A Fast-Time Simulation to Measure the Effects of Temporally Inaccurate Convective Weather Forecasts in Terminal Airspace

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16. Abstract
Several improvements in NextGen require enhanced weather information with greater accuracy than is available with today's forecast technologies. The FAA's Aviation Weather Division, Policy and Requirements Branch (ANG-C64) enlisted the services of the FAA Modeling and Simulation Branch (ANG-C55) to quantify the effects of inaccurate weather forecasts on the NAS using fast-time computer simulation. This effort focused on the impacts of inaccurate temporal information for 1-hour convective weather forecasts in a terminal environment.

Three scenarios were simulated to establish a frame of reference for comparing the effects of the inaccurate forecasts: no weather constraints were employed in the Nominal scenario; an infinite knowledge of the weather was represented in the Omniscient scenario; and purely tactical weather avoidance strategies were used in the Tactical scenario. Seven 1-hour forecasts with varying degrees of temporal accuracy were simulated. One (Perfect) simulation scenario was conducted to represent a weather forecast with no temporal error; the onset and cessation time of the weather is perfectly predicted in this scenario. Then, 3 Early forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes earlier than the actual weather, and 3 Late forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes later than the actual weather start and end times.

In general, more maneuvers were required and flight efficiency was decreased as the temporal inaccuracy increased. Also, arrival flights experienced much greater impacts than did departure flights. This is largely because departure flights were able to wait on the ground until the weather cleared without incurring additional flight time, distance, or fuel burn; however, this caused departures to be impacted by increased ground delay. Also, results indicate that early forecasts cause more disruption to the NAS than do late forecasts. ATC was required to implement more weather avoidance maneuvers when the forecast was early in its prediction and flights flew longer distances, were in the air longer, burned more fuel, and spent more time in holding when the forecast was early.

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Executive Summary

The National Airspace System (NAS) in the United States is in the process of modernization through the efforts of the Next Generation Air Transportation System (NextGen) program. Several improvements in NextGen require enhanced weather information with greater accuracy than is available with today's forecast technologies. To establish a path toward the acquisition of weather products that meet NextGen demands, the Federal Aviation Administration (FAA) Aviation Weather Division, Policy and Requirements Branch (ANG-C64) established a goal to develop validated NextGen Mid-Term performance requirements for enhanced weather information that are based on NextGen concepts defined in the NextGen Mid-Term Concept of Operations and the NextGen Segment Implementation Plan.

An understanding of the impacts of inaccurate weather forecasts on the NAS is necessary to develop valid requirements for weather information. FAA Policy and Requirements enlisted the services of the FAA Modeling and Simulation Branch (ANG-C55) to quantify these effects on the NAS using fast-time computer simulation. While forecasts of several types of weather information must be studied to develop and validate a complete set of requirements, this effort focused on the impacts of inaccurate temporal information for 1-hour convective weather forecasts in a terminal environment.

Three scenarios were simulated to establish a frame of reference for comparing the effects of the inaccurate forecasts. First, a Nominal scenario was run with no weather constraints; flights were most efficient in this scenario as no maneuvers were necessary. Next, infinite knowledge of the weather was represented in the Omniscient scenario; flights in this scenario were maneuvered as strategically as possible when weather was present. Finally, purely tactical weather avoidance strategies were used in the Tactical scenario.

Seven 1-hour forecasts with varying timing accuracy were simulated. One (Perfect) simulation scenario was conducted to represent a weather forecast with no timing error; the onset and cessation time of the weather is perfectly predicted in this scenario. Then, 3 Early forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes earlier than the actual weather, and 3 Late forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes later than the actual weather start and end times.

In general, more maneuvers were required and flight efficiency was decreased as the forecast timing error increased. Also, arrival flights experienced greater impacts than departure flights. This is largely because departure flights were able to wait on the ground until the weather cleared without incurring additional flight time, distance, or fuel burn; however, this caused departures to be impacted by increased ground delay.

Results showed that early forecasts caused more disruption to the NAS than late forecasts. ATC was required to implement more weather avoidance maneuvers when the forecast was early in its prediction and flights flew longer distances, were in the air longer, burned more fuel, and spent more time in holding when the forecast was early. The difference in impact between early and late forecasts is significant; however, separate requirements for accuracy may not be necessary if they are defined to capture the effects caused by early forecasts.

The Modeling & Simulation Branch recommends further research into the effects of inaccurate convective weather forecasts. Additional forecast lead times and magnitudes of error should be studied before finalizing requirements. A Monte Carlo simulation or the development of a predictive model with the use of Design of Experiments (DOE) could be used to maximize the amount and quality of data.

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1 Introduction

The NAS is in the process of modernization through the efforts of the Next Generation Air Transportation System (NextGen) program. Several improvements in NextGen require enhanced weather information with greater accuracy than is available with today's forecast technologies. In order to establish a path toward the acquisition of weather products that meet NextGen demands, the Federal Aviation Administration (FAA) Aviation Weather Division, Policy and Requirements Branch (ANG-C64) established a goal to develop validated NextGen Mid-Term performance requirements for enhanced weather information. These requirements will be based on NextGen concepts set forth in key NextGen artifacts such as the NextGen Mid-Term Concept of Operations, National Airspace System (NAS) Operational Improvements, and the NextGen Segment Implementation Plan.

An understanding of the impacts of inaccurate weather forecasts on the NAS is necessary to develop valid requirements for weather information. FAA Policy and Requirements enlisted the services of the FAA Modeling and Simulation Branch (ANG-C55) to quantify these effects on the NAS using fast-time computer simulation. While forecasts of several types of weather information must be studied to develop and validate a complete set of requirements, this effort focused on the impacts of inaccurate temporal information for 1-hour convective weather forecasts in a terminal environment.

1.1 *Purpose*

The objective of this study is to quantify the NAS impacts of timing inaccuracies found in 1-hour convective weather forecasts in the terminal area. The research question listed below is addressed in this activity. Results of this study will be used towards the development and validation of technical requirements for aviation weather technologies pertaining to the forecast of convective weather.

> *What is the impact of temporal error in a 1-hour convective weather forecast in the terminal area on flight efficiency and air traffic control (ATC) task loads?*

1.2 *Background*

In 2010, a joint FAA/National Weather Service (NWS) Traffic Flow Management (TFM) Requirements Working Group (TRWG) developed a set of requirements for weather forecasting products that could support the needs of NextGen in the Mid-Term timeframe. The TRWG's requirements for convective weather forecasting defined acceptable amounts of error in location, probability of detection, timing, and false alarm rates that varied by forecast lead time and the affected NAS domain (terminal or en route airspace). For both onset and cessation times, the TRWG required less than or equal to 5 minutes of timing error for a 1-hour forecast of convective weather in terminal airspace. However, this requirement was not validated through NAS research.

A translation of the needs of NextGen improvements into performance requirements for weather forecast information is ongoing. Konyak (2013) developed a methodology for using fast-time simulation to validate requirements for weather technologies such as those defined by the TRWG. In 2014, the Policy and Requirements Branch contracted AvMet Applications Inc. to prepare an approach for using simulation to develop and validate requirements for convective weather information in terminal and en route environments. The approach uses real convective weather in four terminal locations and three large en route airspace locations to test the effects of inaccurate forecasts on the NAS (Newton, Klopfenstein, Hahn, and Robinson, 2015).

The FAA's Policy and Requirements Branch tasked the FAA's Modeling and Simulation Branch with performing a fast-time simulation study to support the development of forecast requirements. The Modeling and Simulation Branch specializes in fast-time simulation and analysis to assess the impacts of proposed changes on the capacity, safety, and efficiency of the NAS. Modeling and simulation are used to measure the performance and benefits of a system whenever detailed analysis or experimental manipulation of the actual system is not feasible. Computational methods in modeling and simulation (commonly referred to as "fast-time simulation") are typically used in the early investigative stages of a proposed change to a system.

1.3 *Document Organization*

The remainder of this document provides details on the methodology used to conduct this study, the results of the analysis, a summary of the study's conclusions and recommendations for next steps.

2 Study Methodology

The Modeling and Simulation Branch simulated three conditions to establish reference points for the impact of convective weather forecasts on the NAS. These included a scenario in which there was no weather present, one where perfect knowledge of the weather was known at all times, and a third where no forecast information was provided. These three scenarios were simulated to establish a reference for comparisons with no weather constraints and a "best" and "worst" case scenario for forecast accuracy. To assess the impact of inaccurate convective weather forecast times, fast-time simulation scenarios representing varying accuracy of a 1-hour forecast were compared to a baseline scenario of a perfect 1-hour forecast for the same weather system.

2.1 *Metric Selection*

Data for the following metrics were collected during the simulation and analyzed.

<u>ATC Task Loads</u>

- Number of Weather Avoidance Maneuvers
    - Pre-departure (ground) reroutes of affected arrival flights
    - Strategic airborne reroutes
    - Tactical airborne reroutes
    - Airborne holds
    - Ground delays for affected departure flights
    - Detoured departure routes for affected departure flights

<u>Flight Efficiency</u>

- Flight distance
- Flight duration
- Fuel burn
- Departure delay
- Airborne holding delay

2.2 *Analysis Design*

This section provides a brief description of the study's analysis methodology including the models and tools used, a detailed description of the factors considered in the experiment, simulation scenario definitions and a listing of the assumptions and limitations of the study.

1.1.1 Models & Tools

The FAA's Modeling and Simulation Branch has a number of fast-time simulation models and analytical tools to assess the benefits of proposed concepts. The following tools were chosen for this analysis based on the study questions.

1.1.1.1 AirTOp Fast-Time Simulation Tool

AirTOp is a commercial, off-the-shelf, multi-agent simulation tool developed by Airtopsoft SA, a European-based company specializing in the development of air traffic simulation and optimization systems (AirTOpsoft, 2007). The AirTOp simulation tool is designed to capture many aspects of the Air Traffic Management domain. AirTOp can model controller roles, tasks and workload for radar controllers, planning controllers and airport controllers. The tool includes a user-defined, rule-based system to define en route restrictions, rerouting, approach and departure sequencing, and runway dependencies. For this study, AirTOp was the primary fast-time simulation tool used to study the effects of inaccurate convective weather forecasts on the NAS.

1.1.1.2 JMP Statistical Software

The statistical software product JMP® was used to analyze the simulation data and quantify the effects of inaccurate forecast times on the NAS. JMP is a commercial, off-the-shelf product of the SAS Institute that provides a user-friendly graphical interface to perform descriptive and inferential statistical analyses and allows the user to easily manipulate data tables and create meaningful graphs.

1.1.2 Scope

The scope of this study is defined in the subsections below. The simulation scenarios modeled flights traveling to and from a major metropolitan airport in the United States and simulated its arrival and departure operations in detail. Conclusions drawn from the study results are limited to the terminal and en route areas. Please note that forecasts of convective weather in en route airspace were not being studied in this activity, but the effects of inaccurate forecasts of convective weather in the terminal area were represented in both domains. This is because aircraft often implement a maneuver strategy in en route airspace to avoid weather in the terminal environment. Ground operations were not represented and not deemed necessary by the analysis team.

1.1.2.1 Airport

The airport modeled in this study was Hartsfield-Jackson Atlanta International Airport (KATL). KATL has five runways that alternate between an eastern and western traffic flow configuration and can accommodate triple arrival or triple departure runways. For this simulation study, an eastern configuration with triple arrival runways (Figure 1) was used. Current Area Route Navigation (RNAV) approach and Standard Instrument Departure (SID) procedures at KATL were modeled in detail to reflect the most commonly used procedures (offload arrival routes were not represented). Typical taxi times and runway selection rules were configured to accurately represent the traffic flow transitioning from the ground to the air.

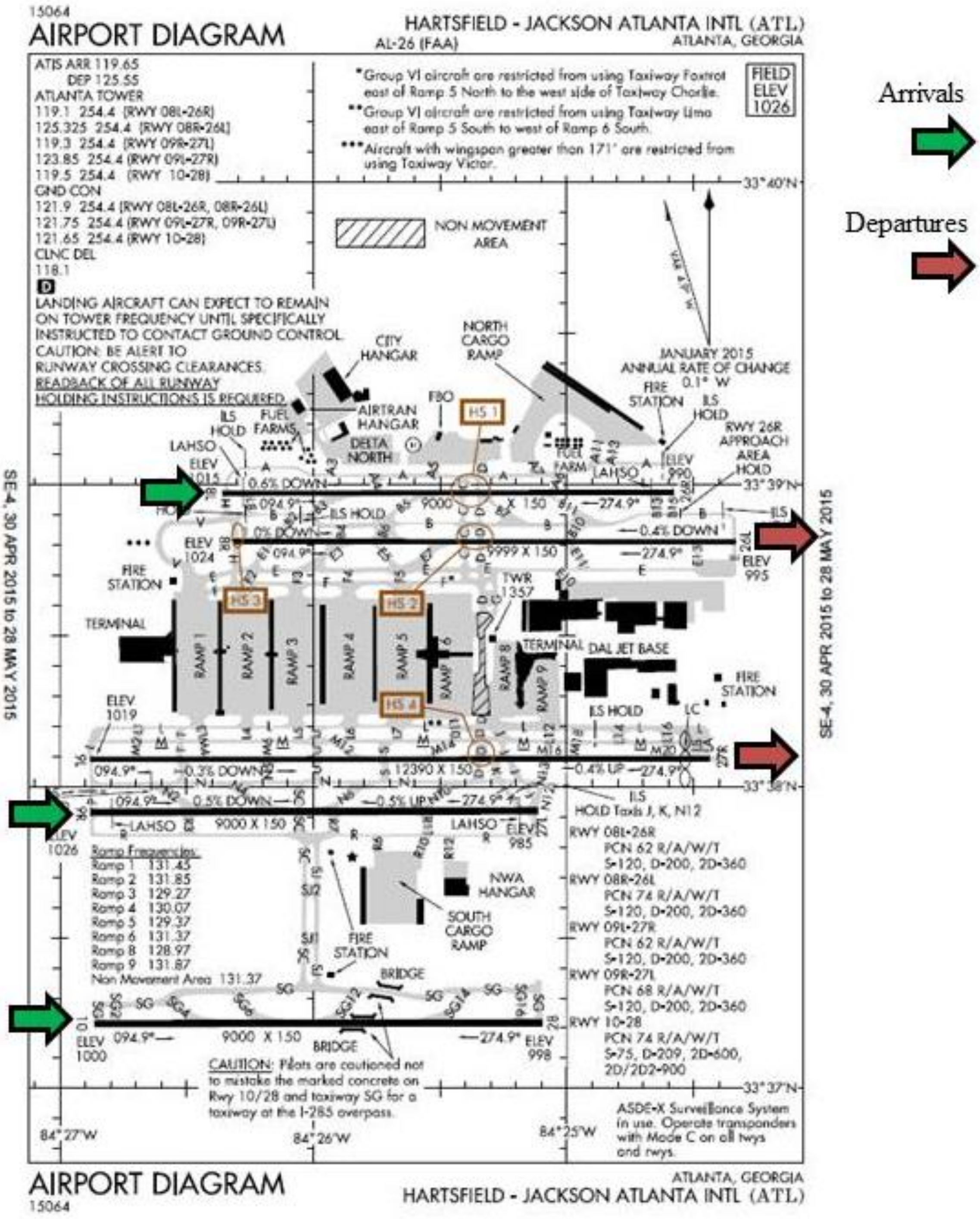

Figure 1. KATL in Eastern Configuration with Triple Arrival Runways

1.1.2.2 Airspace

The airspace modeled for this study consisted of all Air Route Traffic Control Centers (ARTCCs) and their subsectors in the Continental United States. However, the analysis focused on the Atlanta (ZTL) ARTCC only. The Terminal Radar Approach Control (TRACON) airspace for KATL was also modeled in detail. The airspace boundary data for this simulation was obtained from the En Route Automation Modernization (ERAM) system.

1.1.2.3 Air Traffic

The air traffic samples used for the simulations were based on recorded, operational traffic data from ZTL on August 5, 2014. This day of traffic was selected because it represents the 85^{th} percentile of annualized traffic for KATL and is a day on which traffic was not significantly impacted by weather. It is important to use a weather-free day so that the scheduled traffic is as close to unconstrained, planned routings as possible. The recorded flight plan information on this day was obtained through the Traffic Flow Management System (TFMS) database. The same traffic data was used in all simulation scenarios.

1.1.2.4 Weather and Forecasts

The Nominal scenario was simulated with no actual or forecast weather. All other scenarios in this study were simulated with the same convective weather event which blocked the northwestern arrival and western departure routes at KATL. While actual weather cells were not modeled in this activity, the resulting route blockages in KATL terminal airspace and corresponding air traffic management reactions were simulated. The shaded areas in the notional diagram presented in Figure 2 define the terminal airspace that was blocked by convective weather from 1730 Zulu (Z) to 1930Z. It was also assumed that weather blocked en route airspace within 40 nautical miles (NM) of these shaded areas.

The actual weather is held constant in all scenarios; the weather forecast was the independent variable altered between scenarios. This approach was chosen because it isolates the effects of forecast inaccuracies on a given weather system. Weather was not forecasted at all in the Tactical scenario and was forecasted perfectly with an infinite lead time in the Omniscient scenario; these two scenarios were developed solely for reference. The remaining 7 simulation scenarios modeled a 1-hour forecast with varying errors in the start time and end time of the weather event.

For this study, the 1-hour forecast is a prediction of weather activity that is published an hour prior to the event. For example, a forecast is published at 1625Z indicating that weather is going to be present at KATL at 1725Z. The forecast is updated every minute, producing a rolling forecast. The only information given in each forecast is the predicted weather characteristics an hour from its publication time. This means that pilots, airlines, and ATC are made aware of a weather event 1 hour prior to its start, but the duration of the event is unknown.

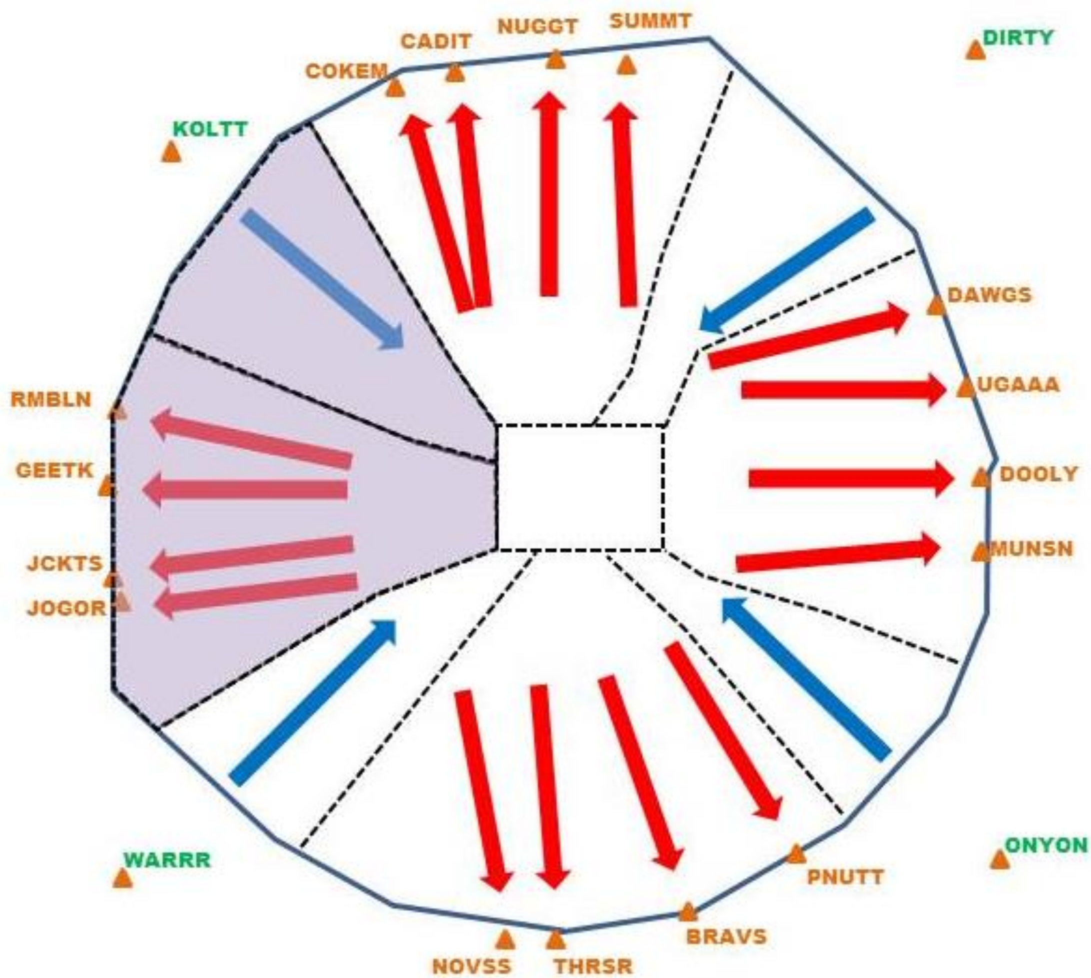

Figure 2. Routes Blocked by Weather at KATL

Several different weather forecasts are represented in this study. With a lead time of 1 hour, the time that forecasted weather is predicted to start blocking routes (referred to as the onset time) varied to represent 0, 5, 15, and 30 minute errors in timing, both early and late. The duration of the weather event is held constant at 2 hours in each scenario, causing the forecasted end time (referred to as cessation time) to have the same error as the onset time. This timing was held constant to avoid introducing confounds caused by varying duration of the weather events. Figure 3 displays the timing of the actual weather that is present in all scenarios as well as the forecast time for each scenario.

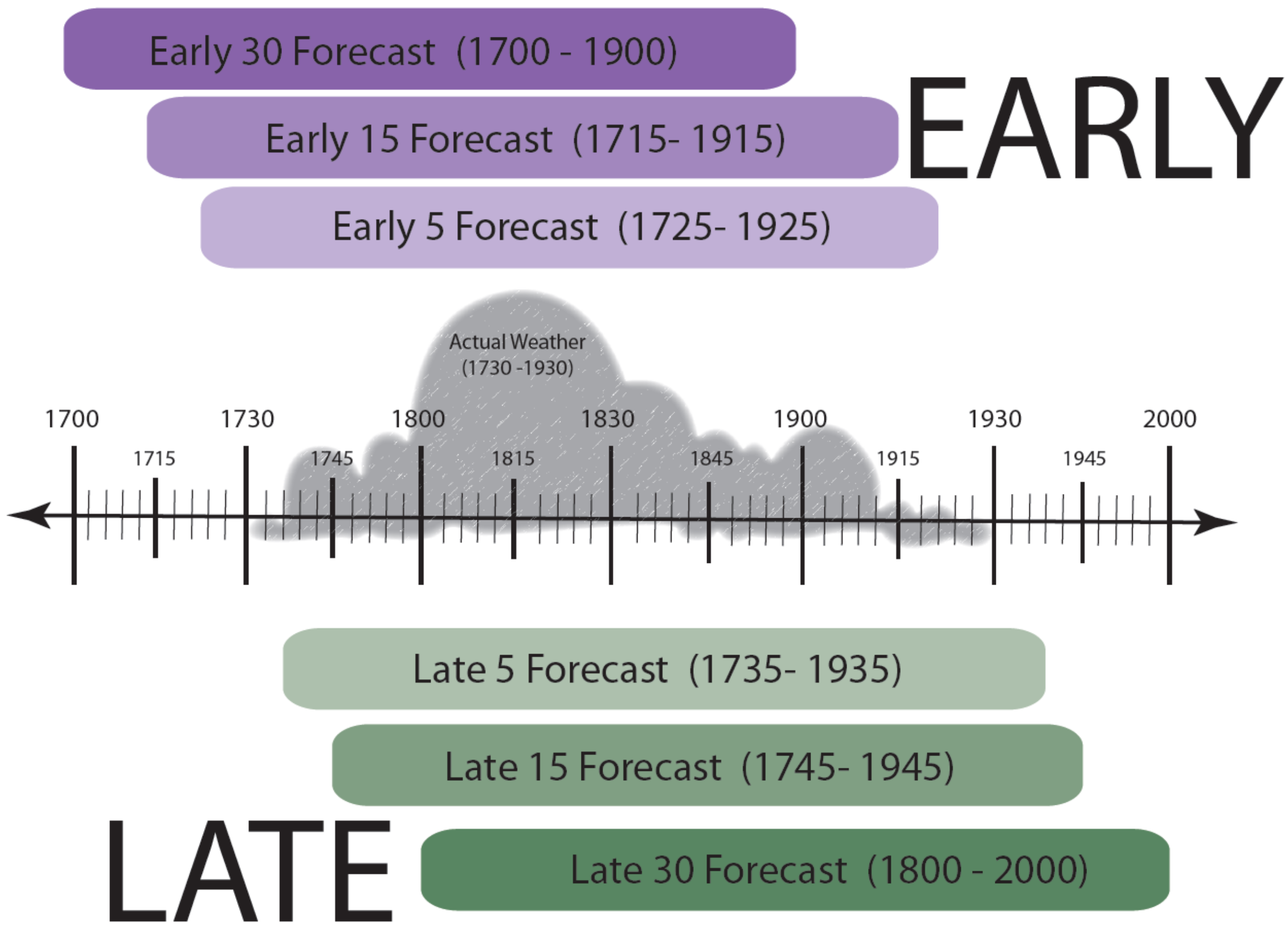

Figure 3. Timing of Forecasted Weather in Each Simulation Scenario

1.1.2.5 Weather Avoidance Strategies

When weather is forecast to block arrival and/or departure routes at an airport, air traffic controllers work with the pilots and airlines to use weather forecasts in coordinating the safest and most efficient avoidance strategies available for flights in en route airspace and for those on the ground that have not yet departed. In cases where weather occurs that was not predicted, controllers may make tactical decisions to place aircraft in a holding pattern and/or reroute flights to maintain safety and efficiency. While this study did not model formal Traffic Management Initiatives (TMIs), it simulated the reactions of air traffic when arrival and departure routes are blocked by convective weather by manipulating individual flights. Established playbook routes were used when possible to define the rerouted paths for flights arriving at KATL. These reactions reflected weather avoidance strategies defined with the input of ATC and TFM Subject Matter Experts (SMEs).

