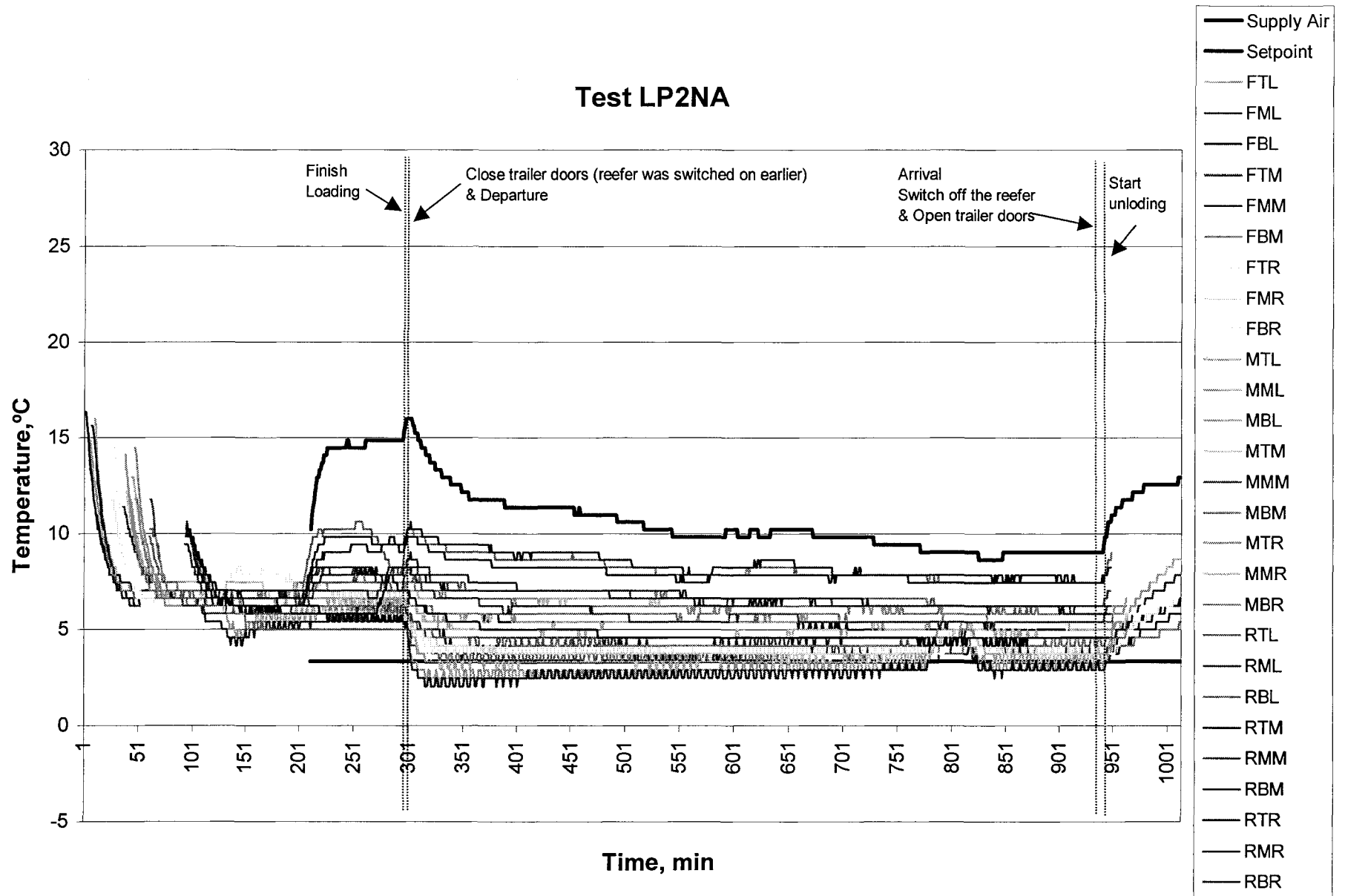


Figure 4.1: Plot of raw data for test LP2NA.

Test Q6HA

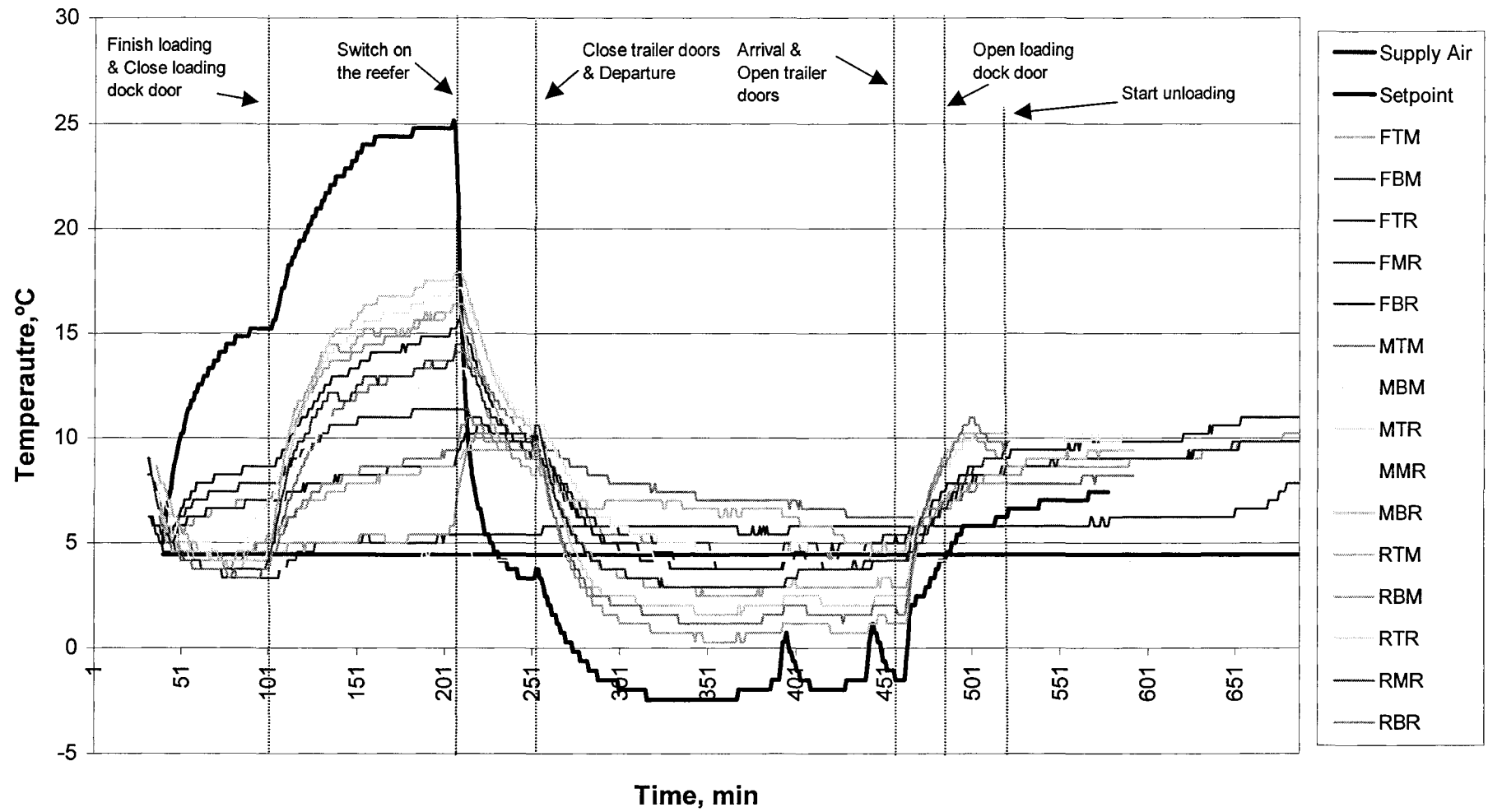


Figure 4.2: Plot of raw data for test Q6HA.