Figure 4 and Figure 5 show the weather avoidance strategies used for this study, employed at different times with respect to the forecasted onset of the weather. When the forecast perfectly predicts the onset and cessation times of the weather, the planned maneuvers seen at the top of the figures were the only strategies taken to avoid the weather. However, when error was present in the forecast times, tactical maneuvers are required to avoid the actual weather or to prevent unnecessary and inefficient reroutes; these unplanned maneuvers are defined at the bottom of the figures.

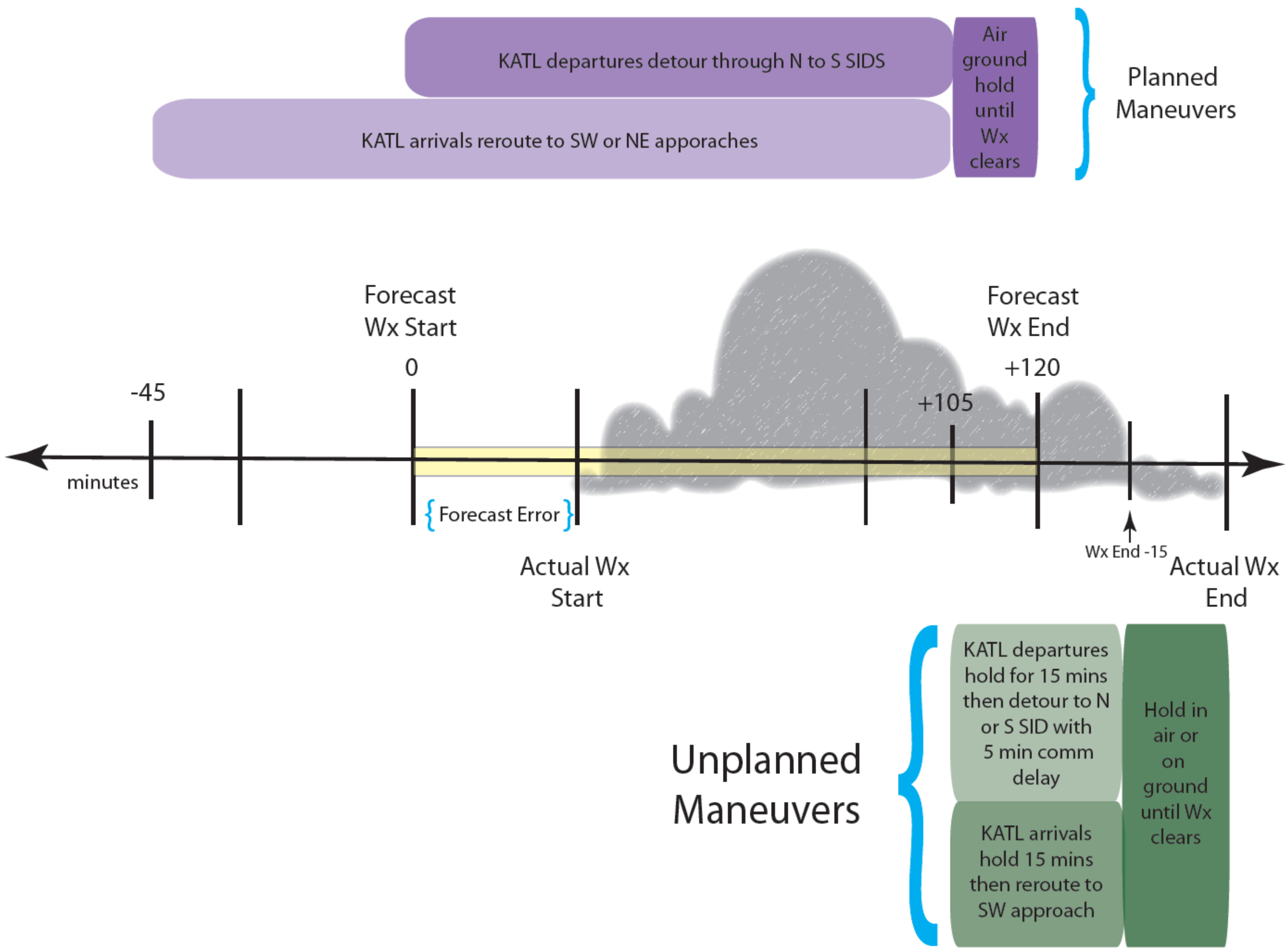

Figure 4. Weather Avoidance Strategies with Early Forecasts

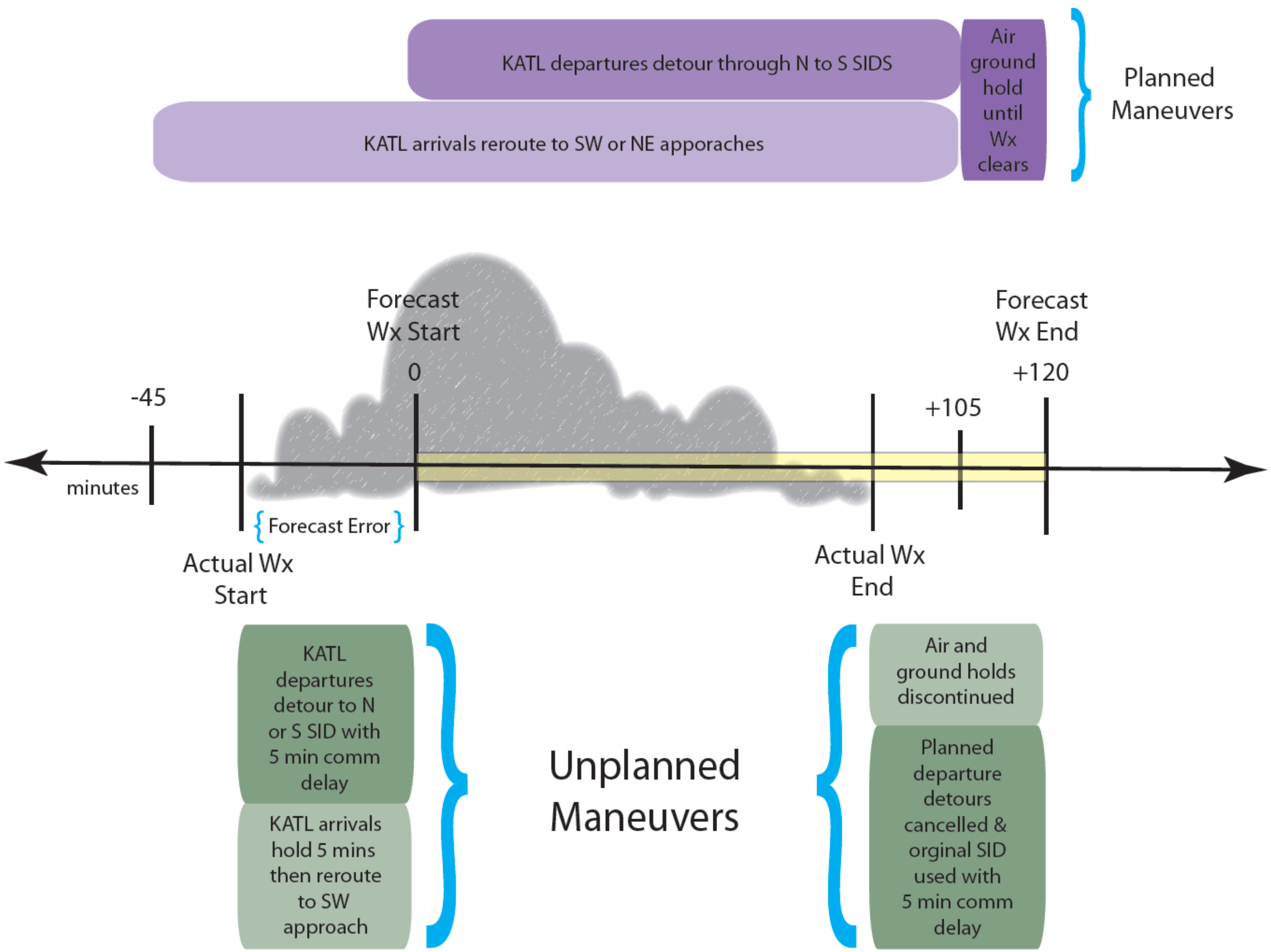

Figure 5. Weather Avoidance Strategies with Late Forecasts

Table 1 lists the weather avoidance maneuvers utilized in this study. The strategic or planned maneuvers taken to avoid weather differed depending on the state of the aircraft when a blockage in the flight's approach route was first forecasted.

When a flight arriving at KATL is an hour away from entering the northwest (KOLTT) approach (whether on the ground pre-departure or in the air), the current forecast was used to determine if a weather avoidance strategy needed to be implemented. If the forecast indicates that weather blocks the KOLTT approach route at the time of the flight's arrival, the subsequent forecasts (updated every minute) are monitored for 15 minutes before an avoidance strategy is assigned. This is because it is assumed that airlines accept up to 15 minutes of holding; thus, if the cessation time is forecast in the 15 minutes of monitoring, the flight continues to the KOLTT approach as planned and enters a holding pattern until the weather clears. If weather is still present in the forecast after 15 minutes of monitoring, a reroute is assigned and the flight proceeds to either the northeast (DIRTY) or southwest (WARRR) approach routes, depending on its current position and flight path. In this case, a flight that has not yet departed and is planned to arrive at KATL's northwest approach during the weather event receives a new route before its departure. Northwestern arrival flights that receive the forecast information indicating a blocked approach while they are airborne are rerouted when they are 45 minutes from reaching the approach, where 45 minutes represents the 1-hour lead time with 15 minutes of assumed monitoring.

Western departure flights at KATL followed the same assumption that a 15 minute ground hold was acceptable and preferred over detouring to a northern or southern SID. Flights planning to depart using the western SIDs RMBLN and GEETK at KATL during the first 1 hour and 45 minutes of the forecasted weather event are detoured to the northern SID COKEM while those planning to use the western SIDs JCKTS and JOGOR detoured through the southern SID NOVSS; during the last 15 minutes of the forecasted weather event, these flights were assigned a ground hold until the weather cleared.

Table 1. Weather Avoidance Maneuvers

Maneuver	Type	Description
KATL Arrival Flights		
Pre-departure Reroute	Strategic	Rerouted flight path that joins existing playbook routes to KATL and is assigned prior to a flight's departure if the forecasted route blockage is known at that time. This reroute may lead to the northeast (DIRTY) or southwest (WARRR) approach routes.
Hold	Strategic	Planned hold of 15 minutes or less that is assigned if end of forecasted weather is within 15 minutes of a flight's arrival time at the northwest (KOLTT) approach. Flights hold near the CALCO or NEUTO waypoints and proceed to the KOLTT approach after exiting this hold.
Strategic Reroute	Strategic	Rerouted flight path that may join a modified playbook route or take an ad-hoc reroute to the northeast (DIRTY) or southwest (WARRR) approach routes. This reroute is assigned 45 minutes before a flight's arrival time at the KOLTT approach if weather is forecasted to block its route.
Hold + Tactical Reroute	Tactical	Unplanned maneuver that is assigned when a flight plans to arrive at the northwest (KOLTT) approach normally but unexpected weather causes it to hold then reroute to the southwest (WARRR) approach route. When a flight has no forecast information in the Tactical scenario, it holds in this situation for 5 minutes to receive a reroute from ATC; in scenarios where a 1-hour forecast is given, a flight holds for 15 minutes, waiting for the weather to clear, before taking an unplanned reroute.
KATL Departure Flights		
Detour SID	Strategic	A different SID at KATL is assigned to a flight when weather is forecast to block its original SID on the West of the airport. A flight planning to take RMBLN or GEETK SIDs detours through the northern SID COKEM while one that is planning to take JCKTS or JOGOR detours through the southern SID NOVSS. All flights rejoin their original flight path as close to KATL as reasonably possible.
Ground Delay	Strategic	A departure flight at KATL waits on the ground up to 15 minutes and departs via its planned western SID when the weather is clear. This is assigned to flights planning to depart KATL in the last 15 minutes of the weather.
Ground Delay + Detour SID	Tactical	Unplanned maneuver that is assigned when a flight plans to depart using a western SID at KATL but unexpected weather causes its departure to be delayed before being detoured through a northern (COKEM) or southern (NOVSS) SID. The ground delay taken includes 5 minutes for ATC to communicate the new SID information to the pilot and may also include up to 15 minutes of waiting for the unexpected weather to dissipate.

It should be noted that this study makes the modeling assumption that reactions to the forecasted weather are made with full confidence in its accuracy. In real operations, some level of doubt in a forecast may exist, but this doubt requires an assumption of inaccuracies in the forecast which is what this study is testing. Assuming a lack of confidence in the forecast would confound the factors in this study, making the scenarios far too complex to identify the NAS impacts of inaccurate weather forecasts.

2.2.1 Simulation Scenarios

This simulation activity consisted of two sets of scenarios which are defined in Table 2 below. Reference scenarios were simulated to establish a source for comparisons with no weather constraints and a “best” and “worst” case scenario for forecast accuracy. The following reference scenarios were simulated: a Nominal scenario where no weather blockages were modeled, and flights arrived and departed at KATL normally with no traffic flow constraints; a Tactical scenario in which weather was encountered with no forecast to inform avoidance strategies, and flights were assigned an unplanned maneuver to avoid the weather; and an Omniscient (strategic) scenario in which a perfectly accurate forecast was provided with an infinite lead time, and all weather avoidance strategies were implemented prior to the departure of affected flights.

In addition to the reference scenarios, 7 scenarios were developed to represent a 1-hour convective weather forecast with varying errors in the forecasted onset and cessation times. In these scenarios, traffic management decisions were made based on a rolling weather forecast with a 1-hour lead time before the event. The baseline run of this group of scenarios models a perfect forecast in which the forecasted onset and cessation times perfectly match those of the actual weather event. The other 6 scenarios are treatment runs with ±5, ±15, and ±30 minutes of onset/cessation time error.

Table 2. Simulation Scenarios

Scenario ID	Forecast Lead Time	Description	Weather Avoidance Strategies
Reference Scenarios			
Nominal	N/A	No weather present	None
Tactical	0	No weather information available	Hold & Tactical Reroute; Ground Delay & Detour SID
Omniscient	Infinite	Perfect knowledge of weather at all times	Pre-departure Reroute or Hold; Detour SID
1-hour Forecast Scenarios			
Perfect	1 hour	Forecast matches the actual weather times	Strategic Reroute or Hold; Detour SID or Ground Delay
Early 5		Forecast predicts start of weather 5 minutes early	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID
Early 15		Forecast predicts start of weather 15 minutes early	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID
Early 30		Forecast predicts start of weather 30 minutes early	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID
Late 5		Forecast predicts start of weather 5 minutes late	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID
Late 15		Forecast predicts start of weather 15 minutes late	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID
Late 30		Forecast predicts start of weather 30 minutes late	Strategic Reroute, Hold, or Hold & Tactical Reroute; Detour SID, Ground Delay, or Ground Delay & Detour SID

2.2.2 Assumptions and Limitations

The following assumptions were made for this simulation activity:

- The impacts of controller workload and sector occupancy on traffic management decisions are not considered. Sectors were modeled with unlimited capacity and air traffic control tasks were performed instantaneously.
- Conflict resolutions were not modeled. Resolutions typically take place in en route airspace; with no overflight traffic simulated, conflict resolutions would not be realistic.
- Modeled air traffic procedures and airspace boundaries reflect the current state of the NAS. However, the technologies found in the Collaborative Air Traffic Management (CATM) Work Package 4 are assumed to be in use, particularly the Arrival Route Status Impact (ARSI) and Integrated Departure Route Planning (IDRP) tools for providing route blockage information to controllers.
- Winds and temperature variations are not modeled.

- Convective weather is represented in the model as route blockages and is fixed in all scenarios.
- Forecasts of the weather are varied and represented by different timing of weather avoidance strategies.
- No spatial inaccuracies are modeled in this study.
- Traffic management decisions in all simulation runs are based on the same set of strategies, detailed in Section 1.1.2.5, and result in changes to individual flights. No formal TMIs were modeled. The strategies represented in the study are considered reasonable by subject matter experts in air traffic management.
- Weather avoidance strategies are determined based on full confidence in the weather forecast information provided.
- No weather information is known beyond the 1-hour forecast lead time. For example, no 2- or 4-hour forecast information is available in the scenarios.
- The 1-hour forecast is updated every minute. This creates a rolling 1-hour forecast.
- There are no flight cancellations and no diversions to alternate airports. All aircraft are held or rerouted until they reach their destination.
- Aircraft are willing to accept an airborne or ground hold of up to 15 minutes before electing to reroute. This causes flights to delay implementing reroutes to avoid weather until they know the weather will last at least 15 minutes from their estimated time of arrival at an approach fix, resulting in an unacceptable duration in holding.
- Pre-departure reroutes utilize existing playbook routes to KATL; strategic reroutes implemented while airborne modified the playbook routes to allow for additional sequencing at the arrival fix. Tactical reroutes were designed to include reasonable flight angles for joining the southwest arrival fix. Detour SIDs were designed to join original flight paths as soon as possible with a reasonably smooth path; departures using RMBLN and GEETK detoured through COKEM to the north, and those using JCKTS and JOGOR detoured through NOVSS to the south

3 Analysis

This section documents the analysis performed for this study with a brief description of the methods employed in Section 3.1 and the analysis results in Section 3.2.

3.1 *Methods of Analysis*

Output from the AirTOp model was collected from files created during the simulations. These included statistics on distance flown, flight duration, fuel burn, holding delay, and take-off delay per flight. The number of flights maneuvered to avoid the weather (forecasted or actual) was also recorded. The output of the 3 Early and 3 Late 1-hour forecast simulation scenarios are compared against that of the Perfect 1-hour forecast scenario in order to determine the potential effects of inaccurate forecast times. Output for the reference scenarios (Nominal, Tactical, and Omniscient) were also studied and displayed on the same graphs as the 7 1-hour forecast scenarios for comparison.

3.2 *Results*

Flight efficiency and maneuver counts were used to quantify the effect of inaccurate forecast times. Individual flight distances, durations, fuel burn, holding delays, and take-off delays were analyzed for both directly and indirectly impacted flights. A flight was considered directly impacted if it was maneuvered to avoid the forecasted or actual weather represented in at least one simulation scenario. There were a total of 128 directly impacted flights across all scenarios: 71 arrivals and 57 departures. A flight was considered indirectly impacted if it reached the initial waypoint of a KATL approach or entered a SID in a time range that extended slightly beyond the time the first and last directly impacted flight reached any IAF or SID. Little indirect effects were observed; noteworthy results for indirectly impacted flights are found in Appendix A.

3.2.1 Count of Flight Maneuvers

Some flights were not able to be maneuvered away from the weather due to their location at the start of the weather. Table 3 lists the number of KATL arrivals and departures that were assumed to fly through gaps in the weather and land or depart normally. In each of the scenarios, these arrival flights were already within the area of the weather (40NM from the northwestern approach fix) and departures were on their SID procedure when the weather started at 17:30Z.

Table 3. Number of KATL Arrival and Departure Flights Assumed to Fly Through Weather Gaps

Scenario	Number of Arrivals	Number of Departures
Nominal	0	0
Omniscient	1	2
Tactical	6	2
Perfect	0	2
Early 5	0	2
Early 15	0	0
Early 30	0	0
Late 5	4	2
Late 15	6	2
Late 30	6	2

Maneuvered flights were assigned different strategic and/or tactical weather avoidance strategies depending on the amount of forecast error represented in the scenario. Figure 6 and Figure 7 display the number of maneuvers of arrival and departure flights, respectively, in each scenario. Maneuvers displayed in green are purely strategic while those in red are tactical. Since all of these flight plan changes require at least one action by ATC, the count of maneuvers was used as an approximation of controller task load. It is assumed that tactical maneuvers would be more intensive to implement than strategic ones due to the immediate action required. Based on this assumption, Figure 6 shows that controller task load in managing arrival flights increases as the forecast timing error increases and that ATC task load is higher when the forecast is early in its predicted onset and cessation times than when it is late. Figure 7 shows a similar trend in increased task load as the forecast timing error increases; however, there is only a slight difference in task load for managing departures when the forecast is late as compared to when it is early, and there are many more tactical maneuvers assigned to departure flights in the Late 30 scenario than any other. This is because many of the affected departure flights in the Late 30 scenario were unexpectedly assigned ground delay and a new SID due to the forecast error. In general, fewer maneuvers were required for departure flights to avoid weather than for arrivals flights.

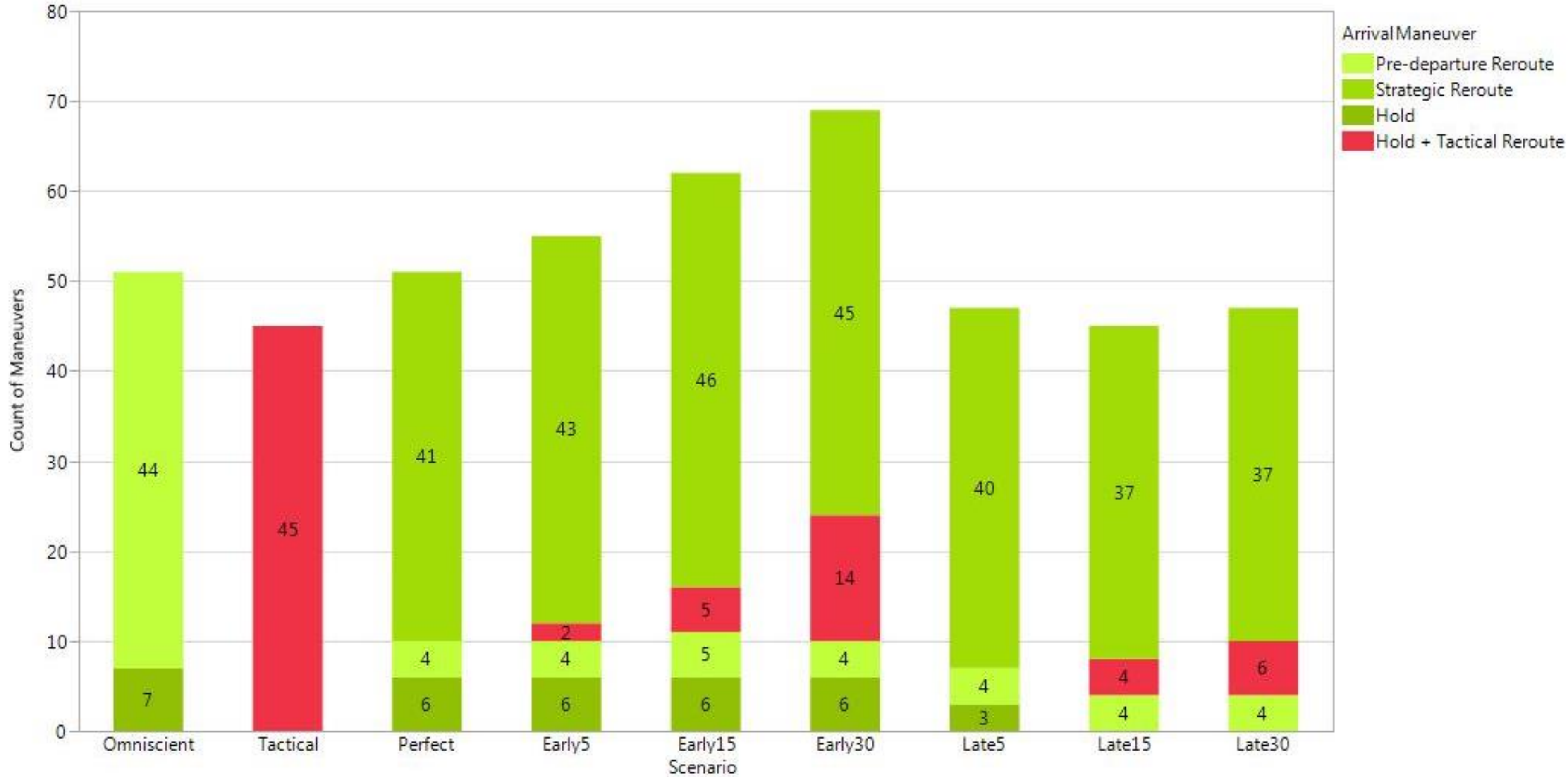

Figure 6. Number of Maneuvers of Arrival Flights by Scenario

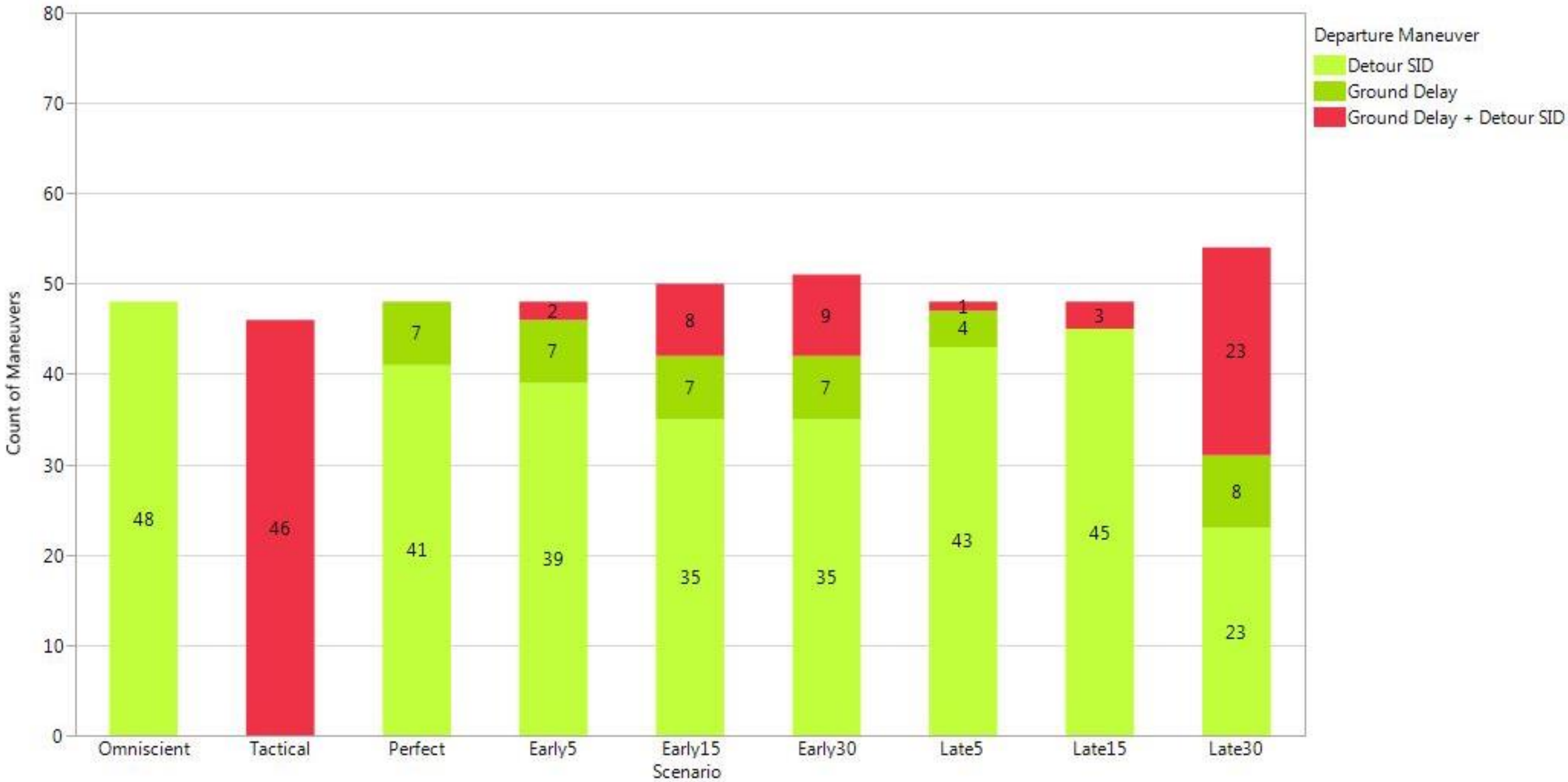

Figure 7. Number of Maneuvers of Departure Flights by Scenario

3.2.2 Effects on Directly Impacted Flights

Flights that were maneuvered to avoid the forecasted or actual weather event in at least one scenario were examined to determine their efficiency given different weather forecast information. Table 4 lists the average total distance, average total duration, and average total fuel burned for these arrival and departure flights in each scenario.

Table 4. Flight Efficiency of Directly Impacted Flights

Scenario	Arrival Flights				Departure Flights			
	Number of Flights	Avg. Total Distance (NM)	Avg. Total Duration (min)	Avg. Fuel Burned (lbs)	Number of Flights	Avg. Total Distance (NM)	Avg. Total Duration (min)	Avg. Fuel Burned (lbs)
Nominal	71	1051.42	148.99	17814.50	57	729.27	104.85	9324.40
Omniscient		1121.00	159.27	18551.13		748.03	108.05	9586.25
Tactical		1137.57	160.28	19102.10		747.88	108.03	9586.25
Perfect		1176.50	166.37	19302.25		746.45	107.77	9556.69
Early 5		1189.94	168.37	19470.36		746.34	107.75	9555.31
Early 15		1211.32	171.45	19769.51		747.21	107.90	9569.87
Early 30		1243.08	176.28	20180.38		747.87	108.01	9581.09
Late 5		1168.36	165.32	19138.40		747.17	107.89	9573.32
Late 15		1167.26	165.16	19281.76		748.06	108.05	9586.17
Late 30		1167.22	165.33	19323.07		747.67	108.00	9580.94

To determine the effect of inaccurate forecast times, these average flight efficiency metrics were displayed on a number line for comparison. Figure 8 shows the average distance flown for directly impacted flights in each scenario; Figure 9 includes the average duration for the same flights in each scenario, and Figure 10 shows their average fuel burn in each scenario. Since there is little variance between scenarios for departure flights, figures showing flight efficiency values are displayed with arrival and departure flights combined. Appendix B contains individual graphs for arrival and departure flights.

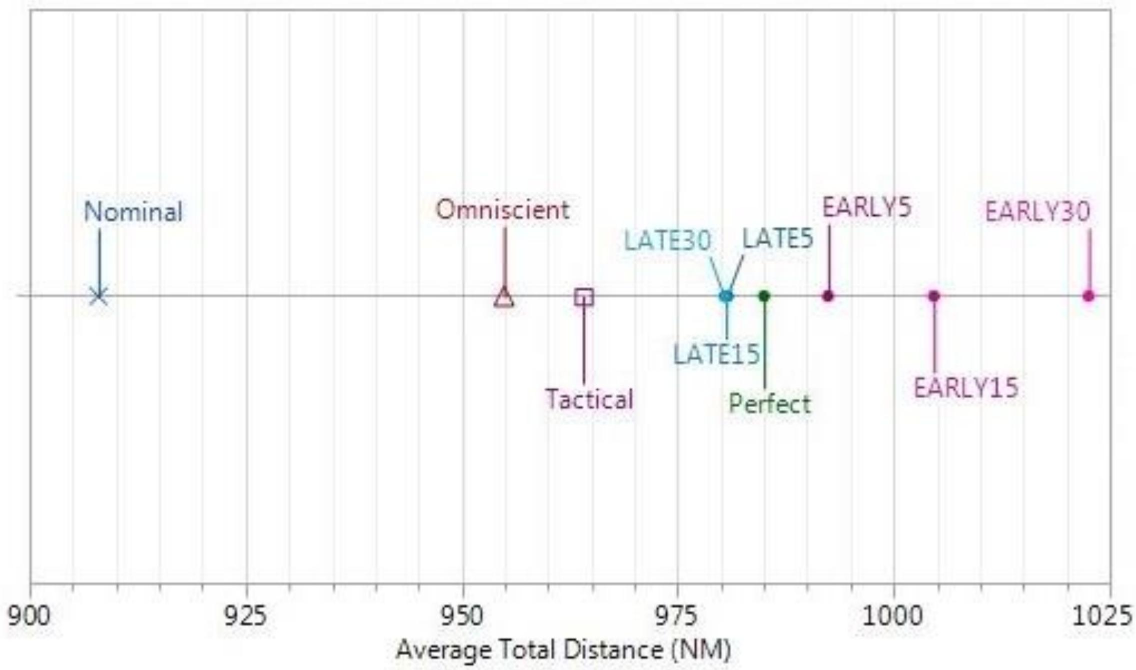

Figure 8. Average Total Distance (NM) for Directly Impacted Flights by Scenario

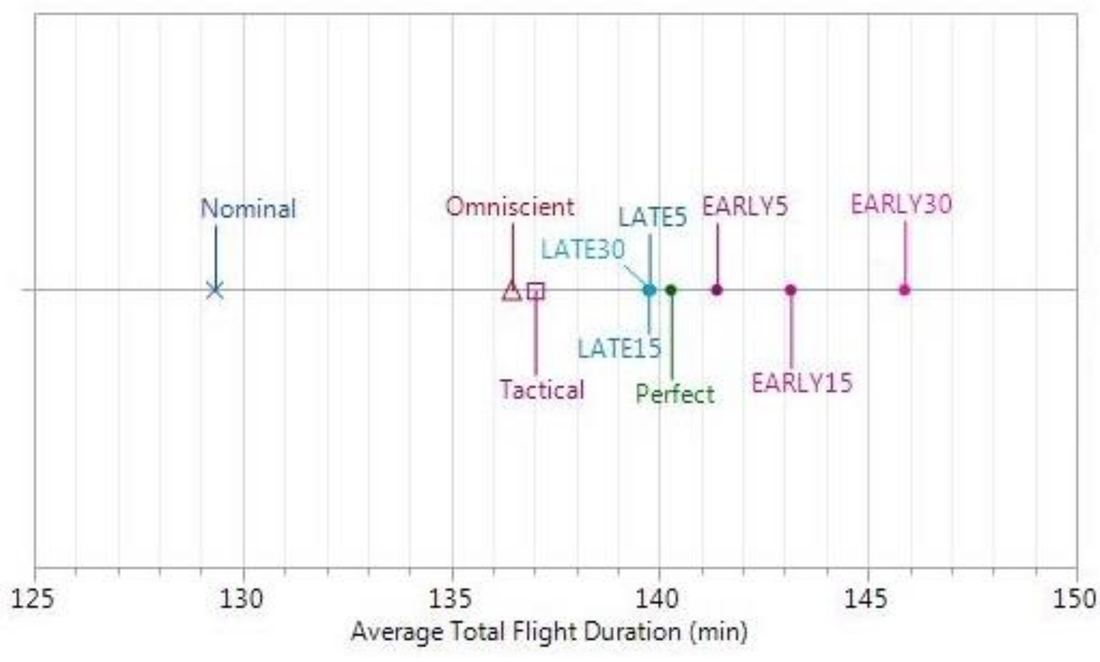

Figure 9. Average Total Flight Duration (min) for Directly Impacted Flights by Scenario

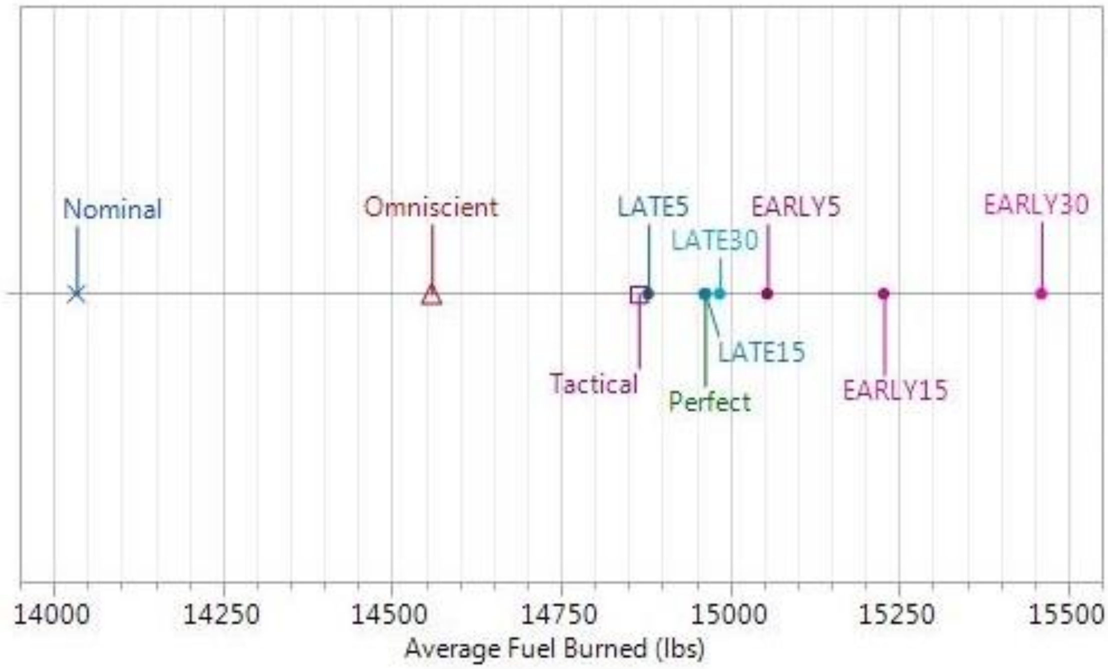

Figure 10. Average Total Fuel Burn (lbs) for Directly Impacted Flights by Scenario

When comparing maneuvered flights across the three reference scenarios, flights were most efficient when there was no weather constraint in the Nominal scenario. When weather was present, an infinite knowledge of the weather as represented in the Omniscient scenario yielded the most efficient flight maneuvers to avoid weather. Purely tactical weather avoidance in the Tactical scenario unexpectedly resulted in more efficient arrival flights than in the 1-hour forecast scenarios. This was because arrival flights traveled their normal, efficient flight path until they were only 40NM from their destination at KATL. Thus, the difference in traveling the extra distance when strategically rerouting farther from KATL was offset by staying on the initial, more efficient flight path for a longer duration.

Departure flights at KATL that were directly impacted in the forecast scenarios were approximately as efficient as those in the Perfect forecast scenario. For example, differences in average total distance ranged from -.11 NM or .01% in the Early 5 scenario to 1.61 NM or .22% in the Late 15 scenario. This small difference in departure efficiency between each scenario can be attributed to ATC being able to adjust departures more efficiently on the ground. Arrivals that were directly impacted in the early forecast scenarios were less efficient than in the Perfect forecast scenario (for example, 13.43 NM or 1.14% added average distance flown in Early 5 scenario, 34.81 NM or 2.96% in Early 15 scenario, and 66.57 NM or 5.66% in the Early 30 scenario). Arrivals were only slightly more efficient in the late forecast scenarios than in the Perfect forecast scenario (differences in average distance flown ranged from -8.15 NM or .69% in Late 5 to -9.28 NM or .79% in Late 30). This is likely because less arrival flights were maneuvered when the forecast was late in its prediction than when it was perfect or early (see Figure 6 above).

A key factor in the changes to total flight duration is time spent in an airborne hold; Table 5 lists the number of directly impacted arrival flights that held in each scenario as well as the time spent in holding. In the Nominal scenario, 9 of the directly impacted arrival flights were held to maintain ATC separation requirements; weather did not cause these flights to be held in this scenario. For all other scenarios, flights could have held outside the weather or prior to arrival at the southwest or northeast approach routes.

Table 5. Airborne Holding of Directly Impacted Arrival Flights

Scenario	Number of Flights	Percent of Directly Impacted Arrival Flights	Avg. Airborne Holding Duration	Standard Deviation	Total Airborne Holding Duration
Nominal	9	12.7%	0:02:46	0:00:49	0:24:51
Omniscient	16	22.5%	0:06:52	0:06:23	1:49:47
Tactical	50	70.4%	0:06:42	0:02:18	5:34:50
Perfect	13	18.3%	0:07:23	0:05:32	1:35:57
Early 5	12	16.9%	0:10:23	0:06:38	2:04:30
Early 15	23	32.4%	0:09:05	0:06:01	3:29:00
Early 30	46	64.8%	0:10:16	0:05:46	7:52:21
Late 5	14	19.7%	0:04:32	0:03:21	1:03:30
Late 15	16	22.5%	0:04:17	0:02:11	1:08:35
Late 30	17	23.9%	0:04:48	0:02:20	1:21:29

Directly impacted arrival flights that held in the Omniscient scenario did so because it was more efficient than flying a different flight path to KATL. This may explain why more flights held in the Omniscient scenario than in the Perfect forecast scenario where decisions to reroute or hold were made based solely on time. This is supported by the larger average duration in holding for the Perfect scenario. All directly affected flights in the Tactical scenario held outside the weather for approximately 5 minutes before being rerouted to the southwest approach route. More flights held at the end of the forecasted weather in the Early scenarios because the weather blocked their route for 5, 15 or 30 minutes longer than expected. The opposite is true at the end of the Late forecasts; arrival flights held for 10 minutes in the Late 5 scenario since the weather ended 5 minutes earlier than expected, and none held at the end of the Late 15 or Late 30 scenarios because the weather ended before they could begin their planned holds. However, more arrival flights held at the start of the Late forecasts than at the start of the Early forecasts because they incorrectly expected, based on the forecast, that their approach path would be clear. Holds at the start of the forecasts lasted 5 minutes before the flights tactically rerouted to a new approach route, whereas holds at the end of the forecasts lasted 15 minutes. This caused the average duration in holding to be higher in the Early scenarios than in the Late scenarios.

Similar to airborne holding delay, ground delay was directly imposed on departures as either a planned delay at the end of the weather forecast or an unplanned delay before rerouting flights to a detour SID. No ground delay was imposed on departure flights in the Nominal scenario since there was no weather to avoid; none was imposed in the Omniscient scenario because all affected departures took planned detours to other SIDs. However, all flights departing from KATL during the weather in the Tactical scenario received a 5 minute ground delay to represent the time for ATC to communicate a new detour SID to the pilot. Table 6 lists the number of impacted departure flights and the ground delay for those flights.

Table 6. Ground Delay of Directly Impacted Departure Flights

Scenario	Count	Percent of Directly Impacted Departure Flights	Avg. Ground Delay	Standard Deviation	Total Ground Delay
Nominal	0	0	0:00:00	0:00:00	0:00:00
Omniscient	0	0	0:00:00	0:00:00	0:00:00
Tactical	46	80.7%	0:05:00	0:00:00	3:50:00
Perfect	7	12.3%	0:07:17	0:05:13	0:51:00
Early 5	9	15.8%	0:10:07	0:07:12	1:31:00
Early 15	15	26.3%	0:14:04	0:07:24	3:31:00
Early 30	16	28.1%	0:14:26	0:07:18	3:51:00
Late 5	5	8.8%	0:03:48	0:02:35	0:19:00
Late 15	3	5.3%	0:05:00	0:00:00	0:15:00
Late 30	31	54.4%	0:05:00	0:00:00	2:35:00

When the forecast perfectly predicted the onset and cessation of the weather in the Perfect scenario, only affected departure flights taking off from KATL during the last 15 minutes of the weather received a planned ground delay instead of detouring to a new SID. In the Early forecast scenarios, departure flights plan to hold on the ground for a maximum of 15 minutes while waiting for the weather to clear, but the weather is blocked for an additional 5, 15, or 30 minutes depending on the scenario. As a result, some departure flights in the early scenarios held on the ground for 20 minutes (15 minutes of waiting and 5 minutes of communication delay) before taking a detour to a new SID. In contrast, departure flights that planned to wait up to 15 minutes for weather to clear in the late forecast scenarios did not have to hold as long as expected. In fact, some flights in the Late 15 and Late 30 scenarios planned to take a less efficient detour SID but took a 5 minute communication delay and were rerouted back to their original SID before their departure. This caused more flights to hold on the ground and for longer durations in the Early forecast scenarios than in the Late forecast scenarios.

3.2.3 Flight Examples

Flights examples are provided in order to demonstrate the effect of different prediction timing on the Nominal path of a flight. The paths of one arrival flight simulated in 4 different scenarios are presented in the first example while the simulated path of a departure flight in two different scenarios is presented in the second example.

Solid lines represent the simulated path of the flight in a given scenario, while dotted lines link descriptive text to each relevant object.

3.2.3.1 Arrival Example

Figure 11 depicts the end-to-end paths of a single flight traveling from KCID (Eastern Iowa Airport) to KATL in 4 different scenarios: Nominal (blue), Omniscient (green), Perfect (black), and Early30 (red). These paths represent the following interventions as described in Table 7, and the simulated flight paths are described below and depicted in greater detail in Figure 2 to Figure 4.

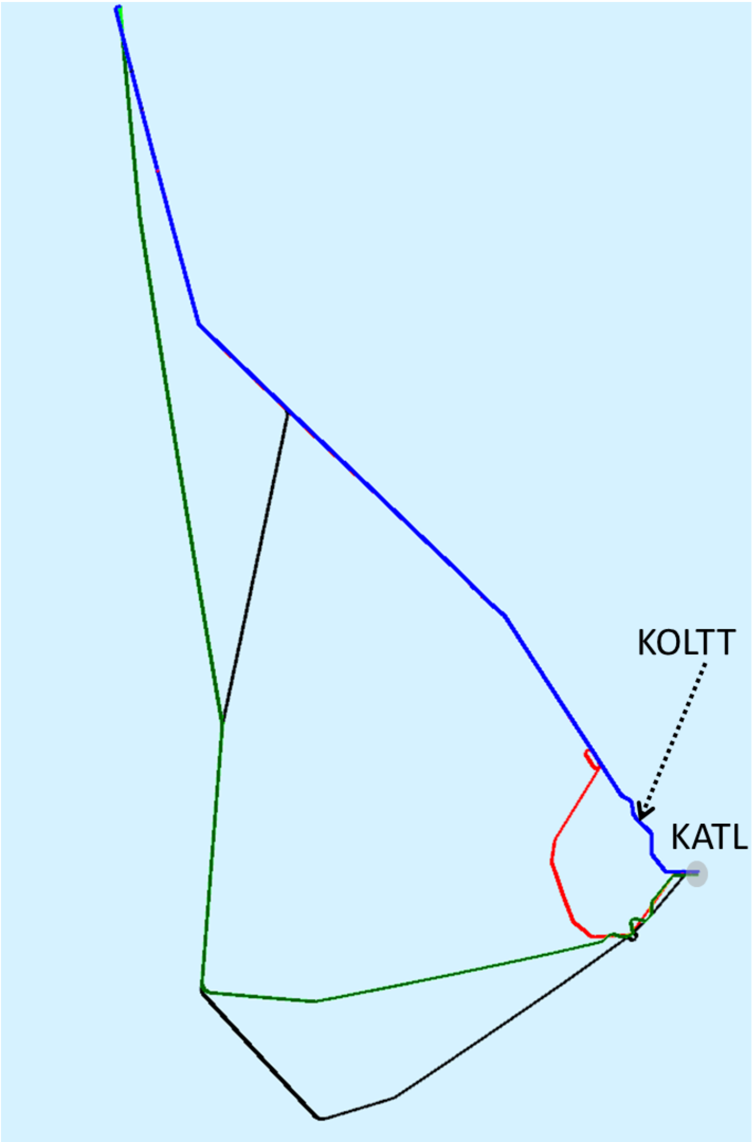

Figure 11. End to end view of simulated flight traveling from KCID to KATL in 4 different scenarios

Table 7. Description of Simulated Flight Paths of One Arrival Flight Example in 4 Scenarios

Scenario	Description	Maneuver
Nominal	No weather is modeled, so the flight travels along its originally filed flight plan without any intervention.	N/A
Omniscient	Weather is perfectly predicted with sufficient lead time. A ground-based reroute to the IAF WARRR is performed prior to the departure.	Ground-based reroute
Perfect	Weather is accurately predicted with a one hour lead time. A reroute to the IAF WARRR occurs 45 minutes prior to expected arrival at KOLTT.	Stragetic reroute
Early30	Weather is incorrectly predicted to end early, also with a one hour lead time. The flight must be tactically rerouted to the IAF WARRR.	15 minute hold and then tactical reroute

In Figure 12, the early stages of the flight are presented. The “no weather” path (blue) begins by heading south-southeast and then continues southeast into the northwest IAF, KOLTT. The strategic path (black, hidden) is identical to the “no weather” path until the reroute occurs and the flight heads south-southwest (visible), while the tactical path (red, hidden) continues to overlap with the “no weather” path. The omniscient path (green) proceeds from KCID in a south-southeastern direction.

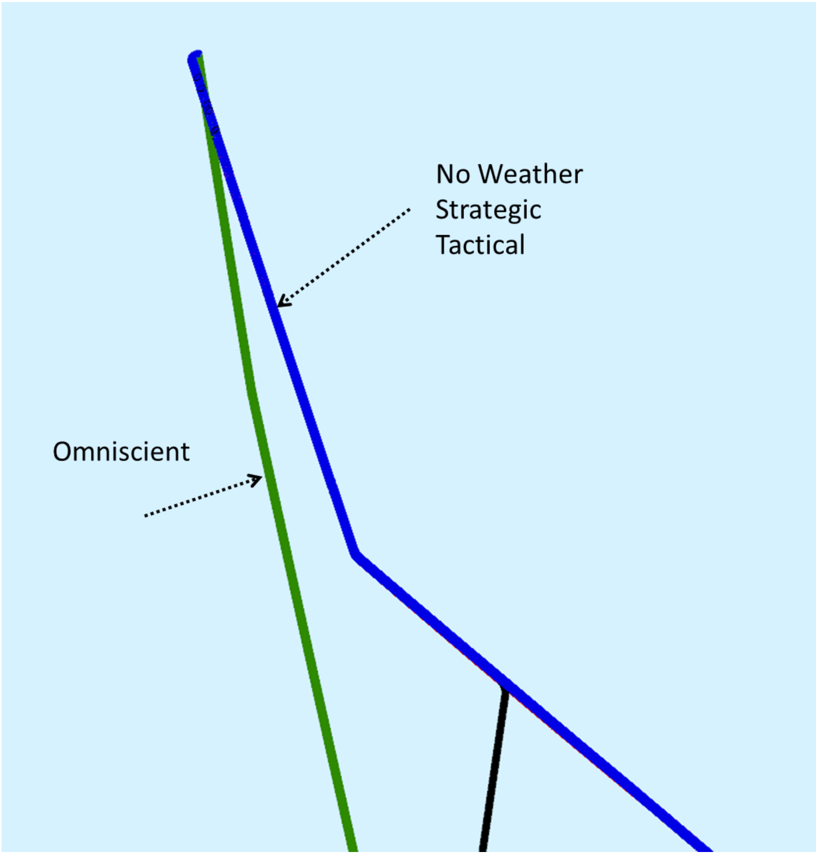

Figure 12. Initial Simulated Track of Arrival Flight Example from Nominal (“No Weather”), Strategic, Tactical, and Omniscient Scenarios. “No weather,” strategic, and tactical initially overlap, and the strategic path eventually deviates south southwest.