4.2.3 Preliminary tests

The preliminary tests: LP2NA, LP3FVA and L1FVA were conducted on the Boucherville-London route during nighttime between May to June 1999. In each test, 27 data loggers were used to monitor air temperature at various locations within the load (Figure 4.3). An additional data logger was used to record supply air temperature. The characteristics of each load are listed in Table 4.1.

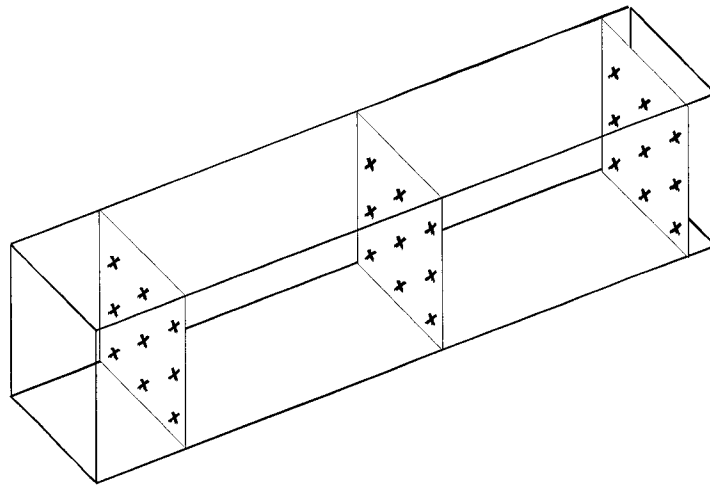


Figure 4.3: Location of data loggers in the preliminary tests. Actual location of data loggers varied with the height, arrangement and number of produce pallets in each load.

4.2.3.1 Uniformity of air distribution

To examine the uniformity of air distribution within the trailer, air temperature measured at each location was correlated to the supply air temperature over time. In each preliminary test, a total of 27 correlation coefficients were calculated over a period of 500 minutes using the SAS system for Windows, Release 6.12 (SAS Institute, Inc., Cary, N.C., U.S.A.). The data points were extracted around the middle of each trip after the cooling system was stabilized. If conditioned air was uniformly distributed inside the trailer, the 27 correlation coefficients would have positive and similar values.

Results from the preliminary tests are presented in Figure 4.4. In this figure, the r -values are grouped by sections (front, middle and rear). In each section, a line joins the r -values on the same horizontal plane (top, middle and bottom).

Table 4.1: Trailer and load characteristics.

Date	Test number	Trailer number	Bracing	Pallet arrangement	Air duct	Bulkhead	Floor	Trailer nominal length	Number of pallets	Trailer Precooling	Refrigeration system	Setpoint	Mode	Travel Time
14-Jun	L2NA	R33175	NA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	26 (full)	Yes	TK SB II di	3.33 °C (38 °F)	-	Night
8-Jul	L6NA	R33236	NA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	20 (incomplete)	-	TK SB II	3.33 °C (38 °F)	Auto	-
5-Jul	L5NA	R33238	NA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	26 (full)	-	TK SB III Max+	3.33 °C (38 °F)	-	-
5-May	LP2NA	S96023	NA	Pinwheel	Yes	Frame	Duct	14.63 m (48 ft)	24 (full)	-	TK SB II di	3.33 °C (38 °F)	-	Night
16-Sep	Q13NA	R33176	NA	Offset	Yes	Frame	Flat	16.15 m (53 ft)	24 (full)	Yes	TK SB II	1.11 °C (34 °F)	Auto	Night
15-Sep	Q11NA	R33228	NA	Offset	Yes	Frame	Flat	16.15 m (53 ft)	24 (full)	No	TK Super II Max+	8.89 °C (48 °F)	Auto	Night
15-Sep	Q10NA	587569	NA	Offset	No	Solid	Flat	16.15 m (53 ft) *	24 (full)	No	TK SB III DE SR	8.89 °C (48 °F)	Auto	Day
16-Sep	Q12NA	587569	NA	Offset	No	Solid	Flat	16.15 m (53 ft) *	24 (full)	No	TK SB III DE SR	8.89 °C (48 °F)	Auto	Day
13-Sep	Q9HA	R33175	HA	Centerline	Yes	Frame	Flat	16.15 m (53 ft)	22 (incomplete)	No	TK SB III Max+	3.33 °C (38 °F)	Auto	Night
3-Sep	Q6HA	R33177	HA	Centerline	Yes	Frame	Flat	16.15 m (53 ft)	24 (full)	No	TK SB II	40 °F (4.44 °C)	Cont.	Day
13-Sep	Q8HA	R33240	HA	Centerline	Yes	Frame	Flat	16.15 m (53 ft)	24 (full)	No	TK SB III Max+	8.89 °C (48 °F)	Auto	Day
3-Sep	Q7HA	R83204	HA	Centerline	Yes	Frame	Duct	14.63 m (48 ft)	22?	No	TK SB III Max	8.89 °C (48 °F)	Auto	Day
1-Sep	Q2VA	912264	VA	Pinwheel	Yes	No	Duct	14.63 m (48 ft)	22 (incomplete)	No	TK SB II di	8.89 °C (48 °F)	Auto	Day
8-Jul	L6VA	R33174	VA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	22 (incomplete)	-	TK SB II	10.00 °C (50 °F)	Auto	Night
3-Jul	L4VA	-	VA	Pinwheel	Yes	Solid	Duct	16.15 m (53 ft)	18 (incomplete)	-	Carrier Phoenix Ultra	-	-	Night
2-Sep	Q4VA	912264	VA	Centerline	Yes	No	Duct	14.63 m (48 ft)	22 (complete)	No	TK SB II di	8.89 °C (48 °F)	Auto	Day
2-Sep	Q5VA	RT8307	VA	Centerline	Yes	Frame	Duct	14.63 m (48 ft)	22 (complete)	No	TK SB I 1200	8.89 °C (48 °F)	-	Day
3-Jun	LP3FVA	R33229	FVA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	26 (full)	-	TK Super II Max+	3.33 °C (38 °F)	-	Night
10-Jun	L1FVA	R33235	FVA	Pinwheel	Yes	Frame	Flat	16.15 m (53 ft)	26 (full)	-	Carrier Phoenix Ultra	3.33 °C (38 °F)	-	Night
15-Jun	L2FVA	R33215	FVA	Pinwheel	Yes	Frame	Duct	16.15 m (53 ft)	24 (incomplete)	-	Carrier	7.22 °C (45 °F)	-	Night