Figure 13 depicts the paths as they approach KATL, either circumventing the blocked arrival and heading to the southwestern arrival (WARRR) or heading to the original northwestern arrival (KOLTT) as in the "no weather" scenario. An elliptical hold in the tactical (red) path is seen just prior to KOLTT, followed by a reroute around the affected region to the southwestern IAF. The strategic (black) path bears south-southwest, merging with the omniscient (green) path and then the two paths split; the omniscient path turns almost directly east into the arrival stream for WARRR, while the strategic path takes a more circuitous route southeast, east, and then east-northeast into WARRR. This more circuitous route allows for greater flexibility in sequencing a flight that was recently rerouted.

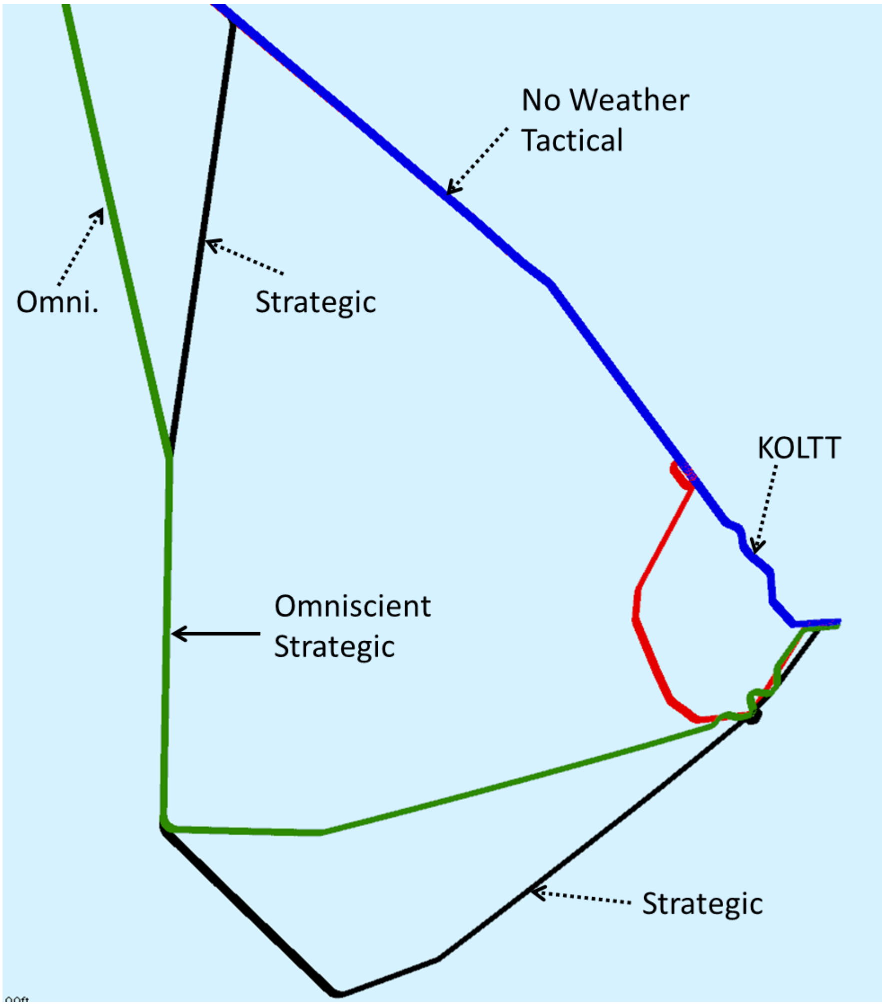

Figure 13. Middle of Simulated Track of Arrival Flight Example from Nominal ("No Weather"), Strategic, Tactical, and Omniscient Scenarios.. "No weather" and tactical continue southeast; Omniscient and strategic paths merge and then diverge.

In Figure 14, a closer view of the KOLTT and WARRR arrivals is presented. The nominal (blue) path passes through KOLTT and lands at KATL. The tactical (red) path is easier to see, as is the reroute toward WARRR. The omniscient (green) and strategic (black) paths also merge at WARRR. Note that attempts at sequencing and vectoring (wavelike curves in the path) are evident in the "no weather" and omniscient paths while a circular hold at the southwest arrival fix WARRR is evident in the strategic path.

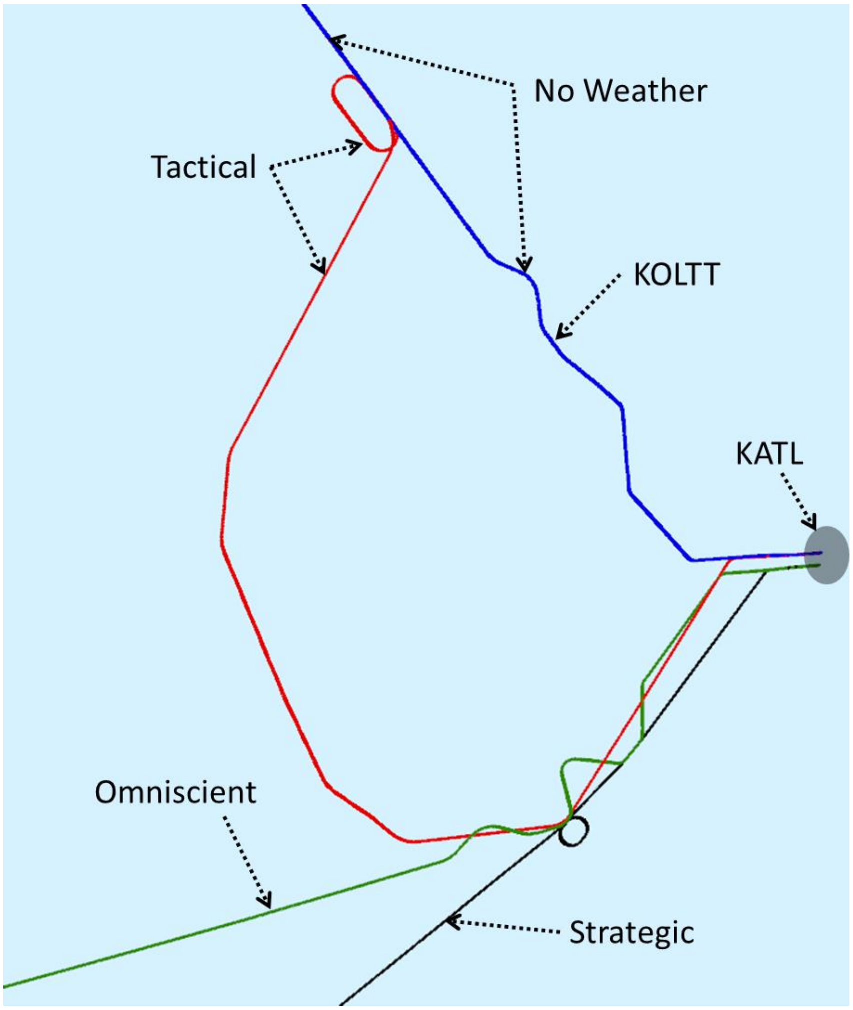

Figure 14. End of Simulated Track of Arrival Flight Example from Nominal ("No Weather"), Strategic, Tactical, and Omniscient Scenarios. Omniscient and strategic paths merge at the southwest arrival fix WARRR. Holding and path stretching is evident. "No weather" continues to KOLTT and tactical holds then diverges, heading to WARRR.

3.2.3.2 Departure Example

Figure 15 depicts the initial phase of a single flight traveling from KATL to KDFW (Dallas Fort Worth International Airport) in two different scenarios: Nominal (blue, "no weather") and Perfect (red, detour). The no weather (northern) path makes use of JOGOR, the southernmost SID on the western side of KATL The SID itself passes within 35 NM of WARRR, the northwestern IAF that is blocked by weather. When weather is predicted to be in that area any departures from KATL through any of western SIDs must detour to either a northern (COKEM) or southern (NOVSS) SID. In the perfect scenario, weather forces this flight to take the detour south through NOVSS, rejoining the original route at a convenient merge point southwest of KATL.

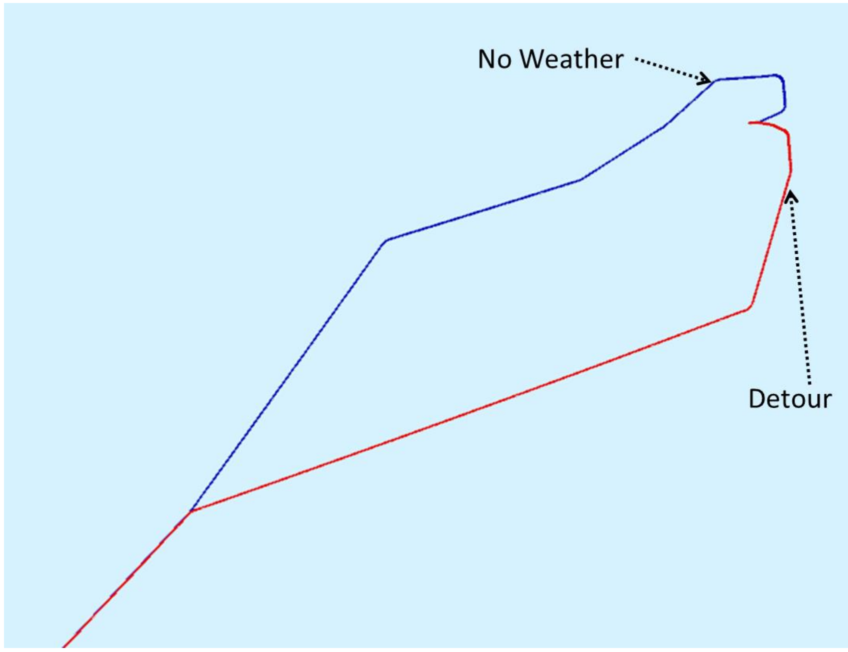

Figure 15. Initial Simulated Track of Departure Flight Example. The "no weather" path tracks north then west, turning southwest approximately 35 NM inside of KOLTT. The "detour" path tracks south then west, avoiding the area surrounding KOLTT.

4 Summary

The following sub-sections summarize the results of this study by describing the conclusions in Section 4.1 and recommendations for future work in Section 4.2.

4.1 *Conclusions*

This study focused on researching the effects of timing error in a 1-hour convective weather forecast for the terminal area, and results shown in Section 3.2 can be used by the FAA's Policy and Requirements Branch to determine appropriate requirements for the accuracy of convective weather forecasting products. While the TRWG set an initial requirement that a 1-hour convective weather forecast must predict the onset and cessation of a weather event with no more than 5 minutes of inaccuracy, timing errors of ±5, ±15, and ±30 minutes were simulated and analyzed to quantify their effects on arrival and departure flights at KATL.

Three scenarios were simulated to establish a frame of reference for comparing the effects of the inaccurate forecasts. First, a Nominal scenario was run with no weather constraints; flights were most efficient in this scenario. Next, infinite knowledge of the weather was represented in the Omniscient scenario; flights in this scenario were expected to be maneuvered as strategically as possible when weather was present. Finally, purely tactical weather avoidance strategies were used in the Tactical scenario. Unexpectedly, flights flew less distance, less duration, and burned less fuel in the Tactical scenario than in the Omniscient. It was more efficient for flights to travel their original route to KATL before holding for 5 minutes and rerouting to the southwestern approach than for them to take an established playbook route that was assigned pre-departure. However, flights spent more time holding in the air and on the ground and more unplanned maneuvers were required by ATC in the Tactical scenario. These unplanned maneuvers require a greater workload and more complex and immediate intervention by the ATC and may be undesirable for this reason. Thus, a lack of forecast information is not beneficial for the NAS in spite of some metrics indicating otherwise.

Seven 1-hour forecasts with varying timing accuracy were simulated. One (Perfect) simulation scenario was conducted to represent a weather forecast with 0 timing errors; the onset and cessation time of the weather is perfectly predicted in this scenario. Then, 3 Early forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes earlier than the actual weather, and 3 Late forecast scenarios were run to simulate forecasts that predicted the onset and cessation times to be 5, 15, or 30 minutes later than the actual weather start and end times. Output from the Early and Late forecast scenarios were compared to output from the perfect forecast scenario to quantify effects of timing errors on KATL flights.

In general, more maneuvers were required and flight efficiency was decreased as the forecast timing error increased. One exception was between the Late 5 and Late 15 forecasts; less weather avoidance maneuvers were needed in the Late 15 scenario because planned airborne and ground holds at the end of the forecasted weather were cancelled once the weather was clear. Also, arrival flights experienced greater impacts than departure flights. This is largely because departure flights were able to wait on the ground until the weather cleared without incurring additional flight time, distance, or fuel burn; also, the detour SIDs resulted in marginal degradation to the efficiency metrics while reroutes for arrival flights impacted the efficiency much more.

Results showed that early forecasts caused more disruption to the NAS than late forecasts. ATC was required to implement more weather avoidance maneuvers when the forecast was early in its prediction than when it was late, and flights flew longer distances, greater durations, burned more fuel, and spent more time in holding when the forecast was early. The TRWG did not specify different requirements for late or early timing errors. However, the difference in impact between early and late forecasts is significant; separate requirements for accuracy may not be necessary if they are defined to capture the effects caused by early forecasts.

4.2 *Recommendations for Next Steps*

This study was limited in scope due to time constraints, and further research should be conducted before finalizing requirements for convective weather forecast times in the terminal area. It is highly recommended to study the impacts to the NAS of convective weather forecasts with greater lead times (for example, a 2 or 4-hour forecast) and with a larger variety of timing errors before determining the appropriate accuracy requirement to meet the needs of NextGen. This can be done using at least two different simulation and analysis techniques.

First, a Monte Carlo simulation could be performed to obtain results for hundreds of simulation runs that would capture every possible forecast timing error. In addition to enabling more magnitudes of error to be modeled, a Monte Carlo simulation could also allow different durations of forecast weather to be studied. While more simulations can be conducted using a Monte Carlo technique, the fidelity of the model is significantly less detailed than was used in this study with AirTOp. A second method that could be employed is design of experiments (DOE). Using DOE, a sample of simulation scenarios could be strategically chosen such that their output could be used to create a predictive model that estimates the effects of timing errors that were not simulated.

List of Acronyms

ARSI	Arrival Route Status Impact
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATM	Air Traffic Management
Avg	Average
CATM	Collaborative Air Traffic Management
DOE	Design of Experiments
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
hr	hour
IDRP	Integrated Departure Route Planning
KATL	Hartsfield-Atlanta International Airport
min	minute
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NM	Nautical Miles
NWS	National Weather Service
RNAV	Area Route Navigation
SID	Standard Instrument Departure
SME	Subject Matter Expert
TFM	Traffic Flow Management
TFMS	Traffic Flow Management System
TMI	Traffic Management Initiative
TRACON	Terminal Radar Approach Control
TRWG	Traffic Flow Management Requirements Working Group
ZTL	Atlanta ARTCC
Z	Zulu Time

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Appendix A: Effects on Indirectly Impacted Flights

A flight was included in the analysis of indirect effects if it reached the initial waypoint of its approach or entered a SID at KATL during a specific time interval for each scenario. The start of the time interval is set to be 10 minutes prior to the time that the first directly impacted flight reached any IAF at KATL, while the end of the time interval is set to be 30 minutes after the time that the last directly impacted flight reached any IAF at KATL. The time range for departures is determined in a similar way; 10 minutes prior to when the first directly impacted departure crosses a departure fix (for example, RMBLN or GEETK on the west at KATL until 30 minutes after the last directly impacted departure crosses a departure fix at KATL. Effects were studied across all indirectly impacted flights in these ranges and at each arrival approach and SID; the set of flights studied excluded any directly impacts flights. Data is also grouped by individual approach and SID procedures in order to identify any subsets that may have been impacted to a larger degree than others.

The same analysis was performed for indirect effects as was done for the direct impacts discussed in Section 3 above. Table 8 provides the number of indirectly impacted arrival and departure flights in each scenario as well as their average total distance, total duration, and fuel burned. It is clear that the departure flights chosen for this analysis were not indirectly impacted by the weather in most scenarios; a slight increase in efficiency was seen for 213 departure flights in the Late 30 scenario. Appendix B contains more detailed information on the indirect impacts to departure flights. The remainder of this section will discuss indirect impacts to arrival flights only.

Table 8. Flight Efficiency Metrics for Indirectly Impacted Flights

Scenario	Arrival Flights				Departure Flights			
	Number of Flights	Avg. Total Distance (NM)	Avg. Total Duration (min)	Avg. Fuel Burned (lbs)	Number of Flights	Avg. Total Distance (NM)	Avg. Total Duration (min)	Avg. Fuel Burned (lbs)
Nominal	210	698	105	10968	203	590	87	9345
Omniscient	210	697	104	10982	203	590	87	9345
Tactical	218	690	103	10848	203	590	87	9346
Perfect	214	694	104	10951	203	590	87	9345
Early 5	213	694	104	10964	203	590	87	9345
Early 15	213	696	104	10988	203	590	87	9346
Early 30	210	701	105	11066	203	590	87	9346
Late 5	220	691	104	10846	203	590	87	9346
Late 15	236	680	102	10520	203	590	87	9345
Late 30	236	681	102	10529	213	582	86	9138

Figure 16 through Figure 19 show the average total distance of indirectly impacted arrival flights in each scenario and are separated by the KATL approach route taken by the flight. Appendix B includes similar figures depicting average flight duration and fuel burn for indirectly impacted flights; the three flight efficiency metrics share common trends when comparing across scenarios, therefore, only distance is presented in these figures.

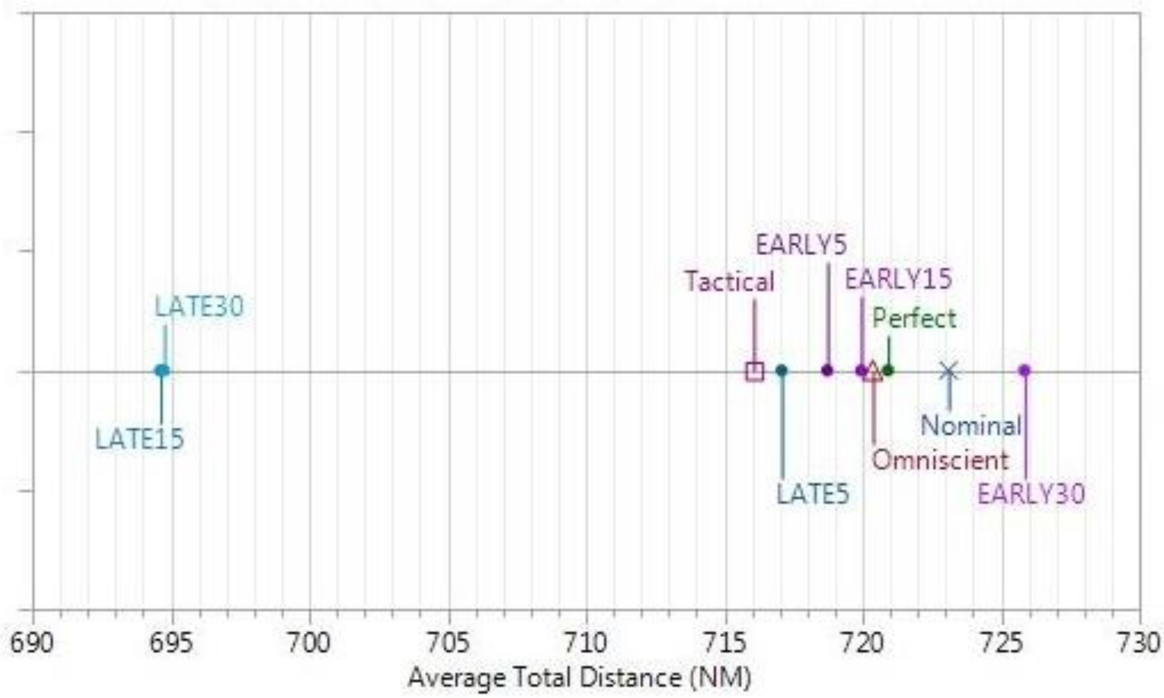

Figure 16. Average Total Distance (NM) for Indirectly Impacted Arrival Flights Using the DIRTY (NE) Approach

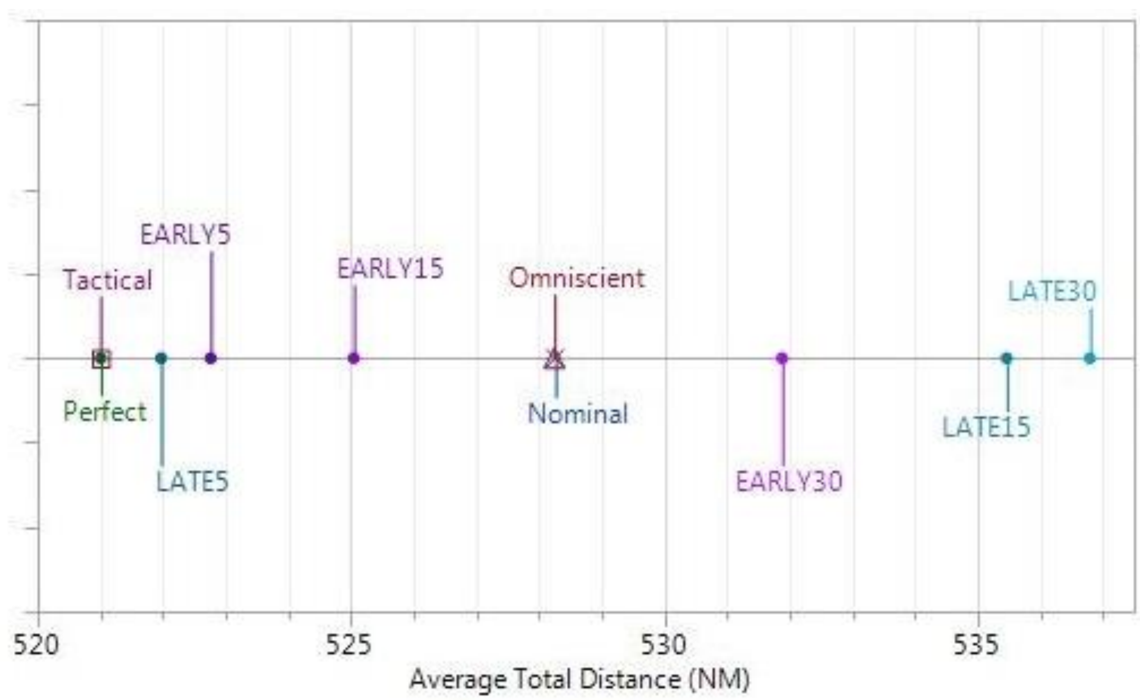

Figure 17. Average Total Distance (NM) for Indirectly Impacted Arrival Flights Using the WARRR (SW) Approach

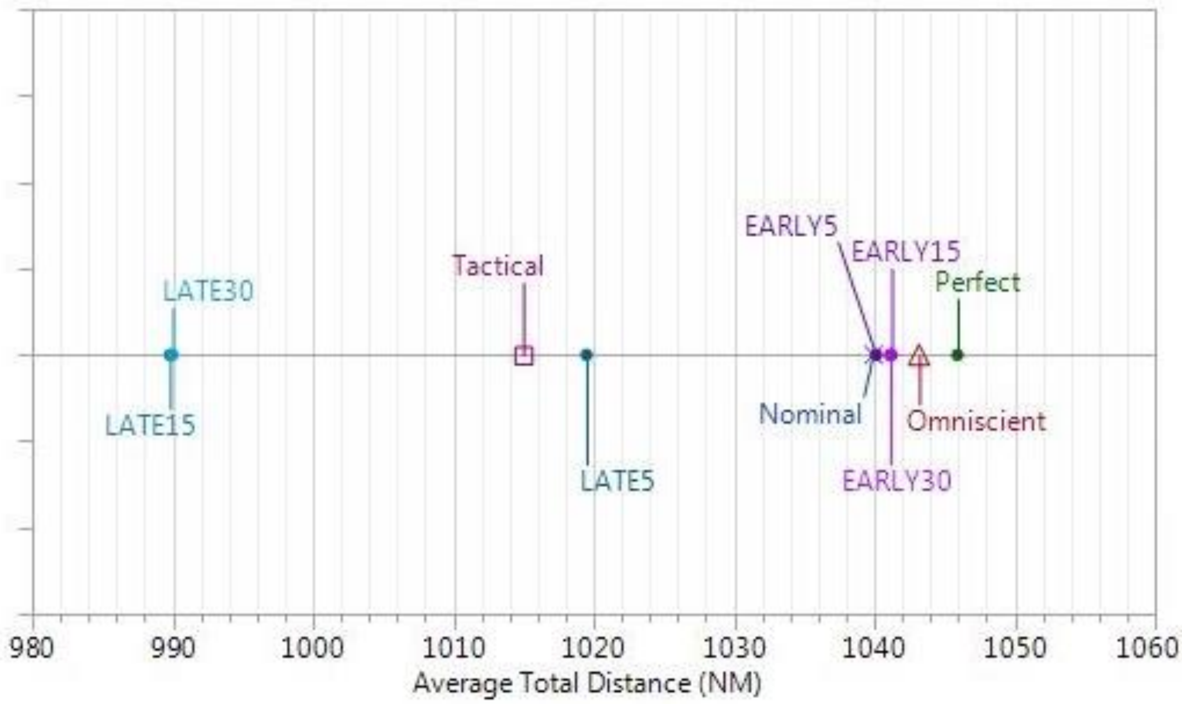

Figure 18. Average Total Distance (NM) for Indirectly Impacted Arrival Flights Using the KOLTT (NW) Approach

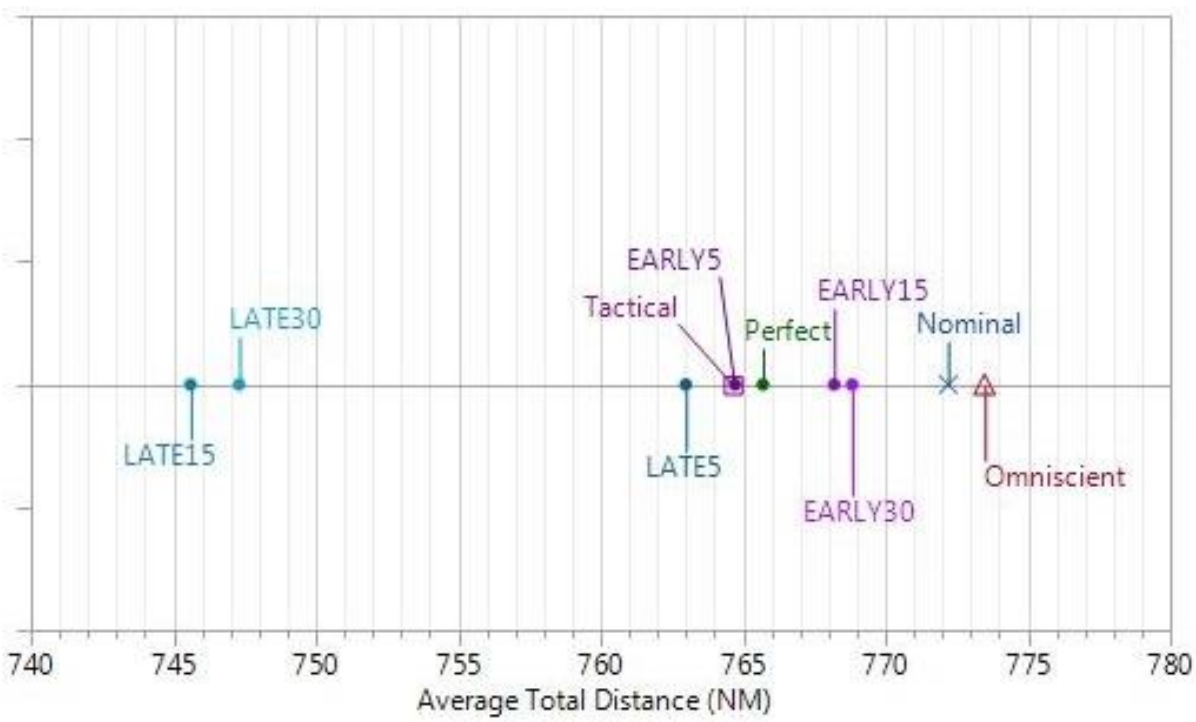

Figure 19. Average Total Distance (NM) for Indirectly Impacted Arrival Flights Using the ONYON (SE) Approach

The indirect impact to airborne hold duration was also studied for arrival flights at KATL due to the weather forecast inaccuracy. As shown in Table 9, there is little change between the three reference scenarios and the Perfect scenario. While the average airborne holding time increases by approximately a minute as the amount of error increases in the Early scenarios, the average amount of holding in the Late scenarios was roughly the same in all three conditions. Figure 20 displays the average airborne holding duration grouped by the approach route used by the indirectly impacted flights in each scenario. Both Table 9 and Figure 20 indicate that the holding duration of indirectly affected arrival flights was not heavily impacted by the actual or forecast weather.

Table 9. Airborne Holding of Indirectly Impacted Arrival Flights

Scenario	Number of Flights	Percent of Indirectly Impacted Arrival Flights	Avg. Airborne Holding Duration	Standard Deviation	Total Airborne Holding Duration
Nominal	20	9.5%	0:02:40	0:01:19	0:53:15
Omniscient	24	11.4%	0:02:40	0:01:12	1:04:02
Tactical	20	9.2%	0:02:40	0:01:19	0:53:15
Perfect	27	12.6%	0:02:37	0:01:21	1:10:29
Early 5	15	7.0%	0:02:25	0:01:35	0:36:11
Early 15	31	14.6%	0:03:21	0:01:54	1:43:39
Early 30	36	17.1%	0:04:39	0:02:33	2:47:18
Late 5	31	14.1%	0:02:26	0:01:16	1:15:36
Late 15	26	11.0%	0:02:17	0:01:11	0:59:13
Late 30	34	14.4%	0:02:31	0:01:13	1:25:32

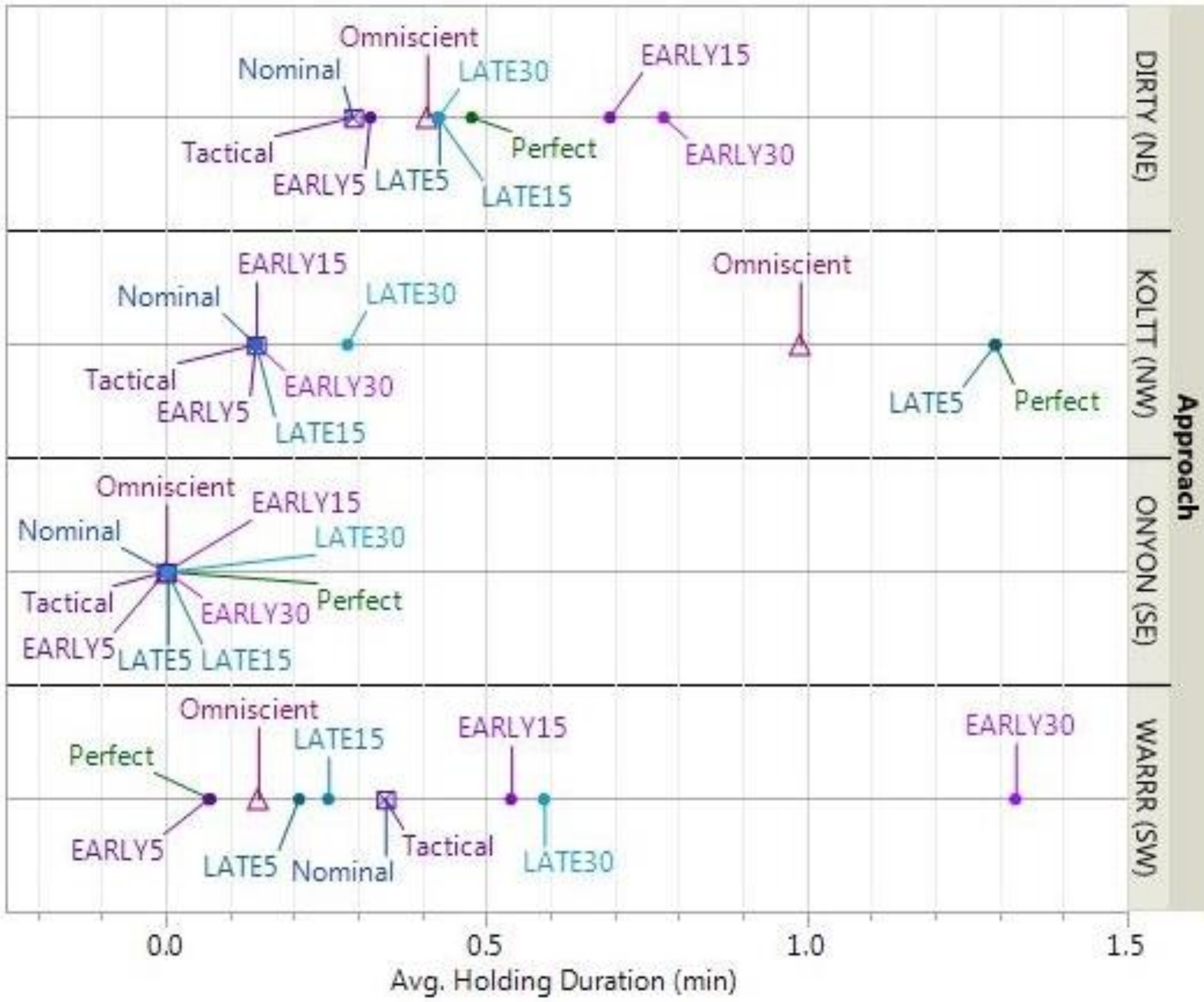

Figure 20. Average Holding Duration (min) of Indirectly Impacted Flights by Approach and Scenario

Appendix B: Additional Graphs

The figures below provide more detailed and additional information on the metrics discussed in Section 3 and Appendix A. Due to the large amount of figures and tables included in this section, a separate itemized list is provided below.

List of Figures in Appendix B

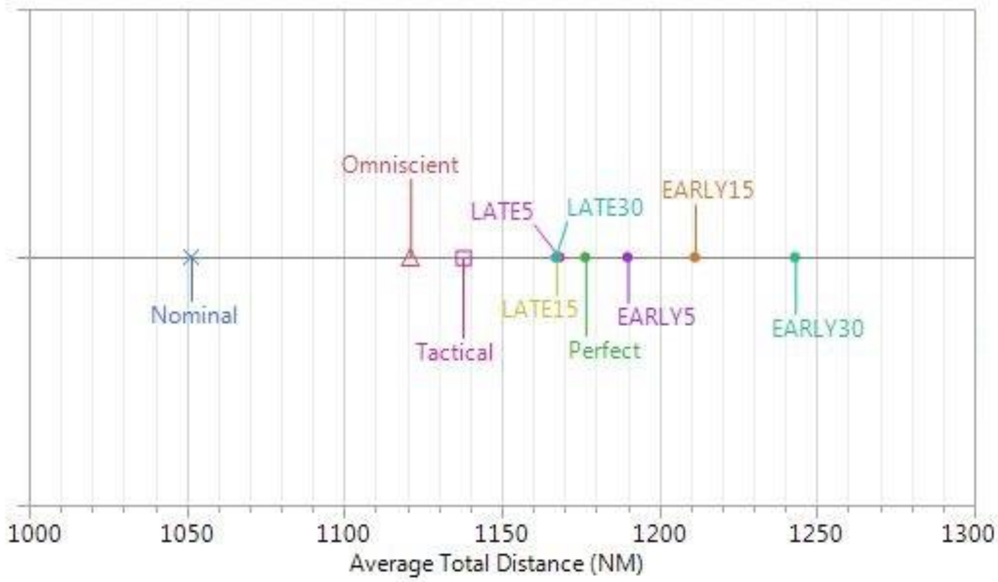

Figure 21. Average Total Distance (NM) for Directly Impacted Arrivals by Scenario

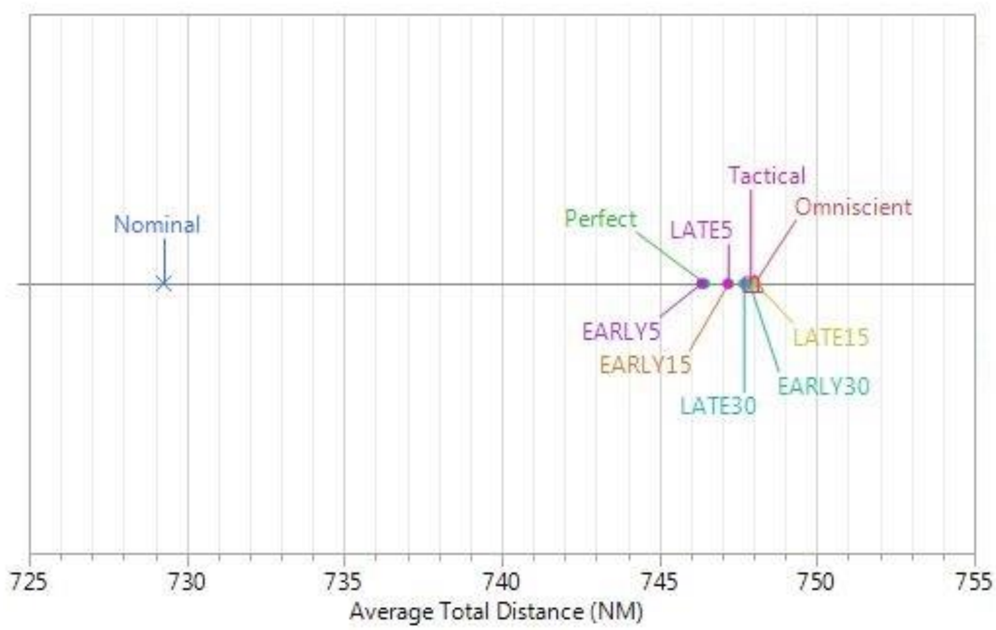

Figure 22. Average Total Distance (NM) for Directly Impacted Departures by Scenario

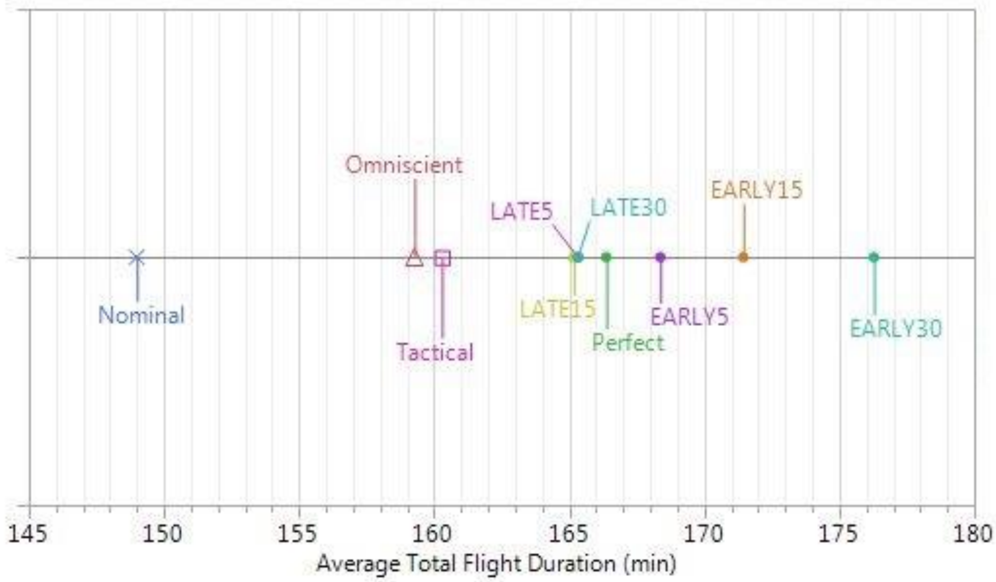

Figure 23. Average Total Duration (min) for Directly Impacted Arrivals by Scenario

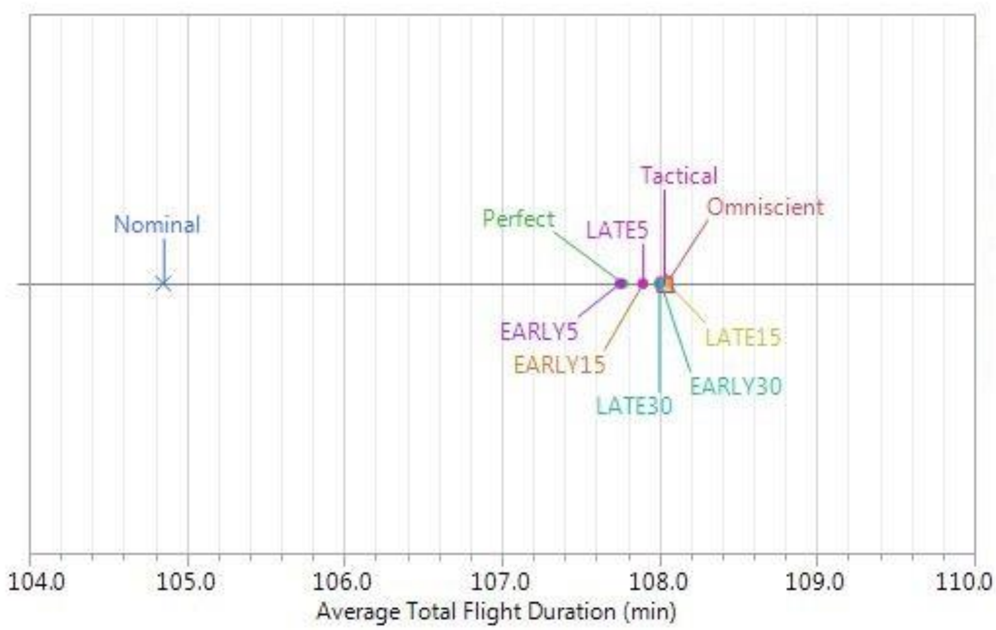

Figure 24. Average Total Duration (min) for Directly Impacted Departures by Scenario

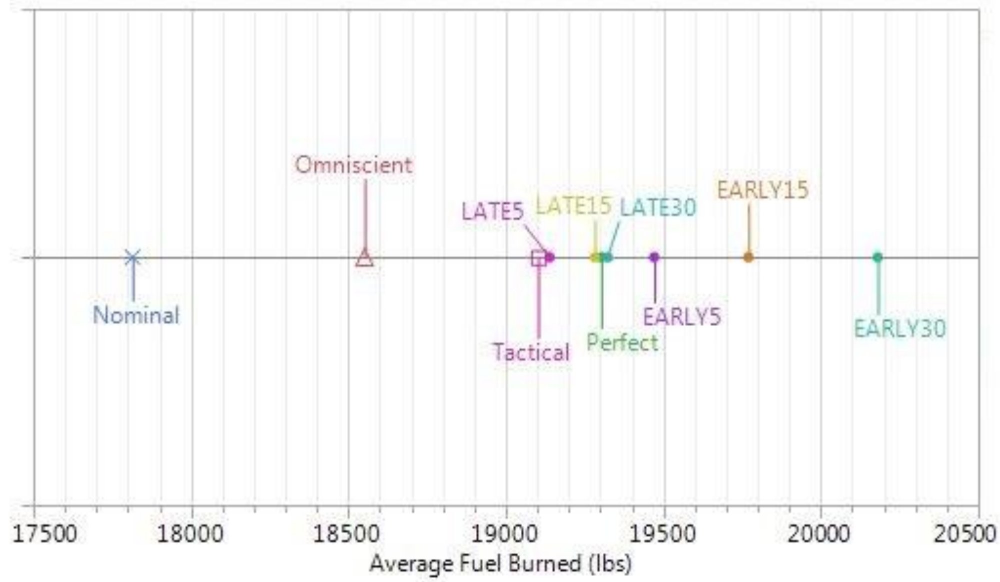

Figure 25. Average Total Fuel Burn (lbs) for Directly Impacted Arrivals by Scenario

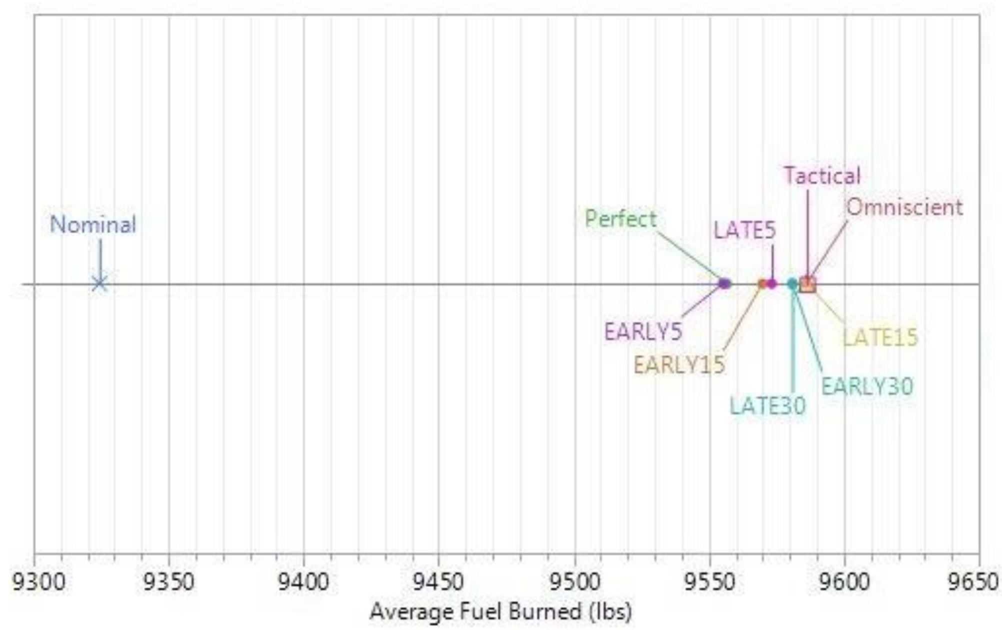

Figure 26. Average Total Fuel Burn (lbs) for Directly Impacted Departures by Scenario

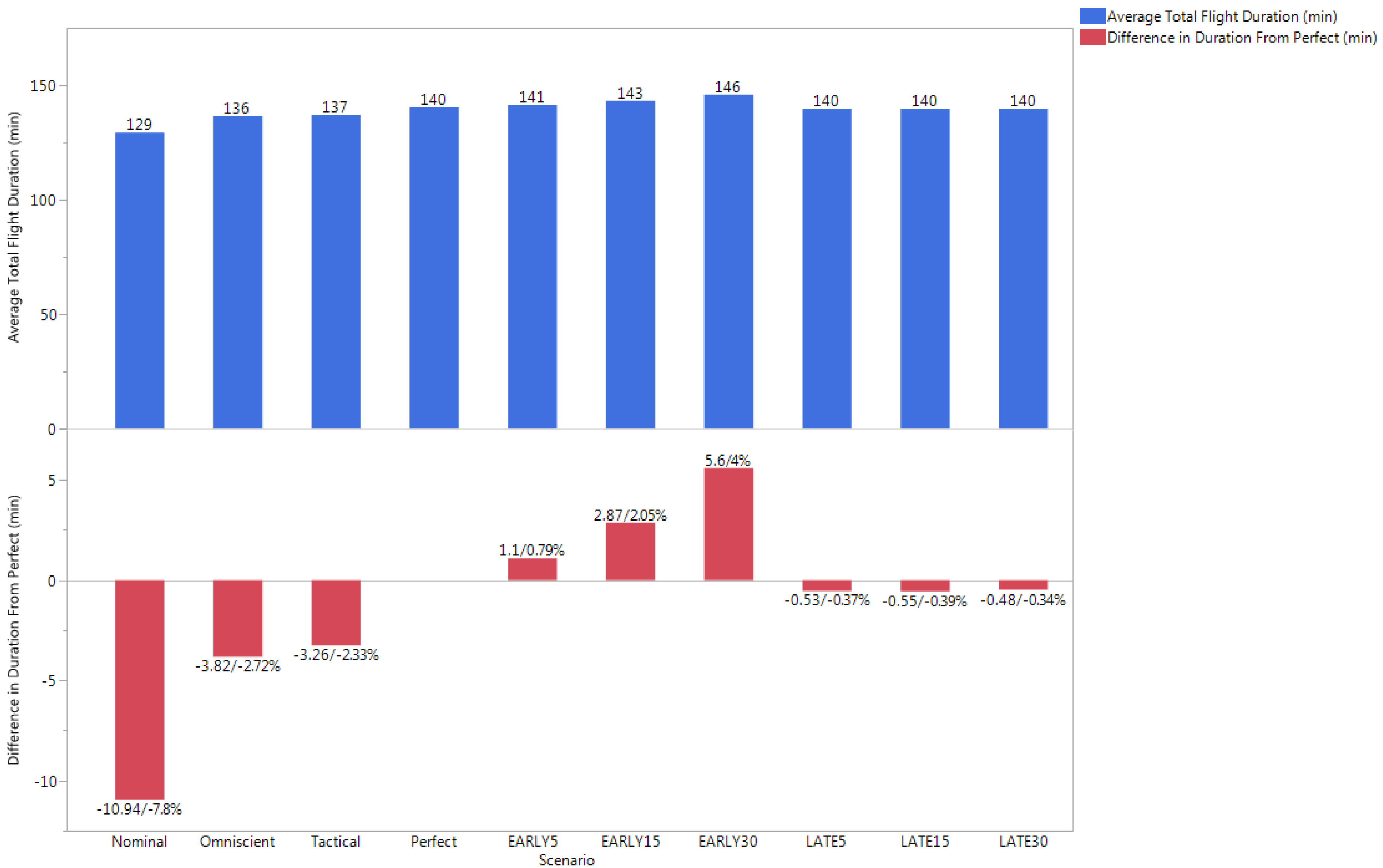

Figure 27: Avg. Change in Flight Duration (min) from Perfect Scenario for All Directly Impacted Flights