* Multi-temperature trailer
 "-" information not available

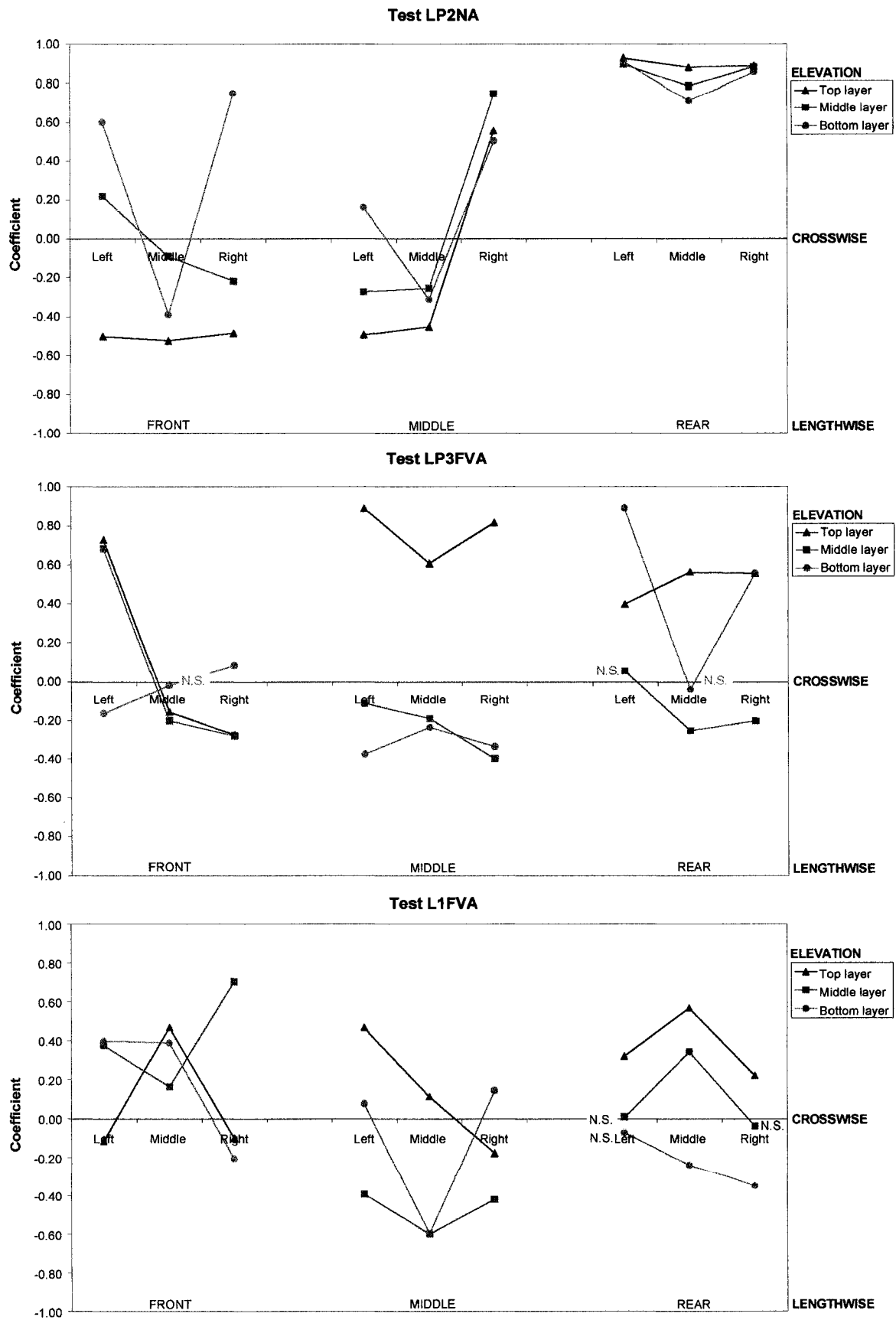


Figure 4.4: Pearson correlation coefficients for the preliminary tests. All values are significant at $P=0.10$, except those indicated by the letters N.S. (not significant).

In general, data obtained from the preliminary tests indicate air distribution inside the refrigerated semi-trailer was not uniform. The values of the Pearson correlation coefficients were spread out from positive to negative (Figure 4.4). If there was good air circulation and air was moving freely everywhere in the trailer, all of the r -values would be above zero. The presence of negative r -values in some locations shows that the air temperature at such point was varying inversely with the supply air temperature. This can happen when air movement is restricted at the specific position. When there is insufficient airflow, air temperature at the point could be greatly affected by produce temperature and external heat sources. Due to such influences, the air temperature may not correlate well with the supply air temperature, thus lowering the value of the correlation coefficient. A zero or negative correlation coefficient is therefore an indicator of poor air circulation at the specific location inside the semi-trailer.

4.2.3.2 Airflow patterns

The airflow pattern varied from test to test. In test LP2NA, the rear section of the load received more air than the middle or the front section (Figure 4.4). In test LP3FVA and L1FVA, the Pearson correlation coefficients were scattered randomly and it is difficult to identify which section(s) received more air. The latter two tests were conducted in similar field conditions. They were conducted in trailers that were 16.15 m (53 ft) long, equipped with air ducts, flat floors and frame bulkheads. Although they were loaded with different types of produce, both had 26 pallets of produce with the pallets arranged in pinwheel configuration. Both loads were braced with air bags placed vertically at every layer (FVA). For two tests conducted in such similar conditions, it is interesting to see how their air distribution patterns did not show any similarity (Figure 4.4).

It is important to note that the experiments were carried out in field conditions and although every effort was made to arrange the pallets in a specific pattern, the overall condition of the two similar loads was not fully identical. It was difficult to move or turn pallets inside the confined area of a semi-trailer. Irregular spaces may exist in-between pallets or around the load. Since air flows through the path of least resistance, it may simply flow through an irregular pathway that is difficult to define. Furthermore, trailers with the same nominal length often have different internal dimensions. The variation in

the trailer's internal width and height can affect the amount of space available for air circulation. The height of produce pallets also varied within a single load, and from load to load, which affect the amount of space available on the top of the load. Since it is difficult to measure the actual spaces between pallets, and between the trailer internal surfaces and the load, it becomes difficult to identify the exact airflow pathways for a specific condition.

4.2.3.3 Symmetry across the width

Results from the preliminary tests showed a certain level of symmetry in air distribution between the left and right sides of the load. This symmetrical distribution suggests that the present configuration of the semi-trailer, with pallets arranged symmetrically, could yield the same airflow pattern around the right and left side of the load. The symmetrical distribution was present in some cases, but not all (Figure 4.4). For example, in test LP2NA, the crosswise distribution was fully symmetrical at the rear of the load (indicated by the V-shape curves) as well as the front-top and front-bottom layer. However, in the middle of the trailer, the right side experienced more airflow than the left side.

Ideally, air temperatures should be measured on both the left and right side of a load. In the main tests, 15 data loggers were used to monitor temperatures only on the right side of each load. The reason for using half the amount of data loggers was mostly logistic. The experiment was carried out with a limited time frame. During the experiment, the produce distributor was undergoing a restructuring process and there was a possibility of interruption of produce deliveries. It was necessary to schedule the field tests in an effective manner by matching closely to the delivery schedules. Field tests were organized as groups of two, but the budget available for purchasing the data loggers was not sufficient to obtain 54 data loggers. For the London deliveries, two field tests were carried out on two consecutive days. On day-1, loading personnel at the receiving dock collected the data loggers. On day-2, a trip was made to the London Distribution Center to retrieve the data loggers from both deliveries. Field tests for the Vanier deliveries were organized in a similar manner, except two field tests were conducted on the same day. One load was instrumented in the morning and another in the afternoon, and a trip was made to the Vanier Distribution Center to retrieve the instruments at night.

The reason for placing data loggers on the right side of the load instead of the left side was simple; some of the trailers that deliver produce to Vanier traveled in the afternoon and the sun would shine on the right side of the trailer body. The majority of the London deliveries occurred at night, therefore there was no such effect from sunlight. Overall, using half the amount of the data loggers allowed the gathering of data in more trailers with the restricted time frame and limited budget.

4.2.4 Main tests

In the main tests, a total of 17 experiments were conducted. In each test, 15 data loggers were used to monitor the temperatures of air circulating across the middle and right side of each load. Results from the three preliminary tests are also included in this section of the analysis, but only temperature data from the middle and right sides of the loads are included. The supply air temperature was also recorded in each test.

In the analysis, the air temperatures were correlated with the supply air temperature at three different levels: individual, plane and overall. At the individual level, the 15 air temperatures were individually correlated to the supply air temperature over time. At the second level, air temperatures were grouped by plane and the average temperature at each plane was correlated to the supply temperature over time. This resulted in three correlation coefficients along the length of the load (front, middle, rear), two correlation coefficients across the width of the load (middle, right) and three correlation coefficients along the height of the load (top, middle, bottom) (Figure 4.5). At the last level, an overall average was calculated based on the 15 air temperature readings. This overall average is then correlated to the supply air temperature over time and one correlation coefficient representing the entire load was calculated.

The range of data used for the calculation of correlation coefficients varied among tests. The travel times of the London deliveries were longer than those to Vanier. Therefore, 500 minutes of data was used for the London trips, while only 120 minutes was used for the Vanier trips. The only exception was test L4VA, because there was a change in the refrigeration system settings at the middle of the trip. For this test, 1000 minutes of data was used in the calculation of Pearson correlation coefficients.