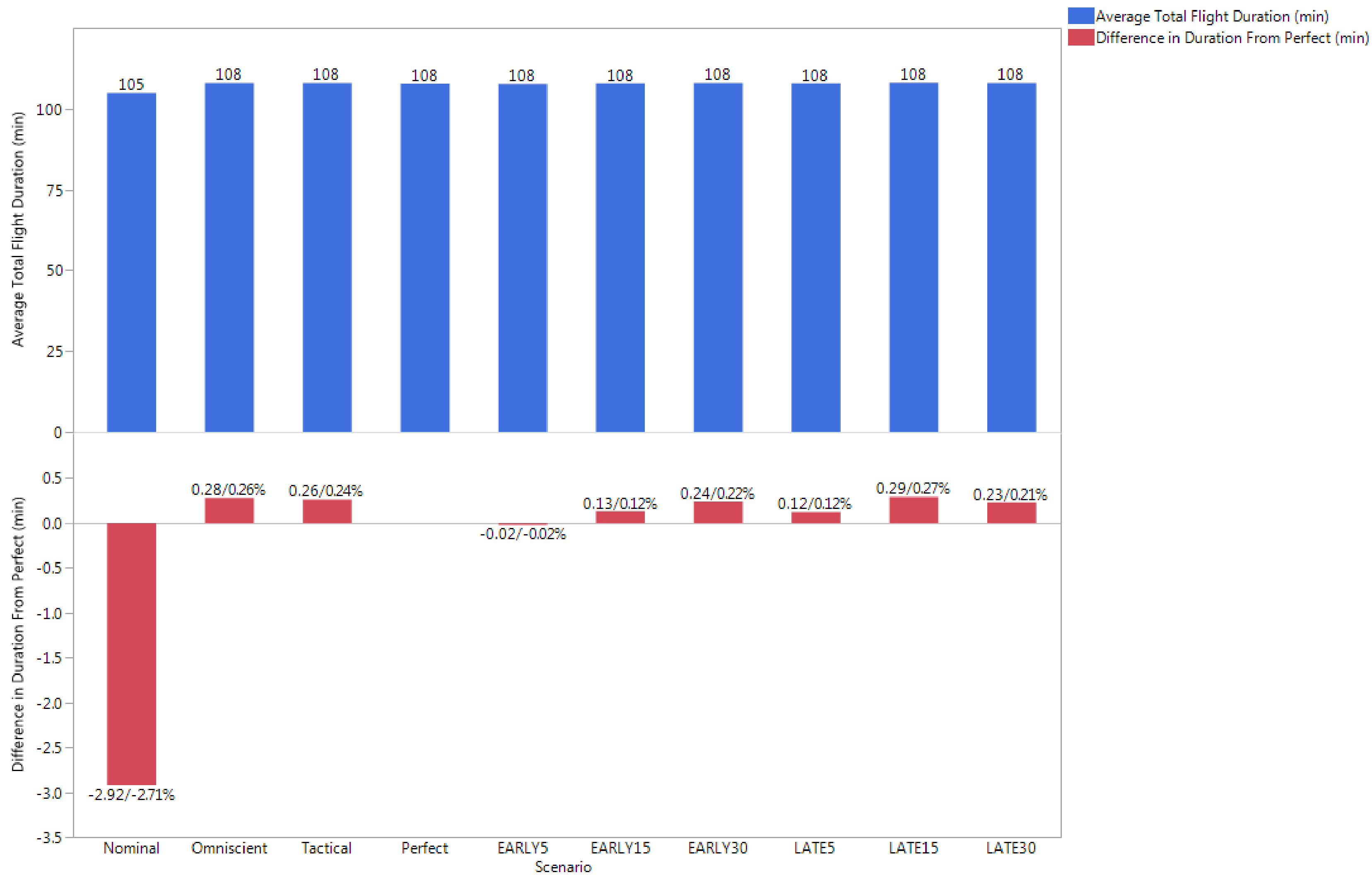

Figure 28: Avg. Change in Flight Duration (min) from Perfect Scenario for Directly Impacted Departures

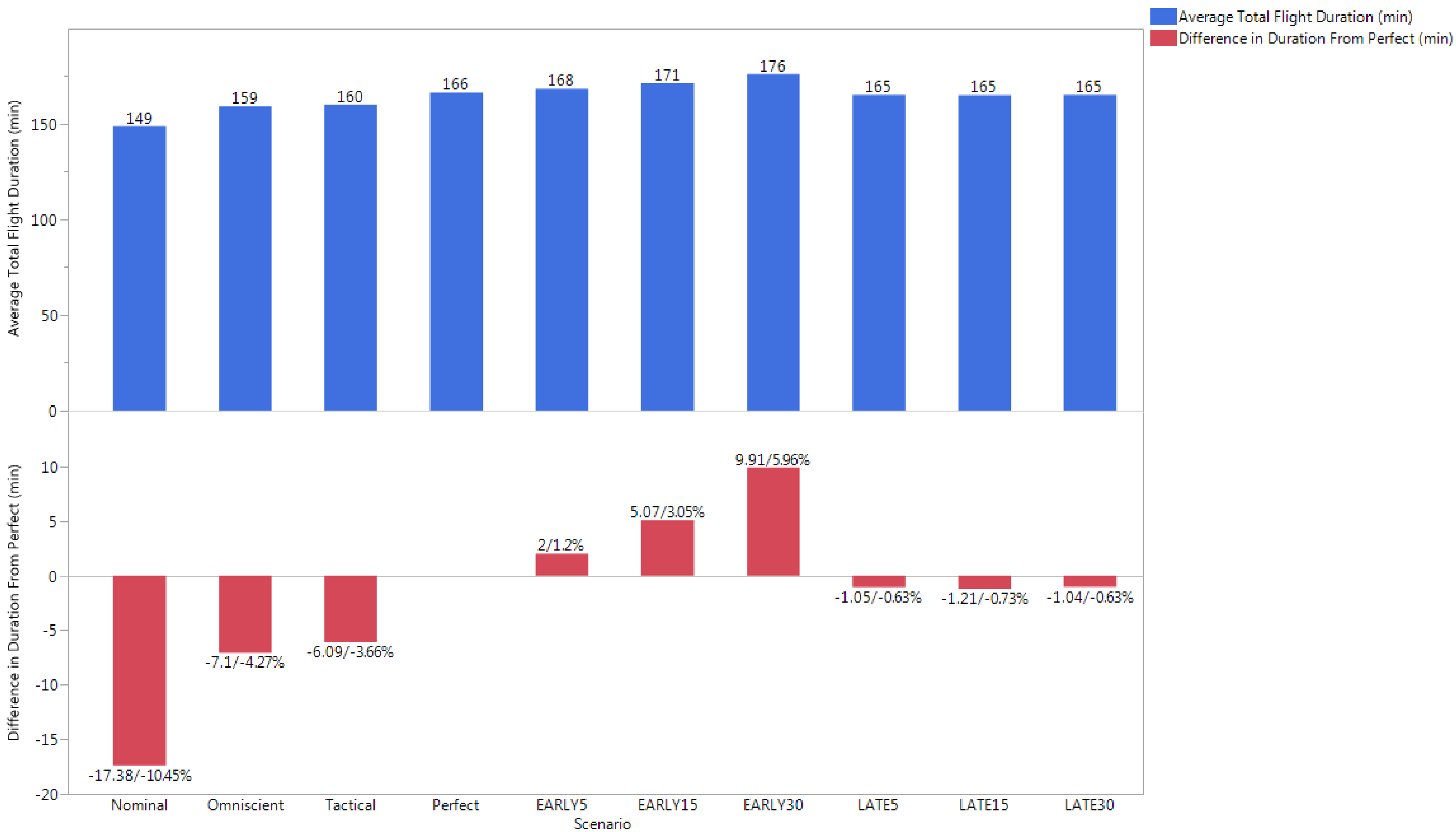

Figure 29: Avg. Change in Flight Duration (min) from Perfect Scenario for Directly Impacted Arrivals

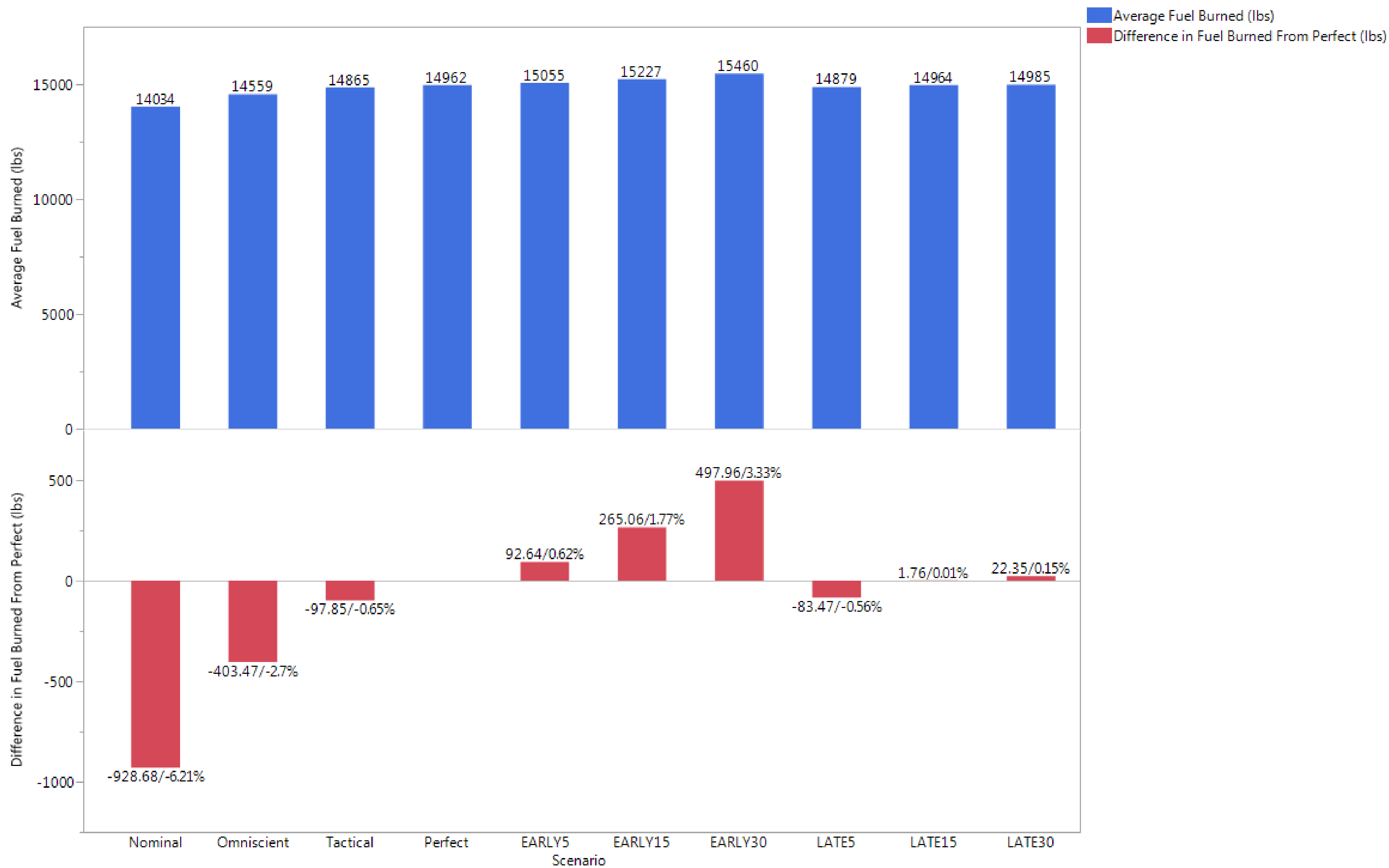

Figure 30: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for All Directly Impacted Flights

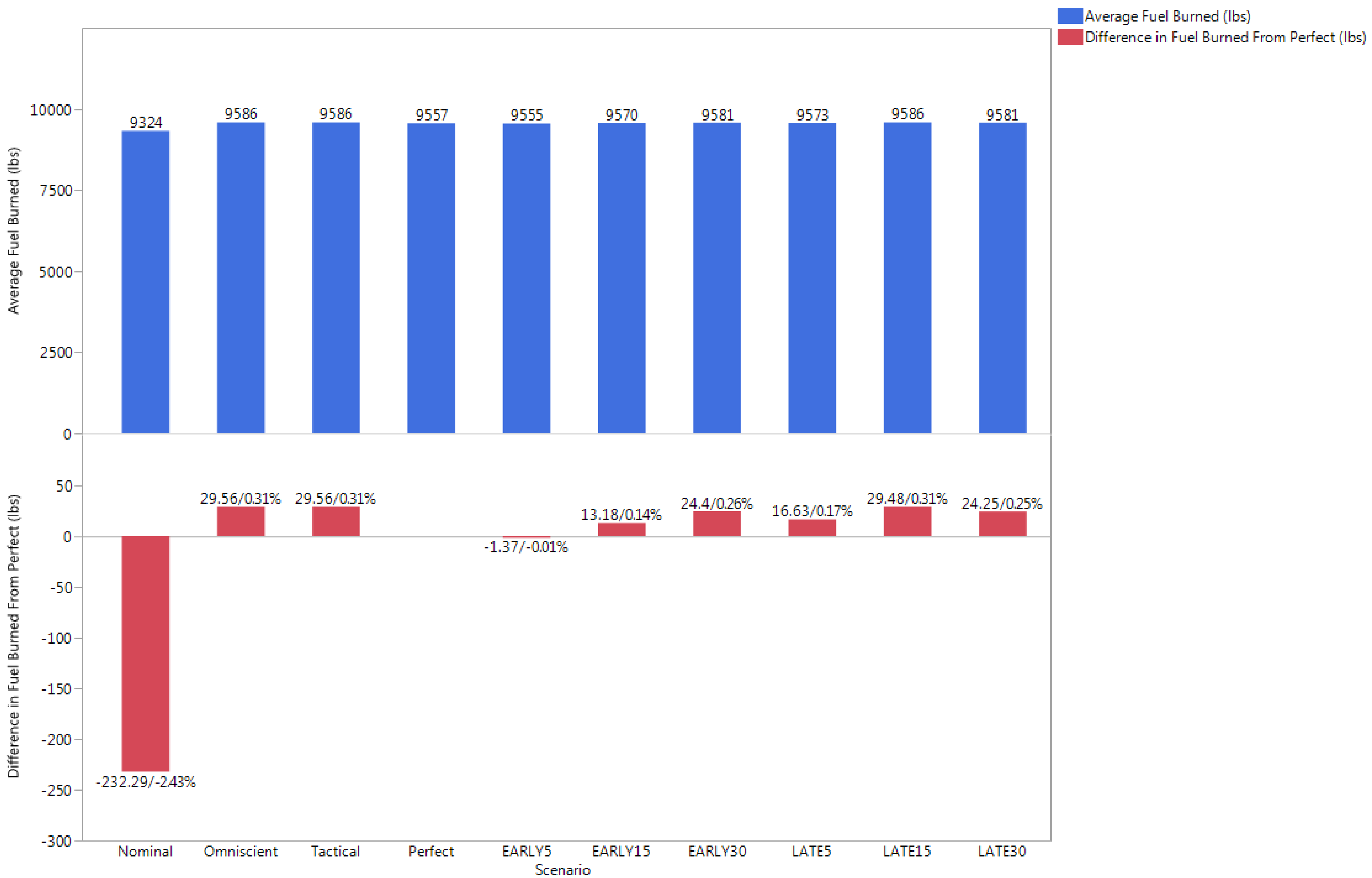

Figure 31: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Directly Impacted Departures

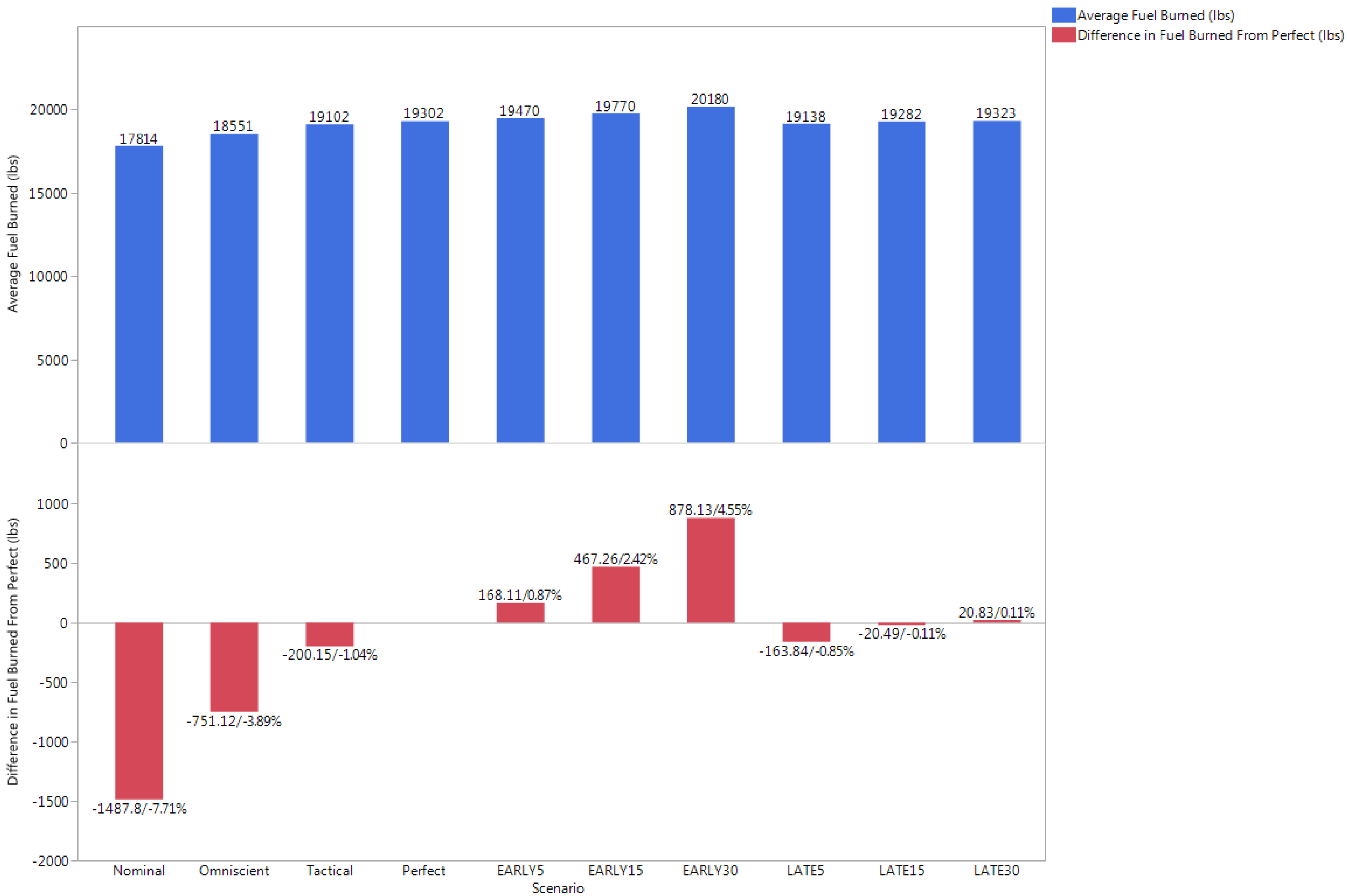

Figure 32: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Directly Impacted Arrivals

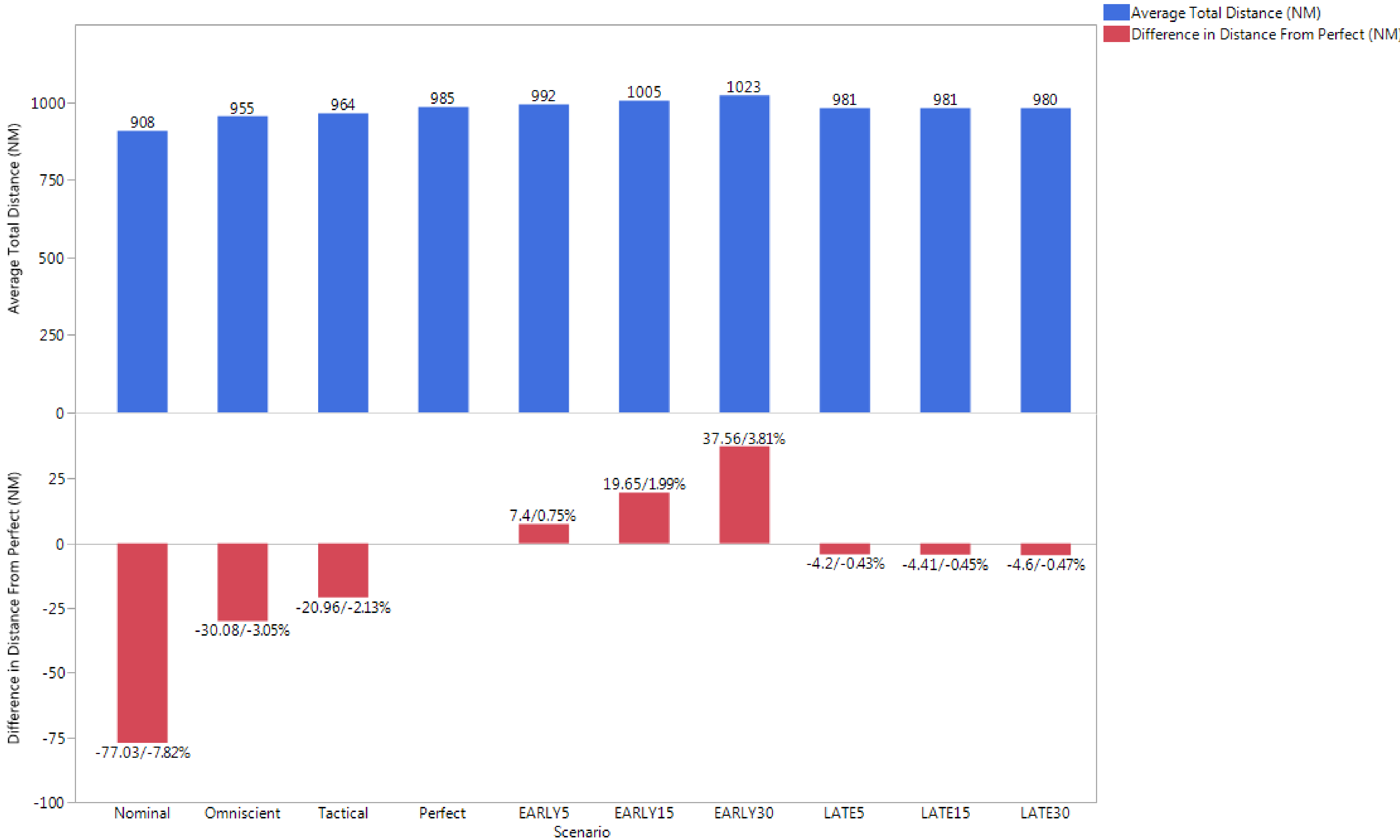

Figure 33: Avg. Change in Flight Distance (NM) from Perfect Scenario for All Directly Impacted Flights

Figure 34: Avg. Change in Flight Distance (NM) from Perfect Scenario for Directly Impacted Departures

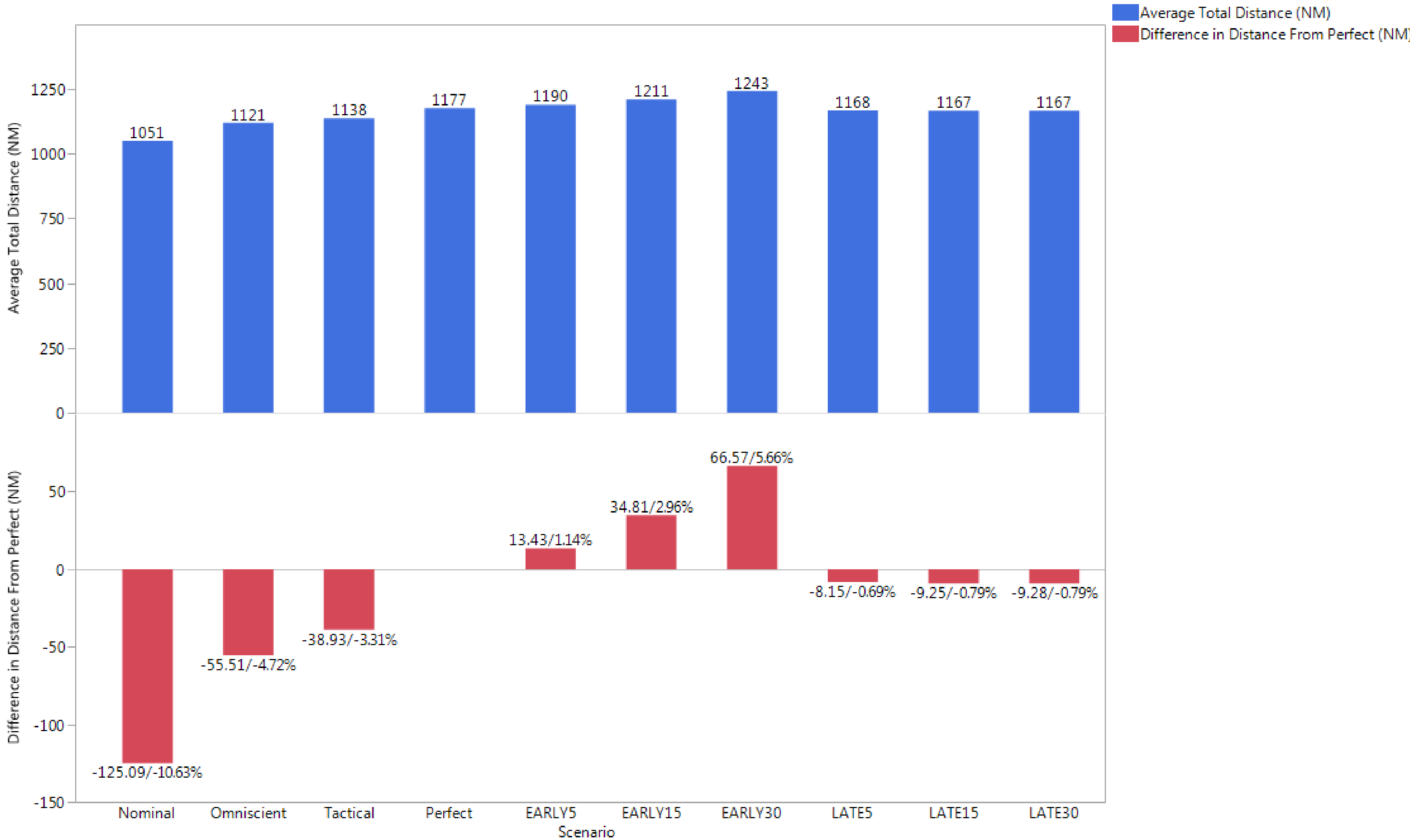

Figure 35: Avg. Change in Flight Distance (NM) from Perfect Scenario for Directly Impacted Arrivals