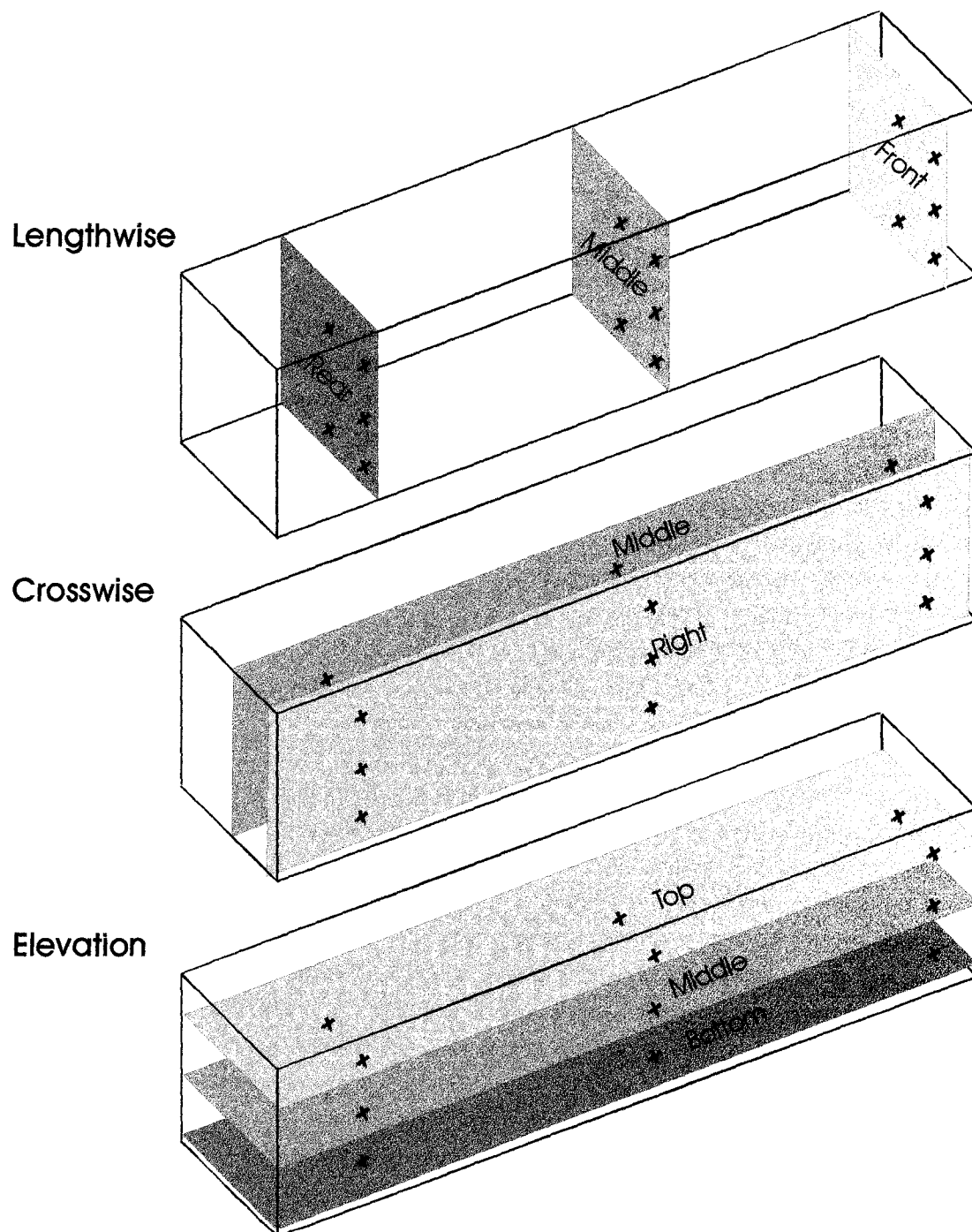


Figure 4.5: The grouping of temperature readings by plane. The actual locations of the data loggers varied with the height, the arrangement and the total number of pallets in each load.

4.2.4.1 Individual correlation coefficients

The individual correlation coefficients for the 20 tests are summarized in Table 4.2. The r -values can be significant or non-significant. If the value is significant, it can be positive or negative. In cases when the correlation coefficients cannot be computed (absence of value), it is denoted by “.” in Table 4.2. When a value is significant, it means the correlation coefficient is different than zero at $P=0.10$. A non-significant value means there was no association between the two temperatures, which can be interpreted as an indication of poor air circulation. When the value is significant and positive, it indicates there is a positive linear association between the supply air temperature and air temperature at a specific point inside the trailer. The higher the value of the coefficient, the more air circulation is expected at such point. A negative r -value indicates the air temperature at a point varied inversely with the supply air temperature. This means that air temperature at the point was affected more by produce temperature or external heat load than the supply air moving across that point. The absent of a value occurs when temperature at a point remained constant over time. In such circumstances, the denominator of Equation (3) would be zero and the correlation coefficient cannot be computed. A negative value or the absence of r -value suggests there was blockage in the airflow, thus indicating that air circulation was poor at the specific location. In summary, non-significant, negative or the absent of correlation coefficient are indicators of poor air circulation.

Looking at the correlation coefficients at the individual level, the air circulation inside the trailers was generally not uniform. There is a large variability in the values of the Pearson correlation coefficient within the loads (Table 4.2). The minimum and maximum r -values for the 20 tests are summarized in Table 4.3. In all tests, the minimum r -values were either not significant or negative, meaning there were locations within the load that were not reached by the conditioned air. In most of the tests, their maximum r -values were high; meaning there were locations inside the load that received more conditioned air. Such variability in r -values demonstrated that the air circulation inside the trailers were generally not uniform.

Table 4.2: Pearson correlation coefficients for the 20 tests.

TEST #	FTM	FBM	FTR	FMR	FBR	MTM	MBM	MTR	MMR	MBR	RTM	RBM	RTR	RMR	RBR
L2NA	0.88	0.01 N.S.	0.84	0.84	0.84	0.91	0.47	0.95	0.73	0.67	0.87	0.89	0.88	0.87	0.63
L6NA	0.77	0.18	0.73	0.62	0.39	0.44	0.49	0.48	0.31	-0.18	0.42	0.43	0.53	0.49	0.14
L5NA	0.80	-0.65	0.90	0.66	0.57	0.67	-0.77	0.90	0.54	0.20	0.91	0.78	0.84	0.84	0.81
LP2NA	-0.52	-0.39	-0.49	-0.22	0.75	-0.45	-0.31	0.56	0.75	0.50	0.88	0.71	0.89	0.88	0.86
Q13NA	0.63	0.68	0.64	0.60	0.48	0.65	0.08 N.S.	0.65	0.56	0.41	0.65	0.65	0.52	0.68	0.62
Q11NA	0.22	0.01 N.S.	0.18	0.06 N.S.	0.13 N.S.	0.59	-0.27	0.56	0.17	0.37	0.85	0.63	0.87	0.90	0.90
Q10NA	0.91	0.29	0.82	0.79	0.23	0.44	.	0.30	-0.35	.	0.36	0.29	0.42	0.33	0.39
Q12NA	0.73	0.07 N.S.	0.68	0.56	0.09 N.S.	0.19	-0.35	0.25	.	.	-0.07 N.S.	.	-0.08 N.S.	-0.08 N.S.	-0.24
Q9HA	0.69	-0.06 N.S.	0.75	0.80	0.68	0.31	-0.56	0.91	0.34	0.64	0.72	.	0.70	0.89	.
Q6HA	-0.19	-0.28	-0.14 N.S.	0.19	0.56	-0.43	.	-0.12 N.S.	0.55	0.42	-0.42	0.59	0.56	0.42	0.66
Q8HA	0.78	N.A.	0.71	-0.41	-0.73	0.46	0.51	0.32	0.20	.	0.32	0.79	-0.08 N.S.	0.44	.
Q7HA	0.64	-0.55	0.97	0.95	0.93	0.58	0.18	0.88	0.82	0.91	0.70	0.74	0.79	0.18	0.84
Q2VA	-0.78	-0.71	0.14 N.S.	-0.06 N.S.	0.34	0.29	-0.04 N.S.	0.56	0.31	-0.07 N.S.	0.73	0.33	0.52	-0.003 N.S.	-0.51
L6VA	0.56	-0.61	0.53	0.50	0.57	0.55	0.10	0.54	0.40	0.23	0.32	0.10	0.55	0.01 N.S.	0.20
L4VA	0.85	0.77	0.85	0.91	0.84	0.76	-0.16	0.67	0.58	0.47	0.79	0.68	0.72	0.65	0.55
Q4VA	-0.21	-0.35	0.44	0.10 N.S.	.	0.20	-0.22	.	0.18	0.0007 N.S.	0.13 N.S.	-0.49	0.20	0.07 N.S.	0.01 N.S.
Q5VA	0.17	.	0.21	0.14 N.S.	0.24	0.20	0.10 N.S.	0.21	0.15 N.S.	0.06 N.S.	0.24	0.13 N.S.	0.25	0.20	0.17
LP3FVA	-0.16	-0.02 N.S.	-0.28	-0.28	0.08	0.61	-0.23	0.82	-0.40	-0.34	0.56	-0.04 N.S.	0.55	-0.20	0.56
L1FVA	0.47	0.39	-0.10	0.70	-0.20	0.11	-0.60	-0.18	-0.42	0.14	0.57	-0.24	0.22	-0.04 N.S.	-0.35
L2FVA	0.60	-0.35	0.71	0.12	0.41	0.58	0.10	0.70	0.23	0.38	0.45	-0.15	0.51	0.17	0.14

All values are significant at P=0.10, except indicated by the letters N.S. (not significant)

N.A. = data not available

"," = correlation coefficient cannot be calculated

Table 4.3: The minimum and maximum r -values for the 20 tests.

TEST #	MIN	MAX
L2NA	0.01 N.S.	0.95
L6NA	-0.18	0.77
L5NA	-0.77	0.91
LP2NA	-0.52	0.89
Q13NA	0.08 N.S.	0.68
Q11NA	-0.27	0.90
Q10NA	-0.35	0.91
Q12NA	-0.35	0.73
Q9HA	-0.56	0.91
Q6HA	-0.43	0.66
Q8HA	-0.73	0.79
Q7HA	-0.55	0.97
Q2VA	-0.78	0.73
L6VA	-0.61	0.57
L4VA	-0.16	0.91
Q4VA	-0.49	0.44
Q5VA	0.06 N.S.	0.25
LP3FVA	-0.40	0.82
L1FVA	-0.60	0.70
L2FVA	-0.35	0.71

All values are significant at $P=0.10$,
except indicated by the letters N.S.
(not significant).

The properties of the trailers and their respective loads are summarized in Table 4.1. As shown in Table 4.1, some tests shared a similar trailer and load characteristics, while others did not. Tests Q6HA, Q8HA and Q9HA had similar characteristics. In order to verify the airflow pattern, the r -values of the three tests results were plotted graphically in Figure 4.6. Similar to the results obtained from the preliminary tests, it is not possible to identify a general airflow pattern for these tests even when conducted in similar field conditions. The Pearson correlation coefficients are scattered randomly in the graphs. By plotting the r -values of the other tests graphically, it was also found that the airflow pattern varied from test to test and no general airflow pattern could be defined for tests that were conducted in similar field conditions.

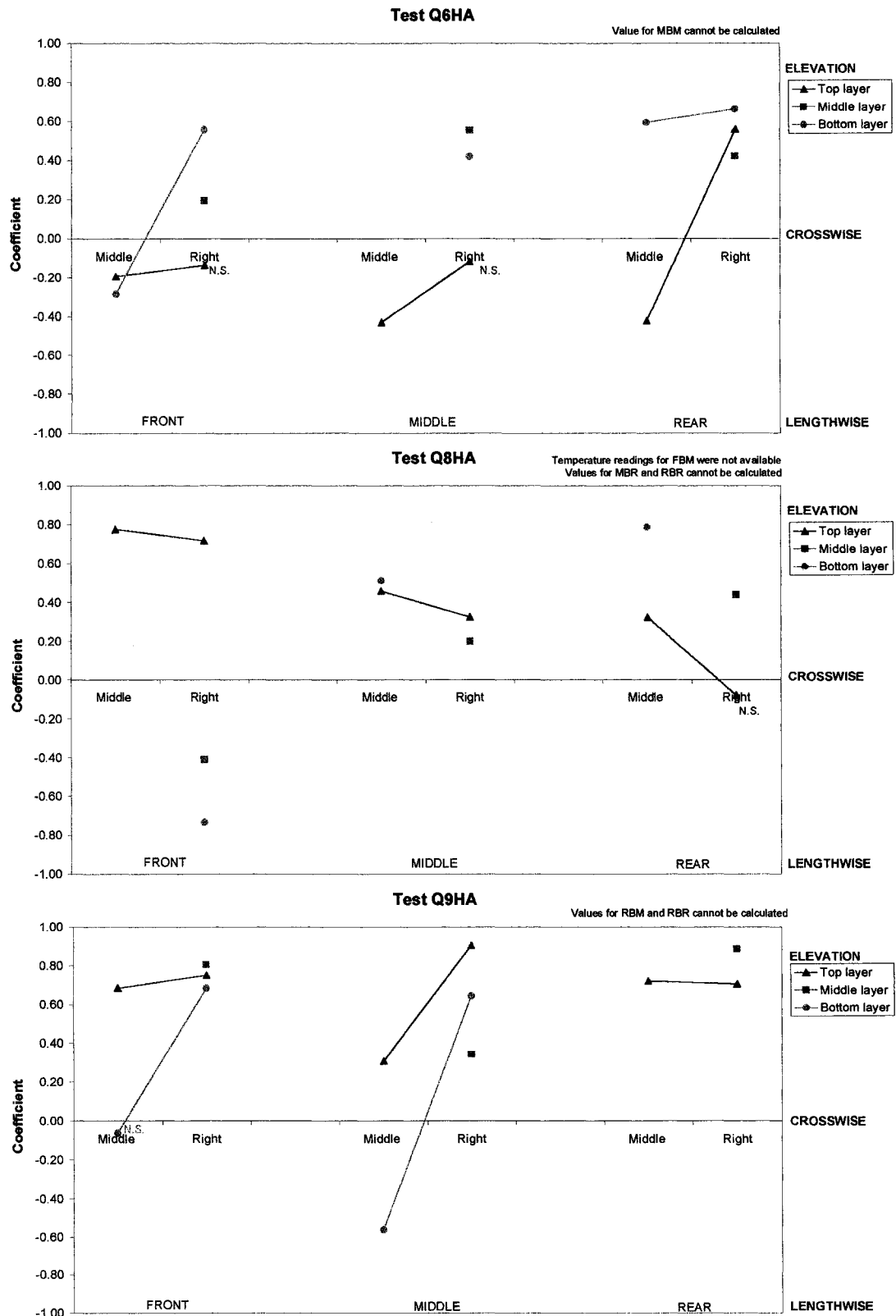


Figure 4.6: Pearson correlation coefficients for Test Q6HA, Q8HA and Q9HA. All values are significant at $P=0.10$, except those indicated by the letters N.S. (not significant).

4.2.4.2 Correlation coefficients across several planes

Table 4.4 summarizes the Pearson correlation coefficient at the different sensing planes across the length, width and height of the loads (Figure 4.5). In general, air distribution inside the trailers was not uniform. Some sections within the trailer received more airflow than others as indicated by their higher correlation coefficients. Secondly, the flow patterns also varied among tests along the sensing planes. For example, some trailers had better air distribution in the front, while others had good air distribution at the rear.

Differences in flow patterns occur not only in tests conducted in dissimilar trailers and loads. It also happened for tests that were conducted in similar conditions. As an attempt to verify the effect of air duct on air distribution, results from tests Q10NA, Q12NA, Q11NA, Q13NA are presented in Figure 4.7. Tests Q10NA and Q12NA were conducted in trailers equipped with solid bulkhead, flat floor and no air duct. Tests Q11NA and Q13NA were conducted in trailers equipped with frame bulkhead, flat floor and air duct. The four trailers had a nominal length of 16.15 m and they were fully loaded with 24 pallets of produce. The loads were arranged as offset pattern. Due to the similarity in the trailer accessories and loads, one may expect the air distribution for test Q10NA to be similar to Q12NA; and results from test Q11NA would be similar to Q13NA. Indeed, both Q10NA and Q12NA had better air distribution at the front, at the right side and at the top of the load (Figure 4.7). These findings correspond well to what was expected since without an air duct, air would circulate more at the front and top sections of the trailer. On the other hand, results from tests Q11NA and Q13NA were not consistent. The two tests were conducted in very similar conditions, but they yield different airflow patterns. Test Q11NA had better air distribution at the rear, right and middle of the load, but test Q13NA had better distribution at the front, middle and top of the load (Figure 4.7). In theory, better air circulation at the rear is expected for trailers equipped with an air duct. However, since the airflow patterns of tests Q11NA and Q13NA were not consistent, it is difficult to draw such a conclusion. Furthermore, the variability of the airflow patterns makes it difficult to conclude whether using an air duct or not would improve the air distribution.