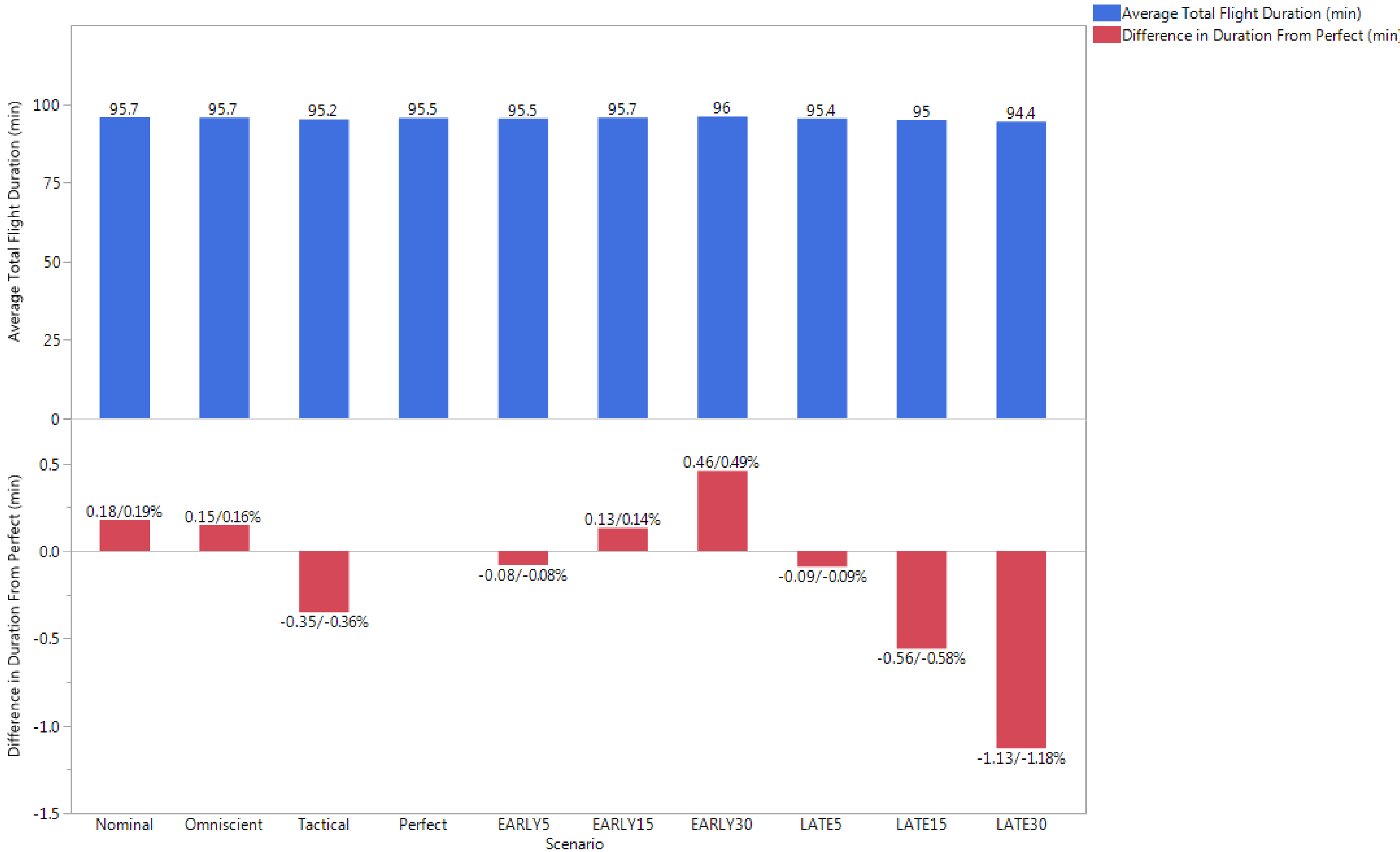

Figure 36: Avg. Change in Flight Duration (min) from Perfect Scenario for All Indirectly Impacted Flights

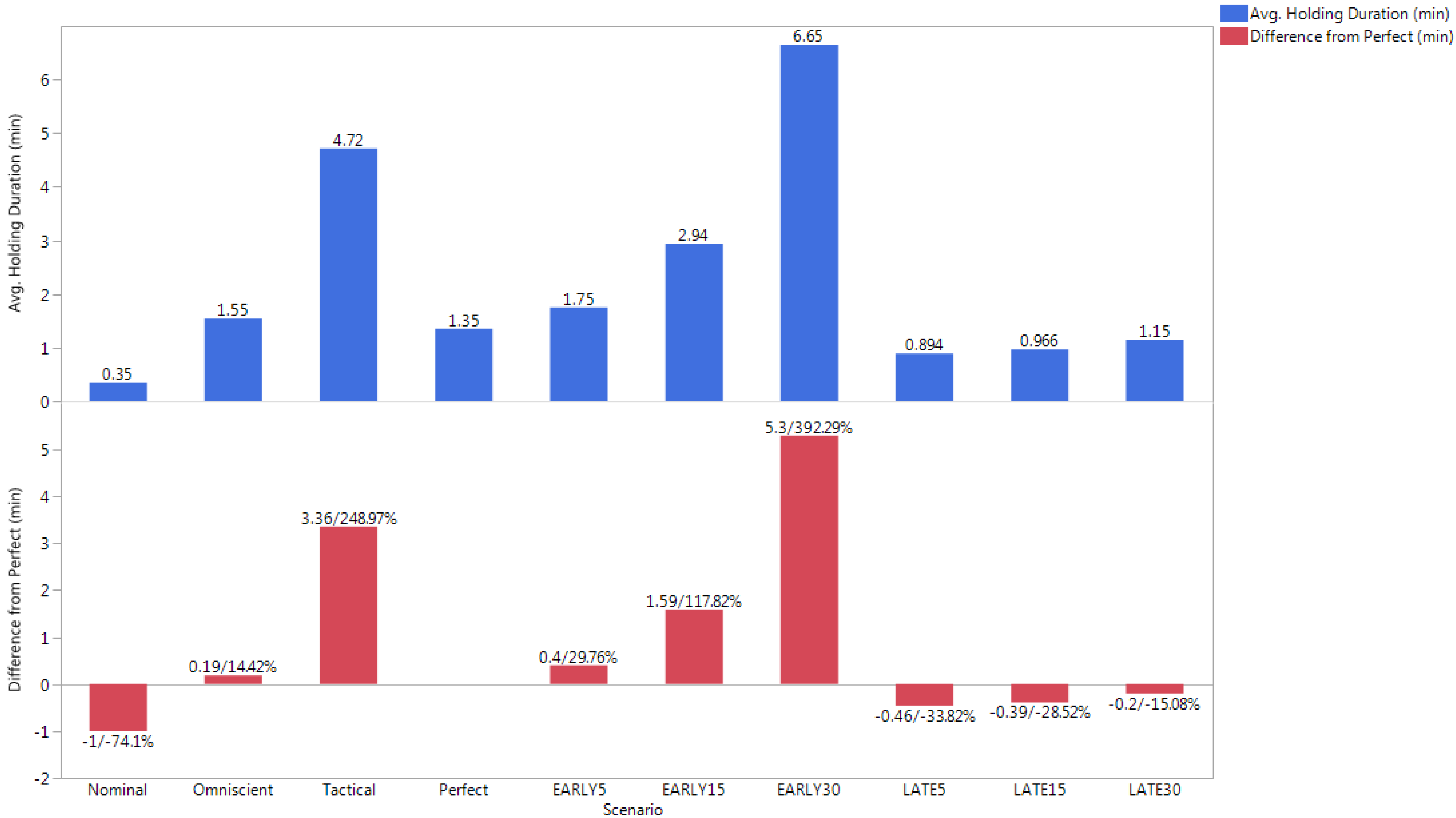

Figure 37: Avg. Airborne Holding Delay (min) for Directly Impacted Arrivals

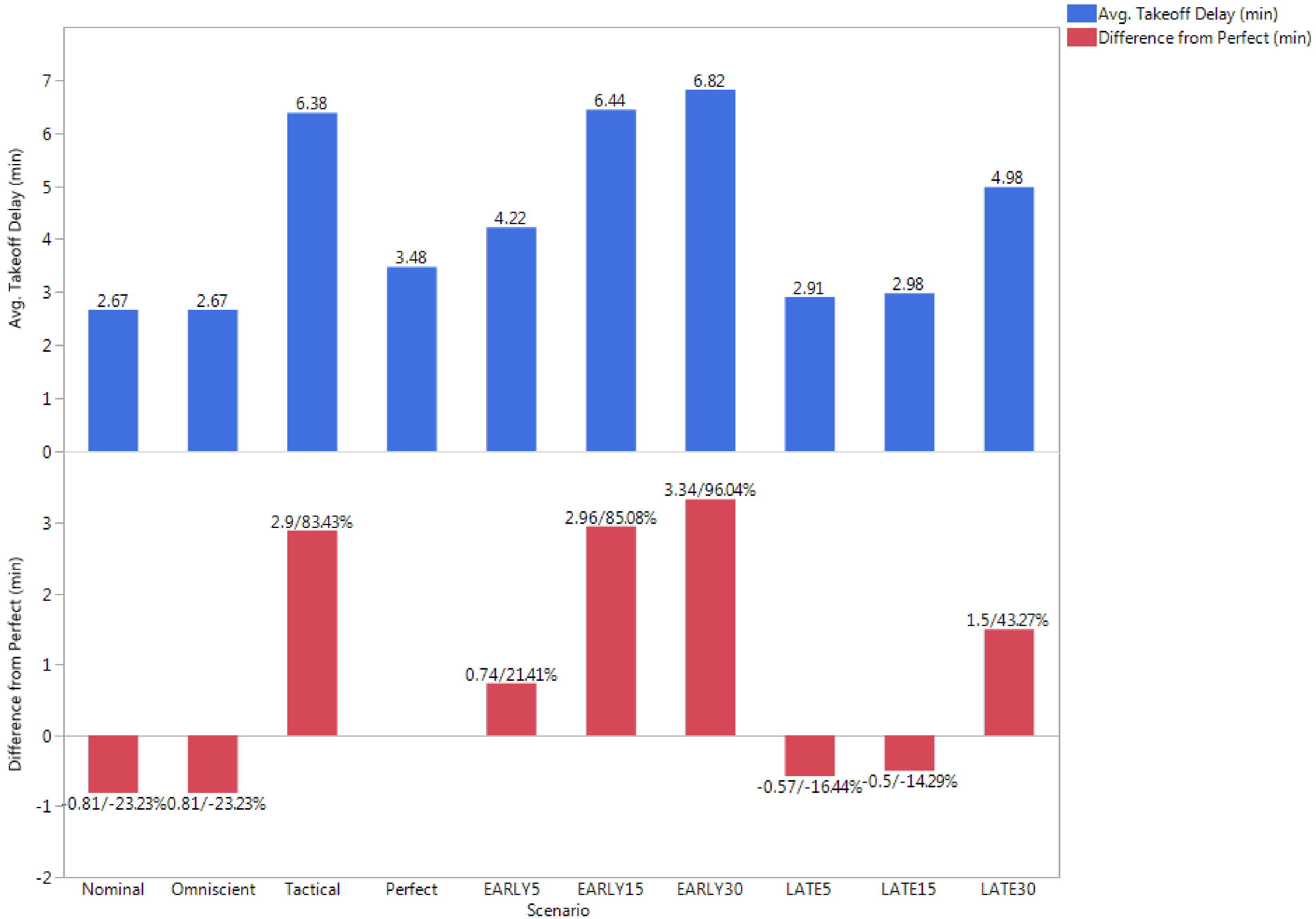

Figure 38: Avg. Departure Delay (min) for Directly Impacted Departures

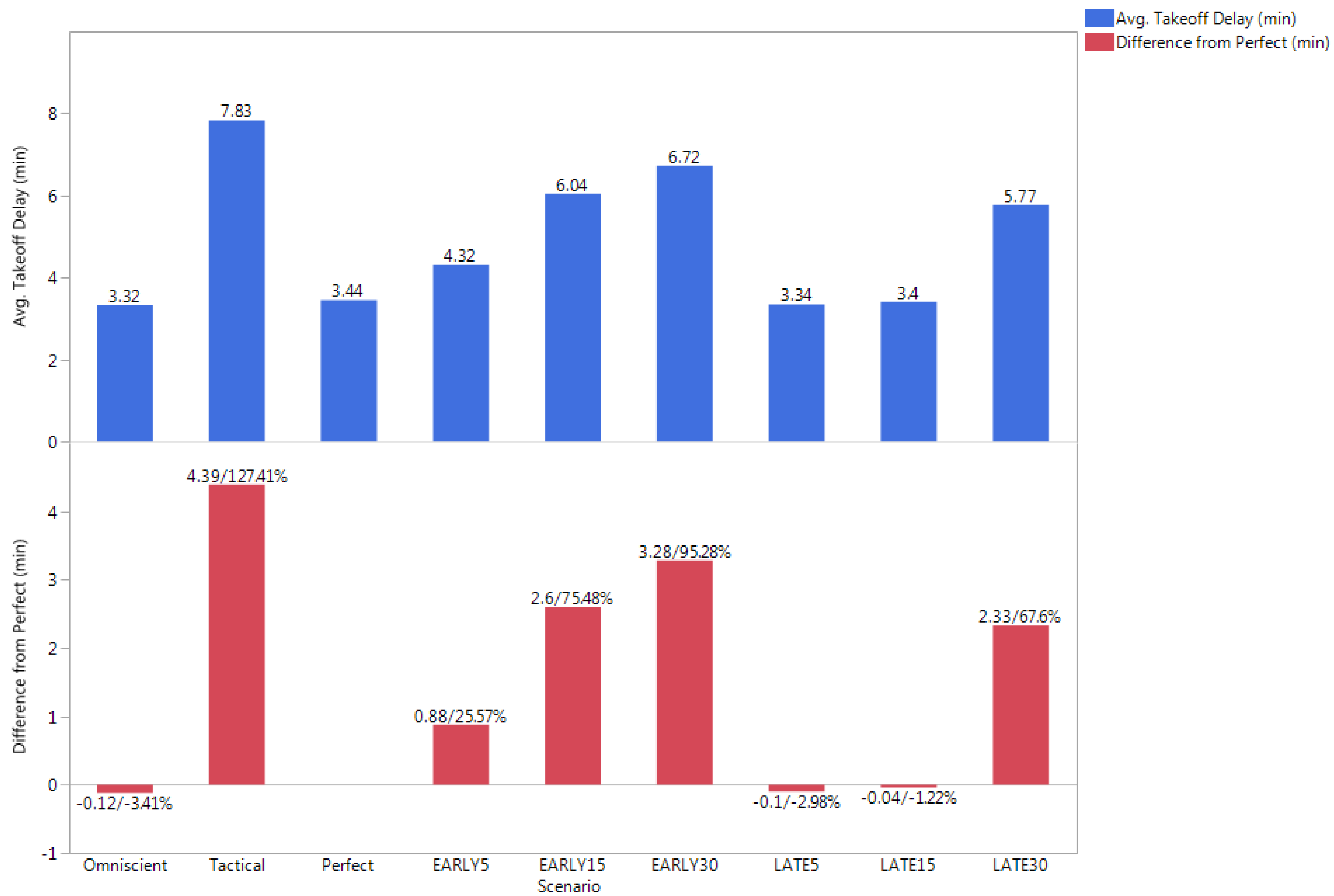

Figure 39: Avg. Departure Delay (min) for Directly Impacted Departures Through COKEM

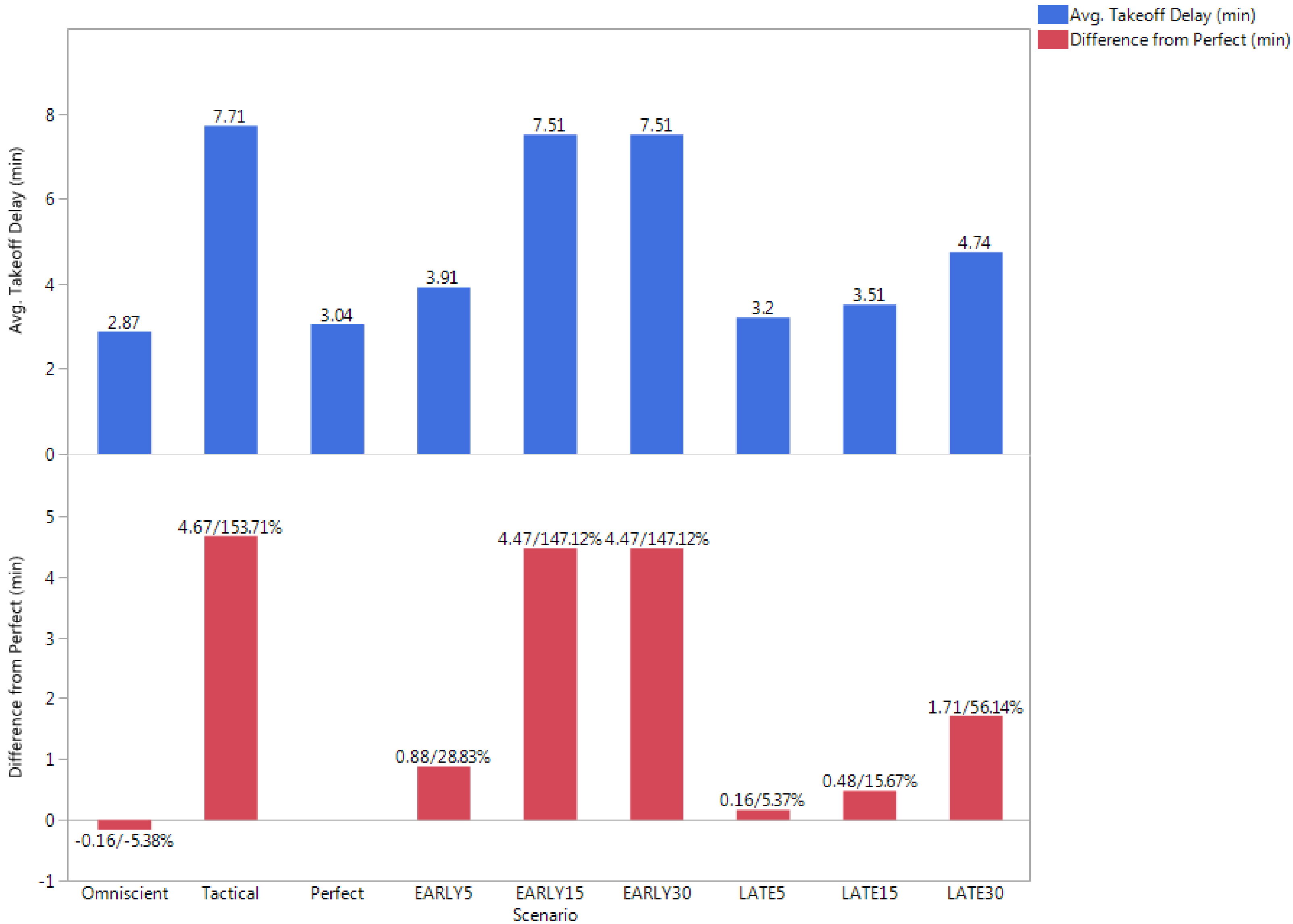

Figure 40: Avg. Departure Delay (min) for Directly Impacted Departures Through NOVSS

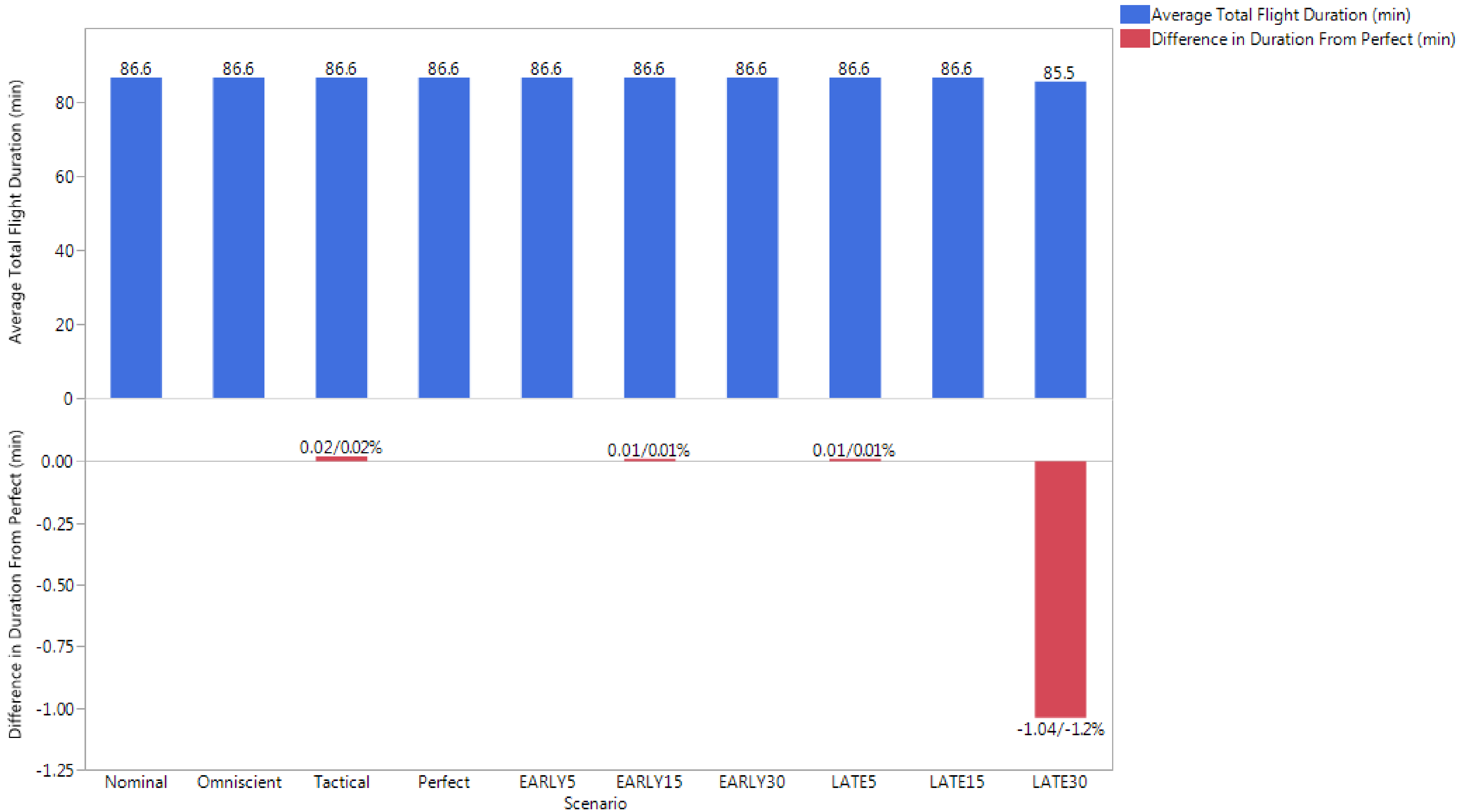

Figure 41: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Departures

Figure 42: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Arrivals

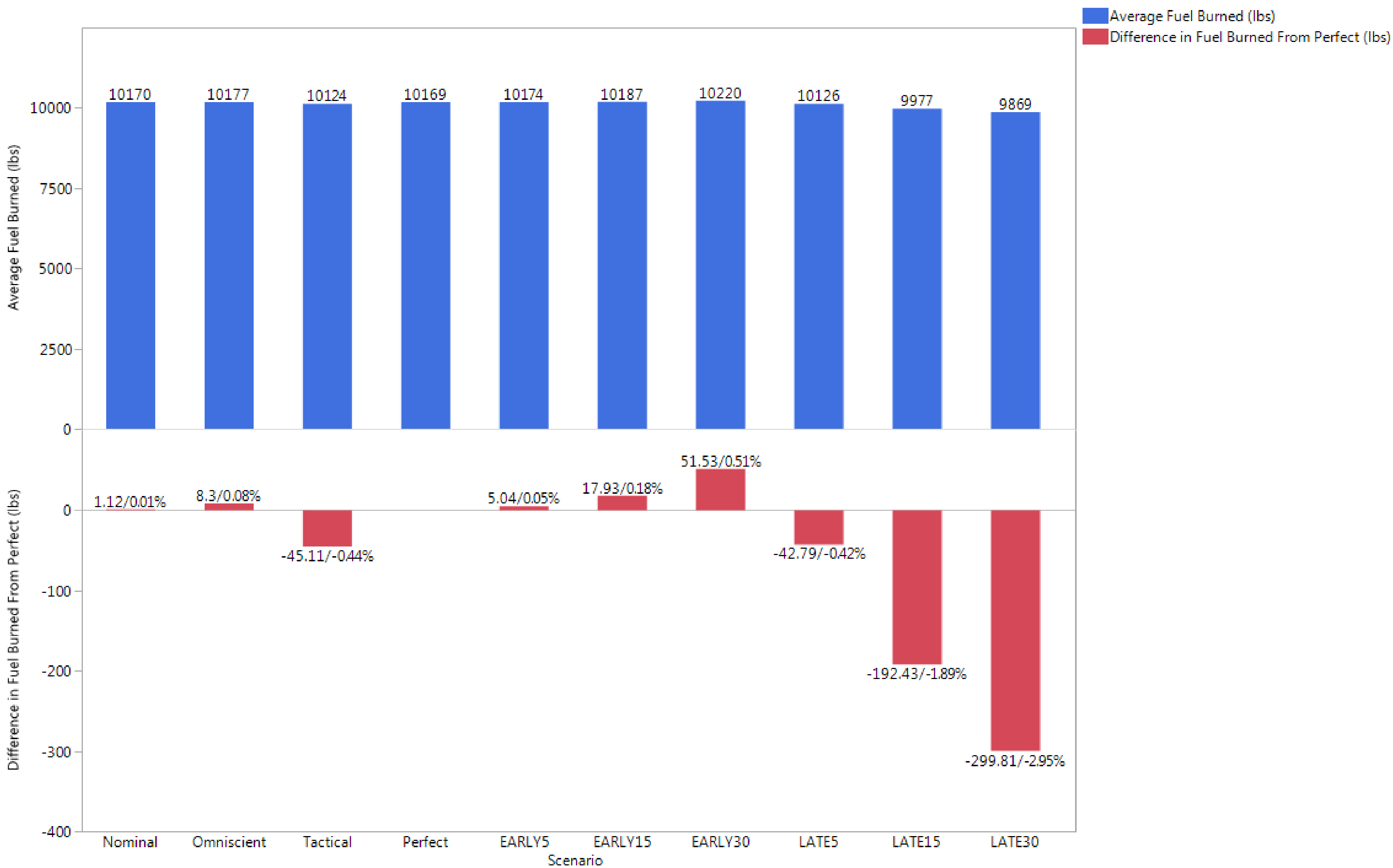

Figure 43: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for All Indirectly Impacted Flights