Table 4.4: Pearson correlation coefficients by plane. All values are significant at $P=0.10$, except those indicated by the letters N.S. (not significant). Shaded values indicate planes with better air circulation.

TEST #	LENGHTWISE			CROSSWISE		ELEVATION		
	Front	Middle	Rear	Middle	Right	Top	Middle	Bottom
L2NA	0.83	0.91	0.87	0.866	0.872	0.90	0.86	0.75
L6NA	0.72	0.47	0.46	0.57	0.60	0.64	0.59	0.34
L5NA	0.81	0.82	0.86	0.78	0.87	0.86	0.81	0.64
LP2NA	-0.25	0.20	0.96	-0.13	0.79	0.27	0.69	0.72
Q13NA	0.68	0.61	0.65	0.70	0.62	0.66	0.64	0.63
Q11NA	0.16	0.46	0.89	0.57	0.81	0.79	0.82	0.53
Q10NA	0.92	0.35	0.40	0.70	0.82	0.84	0.61	0.42
Q12NA	0.72	0.12 N.S.	-0.12 N.S.	0.26	0.37	0.46	0.27	-0.18
Q9HA	0.72	0.59	0.85	0.45	0.87	0.75	0.88	0.43
Q6HA	0.14 N.S.	0.02 N.S.	0.50	-0.30	0.54	-0.26	0.52	0.60
Q8HA	0.45	0.543	0.538	0.76	0.12 N.S.	0.67	-0.02 N.S.	0.50
Q7HA	0.94	0.84	0.79	0.58	0.94	0.87	0.90	0.84
Q2VA	-0.41	0.321	0.324	-0.17	0.20	0.27	0.10 N.S.	-0.25
L6VA	0.44	0.45	0.35	0.29	0.50	0.59	0.40	0.16
L4VA	0.86	0.63	0.71	0.78	0.75	0.79	0.76	0.71
Q4VA	0.06 N.S.	0.07 N.S.	-0.12 N.S.	-0.33	0.29	0.27	0.15 N.S.	-0.39
Q5VA	0.21	0.219	0.222	0.23	0.21	0.23	0.18	0.24
LP3FVA	-0.19	0.10	0.59	0.39	0.07 N.S.	0.65	-0.33	-0.04 N.S.
L1FVA	0.19	-0.25	-0.07 N.S.	0.17	-0.17	0.30	-0.08	-0.21
L2FVA	0.65	0.59	0.40	0.54	0.55	0.65	0.20	0.28
count	8/19	3/19	8/19	6/20	14/20	14/20	3/20	3/20
proportion	42%	16%	42%	30%	70%	70%	15%	15%

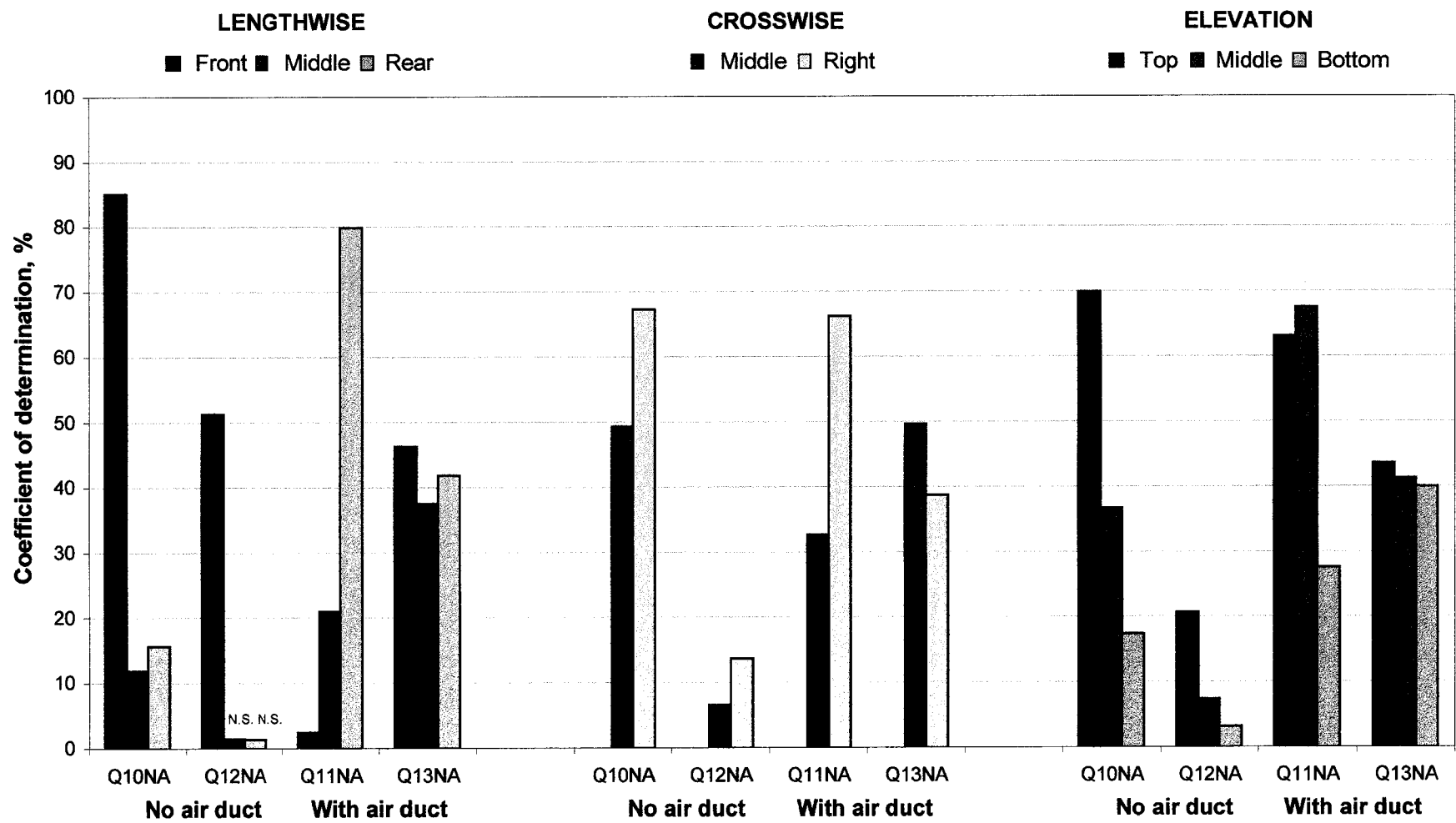


Figure 4.7: Effect of air duct on air distribution ($P=0.10$).

To obtain a global view of the airflow pattern, data was analyzed by sampling frequency. The sections that had the best correlation coefficients are highlighted in Table 4.4. Out of the 20 cases studied, 42% of the loads received more air at the front, with 42% at the rear and 16% in the middle. In the vertical plane, 70% of the loads received more air at the top compared to 15% in the middle and 15% at the bottom. Across the width, 70% of the loads received more air near the right sidewall compared to 30% at the middle. These proportions can change depending on the properties of the sampled trailers and loads, but they help identifying the areas that received less airflow. In general, the areas that had less airflow were the middle section along the length; the middle section across the width, the middle and bottom sections across the height of the loads. The insufficient airflow in these areas corresponds to what was expected since these locations have limited amount of channels for air circulation. Produce pallets were often closely loaded at the middle section of the loads. In addition, the area available for air passages is usually limited at the bottom of the load, as mentioned in the review of literature.

4.2.4.3 Overall correlation coefficients

In each test, the overall correlation coefficient was obtained by correlating the average air temperature of the 15 points with the supply air temperature over time. Figure 4.8 presents two scenarios: one having a high correlation coefficient and the other having a low correlation coefficient. In test Q7HA, the average air temperature followed closely the variation in supply air temperature and a high r -value of 0.88 was obtained. On the other hand, test Q12NA shows the average air temperature not responding very well to the variation in supply air temperature, resulting in a low r -value of 0.33. Knowing that the average air temperature would follow closely the supply air temperature only if there was good air circulation, the Pearson correlation coefficient proved to be a good indicator of air distribution inside the semi-trailers.

One objective of this study was to verify the effect of loading pattern and the use of air bags on air circulation. Each overall correlation coefficient was squared to obtain the coefficient of determination. The coefficient of determination indicates the proportion of variation in the average air temperature that is caused by the variation in the supply air temperature. The values of the coefficient of determination for the 20 tests are

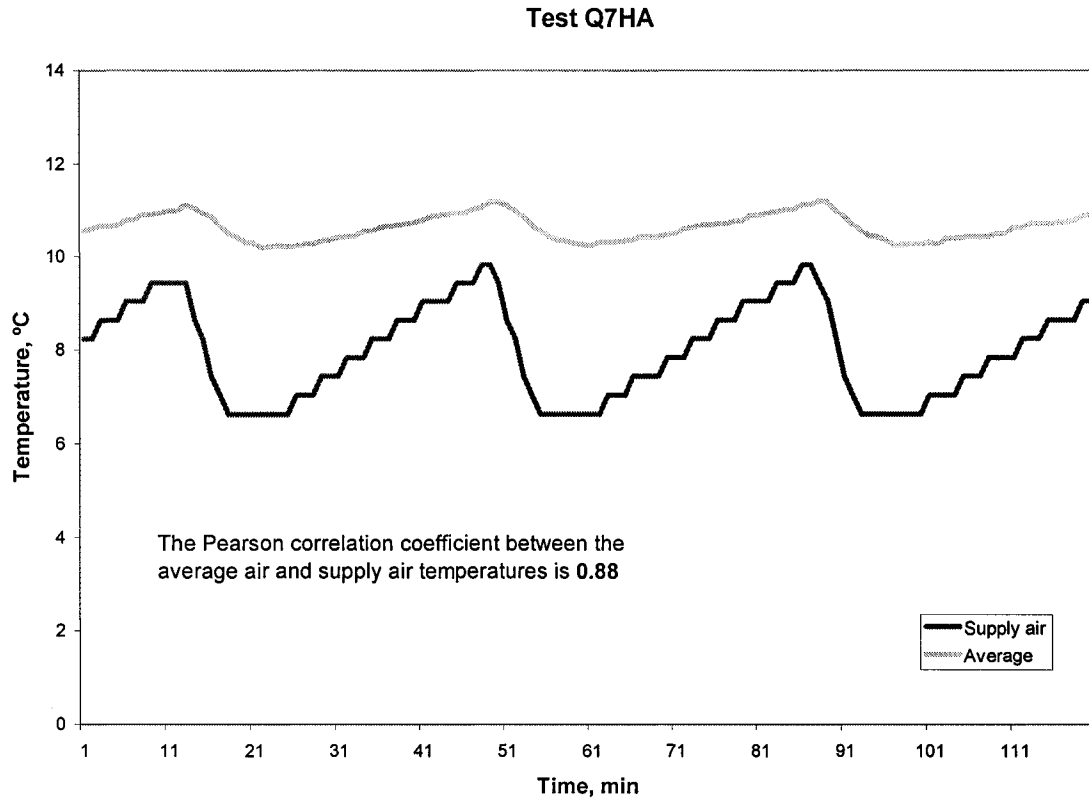
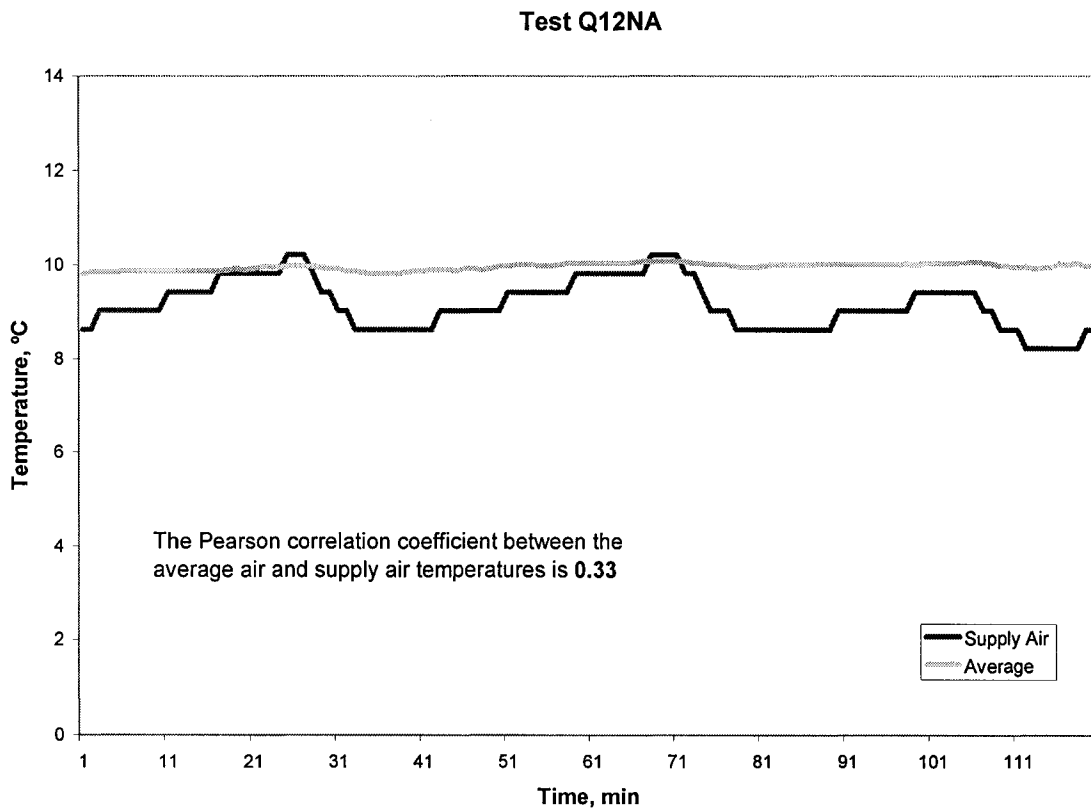
A**B**

Figure 4.8: Pearson correlation coefficients for two scenarios.

summarized in Figure 4.9. The overall coefficients of determination are grouped by loading pattern and the use of air bags. Five loading patterns and two air bag positions were considered: pinwheel NA, centerline HA, offset NA, pinwheel VA, pinwheel FVA and centerline VA (Figure 3.1). Within the same category of load arrangement, the trailers may not share the same characteristics. The trailer characteristics are also illustrated in Figure 4.9. Trailers that were equipped with similar accessories and had the same nominal length shared the same letter.

Results of tests conducted with similar conditions were not consistent (Figure 4.9). For example, tests L2NA, L5NA and L6NA were conducted in trailers having the same characteristics and the pallets were arranged the same manner, however, their coefficient of determination varied from 36% to 76%. The same variability in results was found for tests Q6HA, Q8HA and Q9HA with the r^2 -value ranging from 9% to 58%. The inconsistency in the results for tests conducted in similar conditions suggest the presence of irregular spacing between the load and the trailer internal surfaces, as well as between individual palletized load.

Treating each test as an independent case and grouping them according to the loading pattern and use of air bags, Figure 4.9 suggest several general trends. In terms of the loading pattern, pinwheel tended to assist the air circulation better than offset pattern (Figure 4.9: pinwheel NA versus offset NA). As for the use of air bags, arranging the load as pinwheel NA, centerline HA, offset NA tended to assist air circulation more than pinwheel VA, pinwheel FVA or centerline VA. Bracing the load with air bags vertically (VA or FVA) resulted in a reduction in airflow, as compared to bracing the load horizontally or not using any air bags. The physical explanation for such an observation is that air distribution inside a semi-trailer is mostly longitudinal and placing air bags vertically between the load and the sidewalls create an obstruction to airflow. Nevertheless, the coefficients of determination varied greatly within each category (Figure 4.9). The effect of loading pattern and the use of air bags was not dominant enough to override all other factors that influence air circulation and produce consistent results. With this data, it is not possible to confirm with certainty which type of loading or bracing pattern would assist better the air circulation.

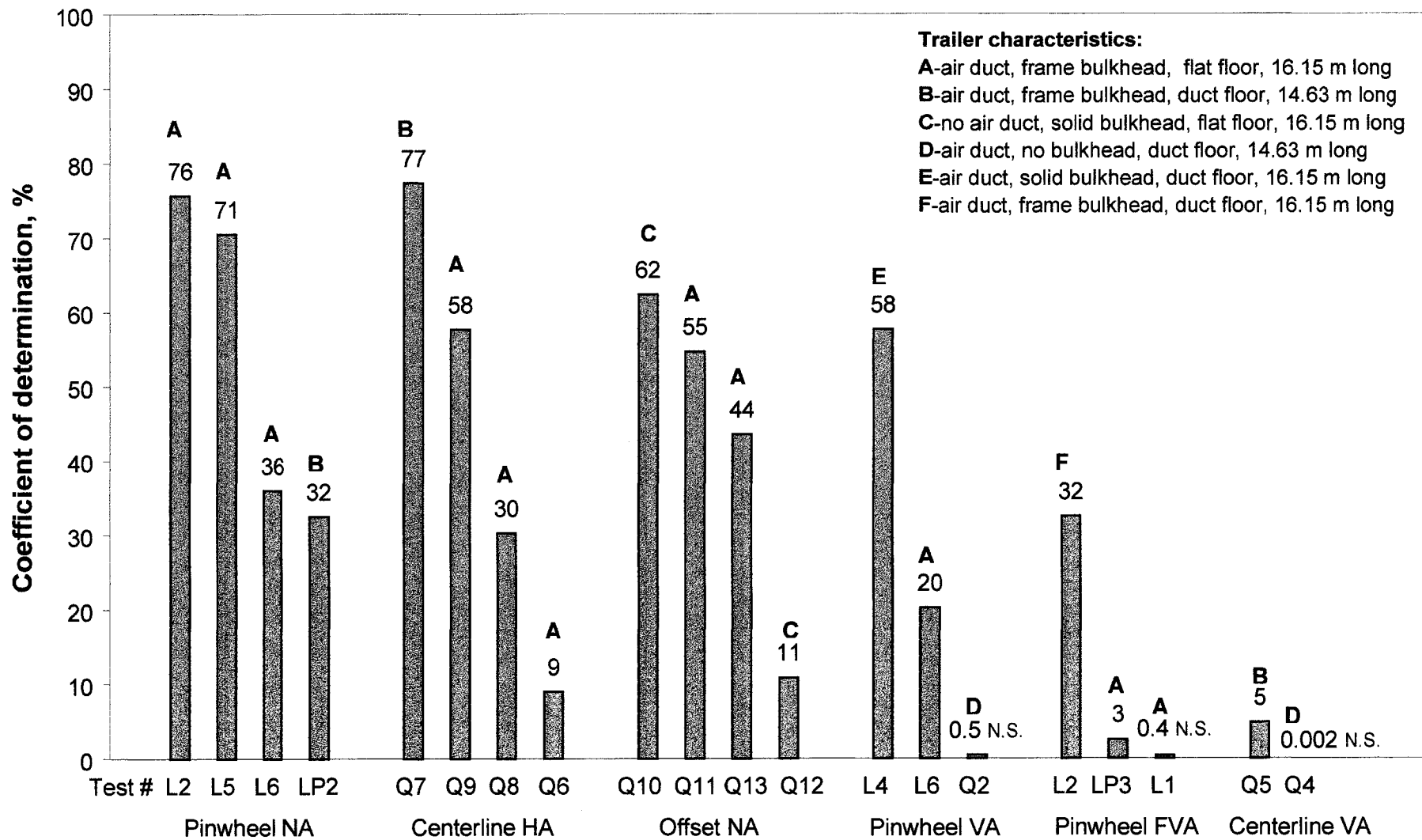


Figure 4.9: Air distribution of semi-trailers grouped according to the loading pattern and use of air bags (P=0.10).

V. CONCLUSIONS

An overview of the equipment and practices currently used in transporting fresh fruits and vegetables was presented. In evaluating the effectiveness of the air circulation system, Pearson correlation coefficient was used as an indicator. A variety of trailers and mixed loads with different characteristics were sampled. From the data gathered, the following conclusions can be made:

1. In general, air distribution inside refrigerated semi-trailers studied was not uniform. The values of the Pearson correlation coefficients ranged mostly from positive to negative. Also, there were sections of the load that were not reached by the conditioned air.
2. The airflow patterns varied greatly among loads. It was not possible to define a general airflow pattern in trailers equipped with similar accessories and loads. The airflow pattern was not consistent for tests conducted in similar conditions. Due to such variability, it was not possible to determine the effect of trailer accessories.
3. Out of the 20 cases studied, 42% of the loads received more air at the front, with 42% at the rear and 16% in the middle. Across the height, 70% of the loads received more air at the top compared to 15% in the middle and 15% at the bottom. Across the width, 70% of the loads received more air near the right sidewall compared to 30% at the middle. In most cases, the areas that had less airflow were the middle section along the length; the middle section across the width, the middle and bottom sections across the height of the loads.
4. In terms of the loading pattern, pinwheel tended to assist the air circulation more than offset pattern (pinwheel NA versus offset NA). As for the use of air bags, bracing the load horizontally or not using any air bags tended to assist the air circulation more than bracing the load vertically (pinwheel NA, centerline HA and offset NA versus pinwheel VA, pinwheel FVA and centerline VA). The coefficients of determination varied greatly within each category of loading and bracing pattern. It was not possible to confirm with

certainty which type of loading or bracing pattern would assist better the air circulation.

5. The irregular spacing, the height of produce pallets and the internal dimensions of the trailers may play an important role on air circulation. They may have contributed to the variability in the results since they affect the availability of air channels through and around the load.

Several observations were made on the handling practices while conducting the experiment. There seems to be a lack of understanding as to how trailer accessories and loading patterns affect air circulation during transport. The shippers showed little concern over the type of trailers being used, whether it is equipped with an air duct, bulkhead or duct floor. They simply load whatever trailer is provided by the carriers. For packers, the choice of loading pattern was based mostly on load volume, ease of loading and load stability, rather than improving air circulation.

VI. RECOMMENDATIONS

The study provided a glimpse of the air circulation problem in refrigerated semi-trailers transporting fresh produce. Further in-depth research is needed to evaluate and improve the air distribution inside the semi-trailers. More research is needed to examine the use of Pearson correlation coefficient in analyzing temperature data. One approach is to conduct the study in laboratory conditions. A lab-scale transparent plastic model can be built to replicate and scale-down the properties of the trailers and loads. Experiments can then be conducted to study the effect of trailer accessories and load arrangement. The individual effect of each factor and their interactions can be studied in detail. The best combination of accessories and practices can then be identified using mathematical modeling.

After conducting the study in laboratory conditions, it would be important to verify the findings in field conditions. Several measures may be helpful in reducing the variability of field results. In terms of placement of data loggers, in this study, the temperature data loggers were placed on the produce containers directly. The effect of produce temperature on the temperature readings was difficult to estimate. One solution to reduce the effect of produce temperature is to isolate the data loggers from produce containers, for example, by placing a piece of Styrofoam in between the data logger and the container.

The variability that is attributed to mixed loading can be reduced if field tests are conducted on straight load (transporting a single type of produce). This may reduce the airflow irregularities caused by the difference in pallet heights. To reduce the dissimilarity among trailers, arrangements can be made to request for a specific type of trailer for the experiment.

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