Figure 44: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Departures

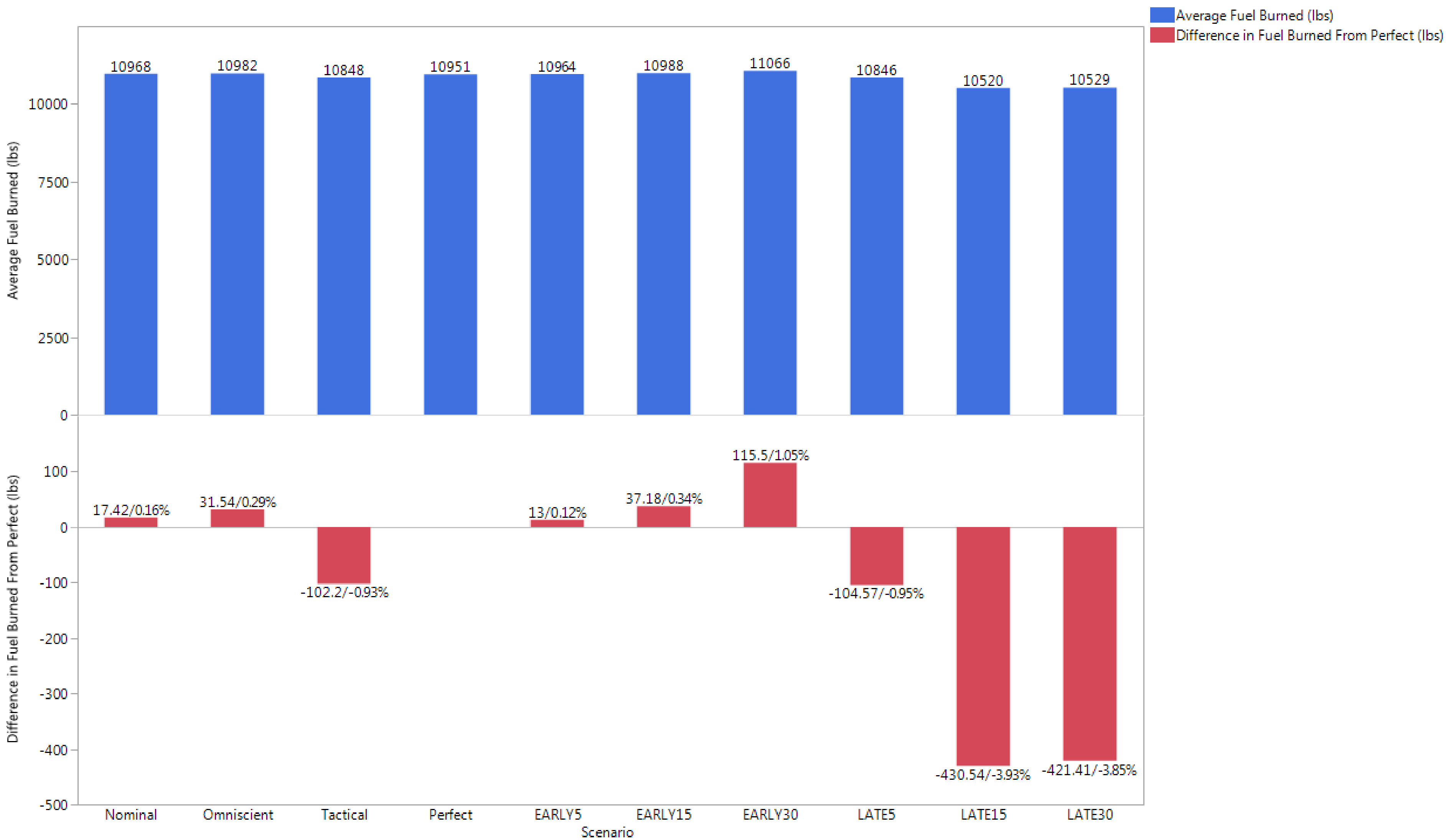

Figure 45: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Arrivals

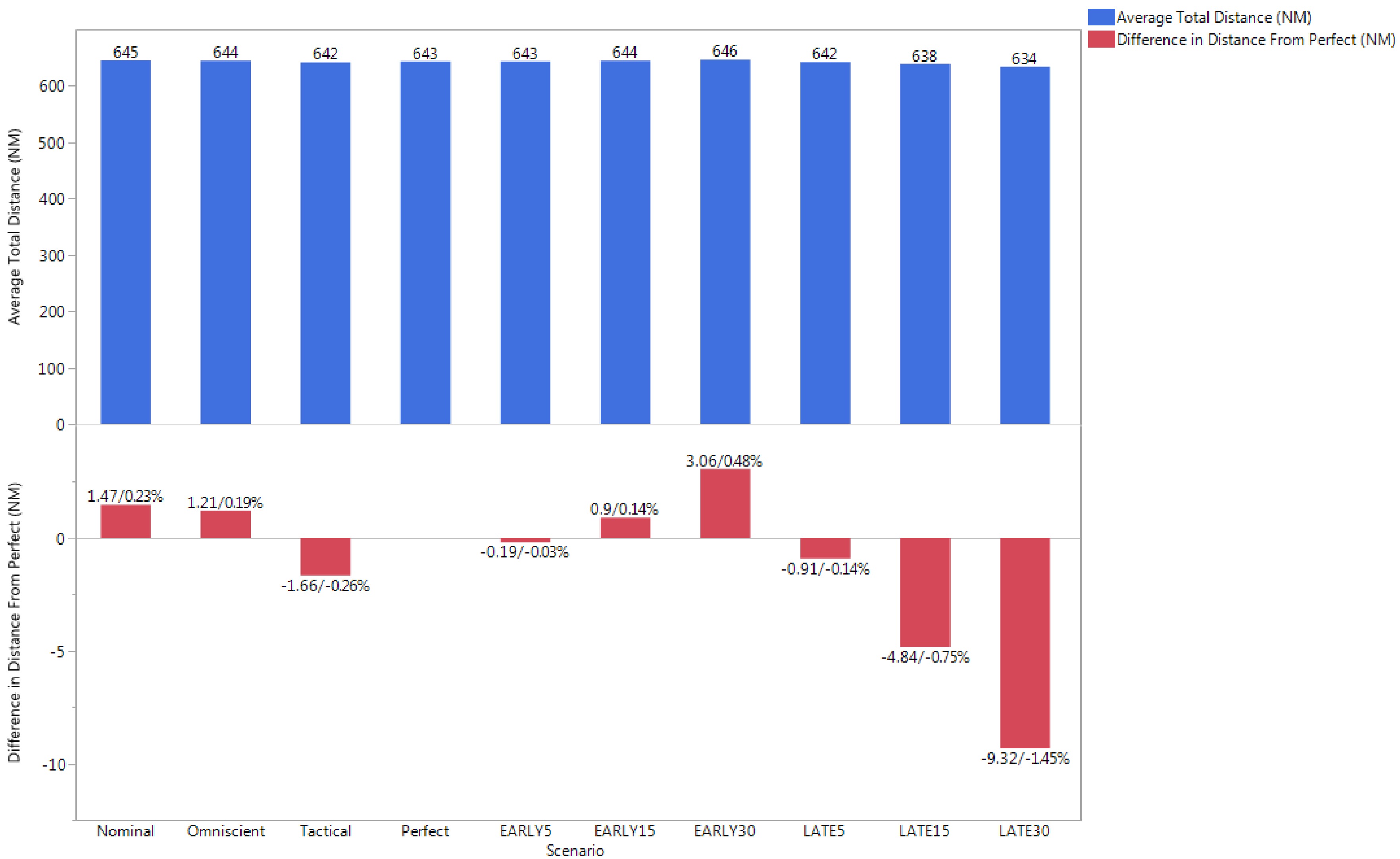

Figure 46: Avg. Change in Flight Distance (NM) from Perfect Scenario for All Indirectly Impacted Flights

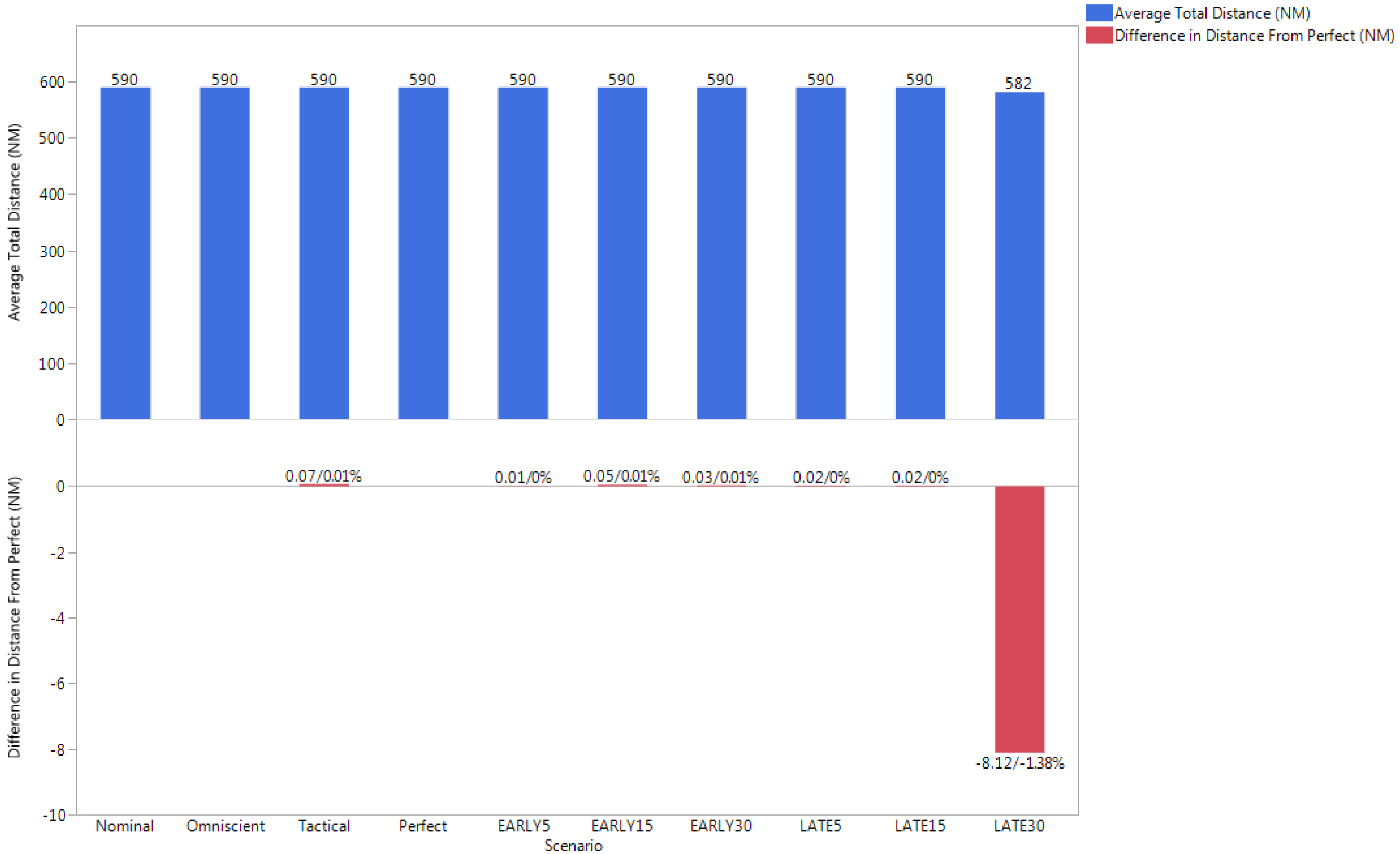

Figure 47: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Departures

Figure 48: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Arrivals

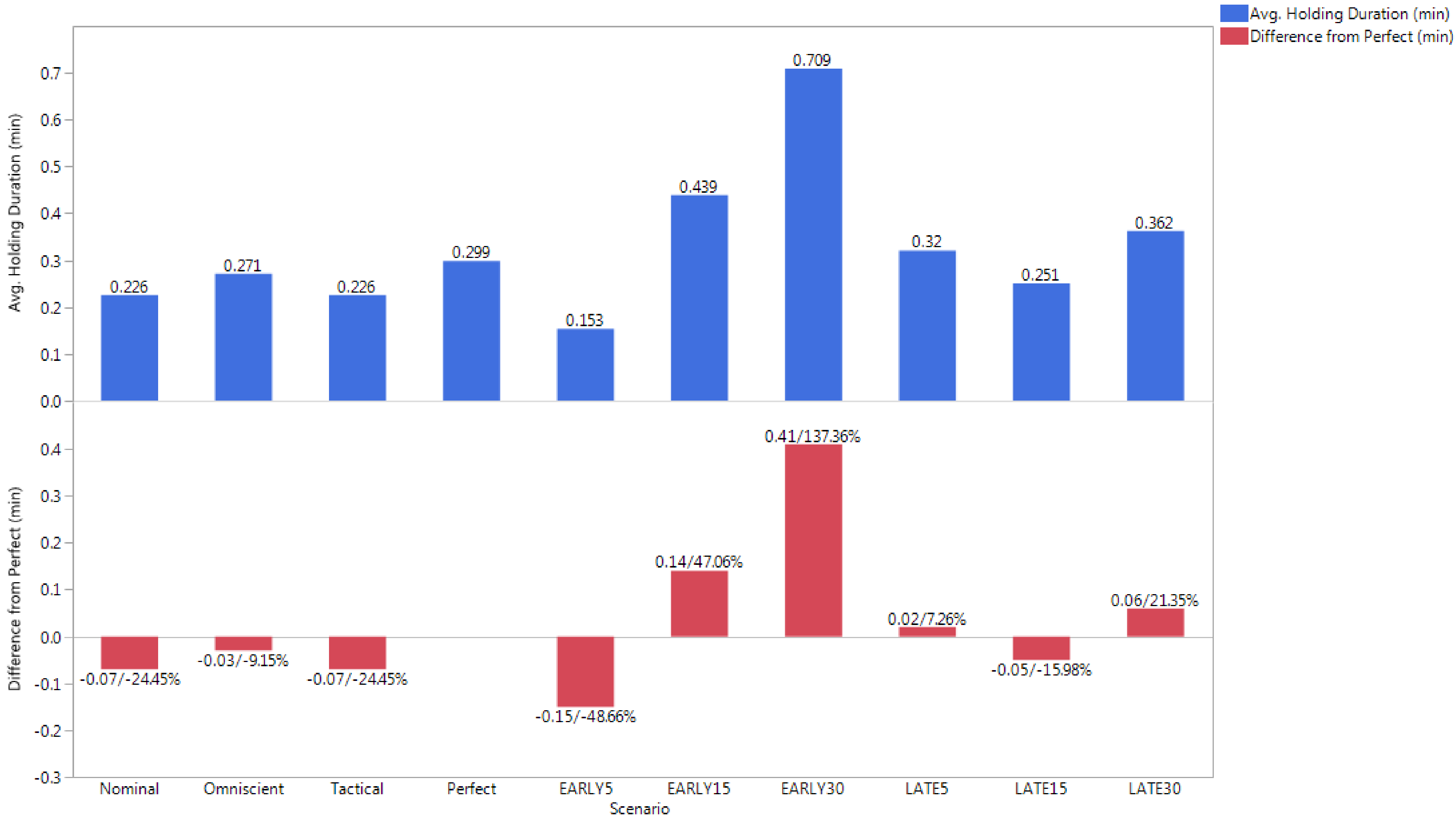

Figure 49: Avg. Airborne Holding Delay (min) for Indirectly Impacted Arrivals

Table 10. Ground Delay for Indirectly Impacted Departure Flights

Scenario	Count	Avg. Ground Delay	Standard Deviation	Total Ground Delay
Nominal	150	0:03:06	0:02:01	7:44:59
Omniscient	150	0:03:06	0:02:01	7:44:59
Tactical	140	0:02:03	0:01:25	4:47:25
Perfect	149	0:02:56	0:02:03	7:15:58
EARLY5	149	0:02:50	0:02:05	7:02:15
EARLY15	140	0:02:37	0:02:09	6:05:35
EARLY30	140	0:02:38	0:02:08	6:08:34
LATE5	148	0:03:06	0:02:01	7:37:54
LATE15	149	0:03:01	0:02:02	7:30:41
LATE30	140	0:02:37	0:01:39	6:05:23

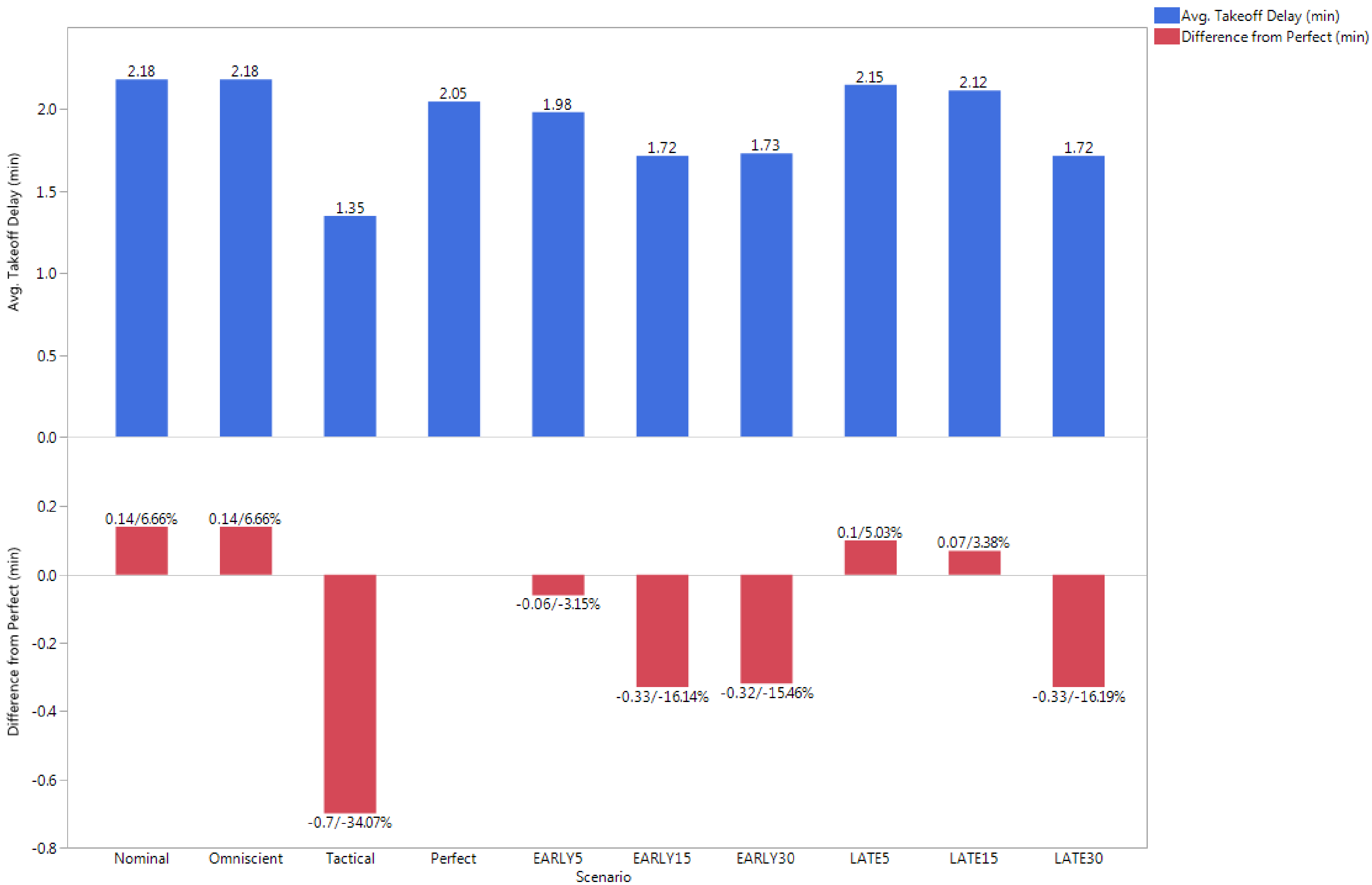

Figure 50: Avg. Ground Delay (min) for Indirectly Impacted Departures

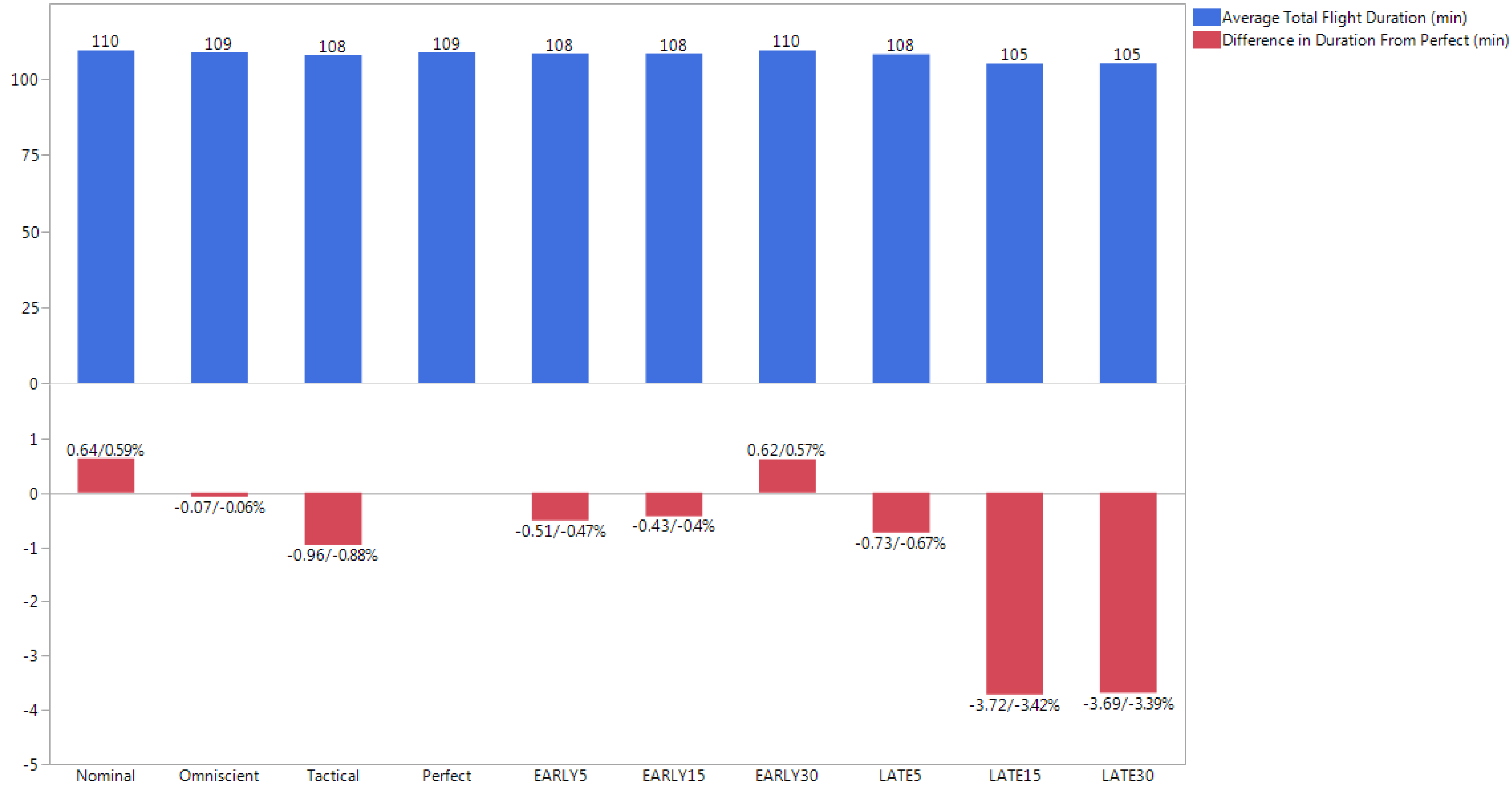

Figure 51: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Arrival Flights Through FLCON

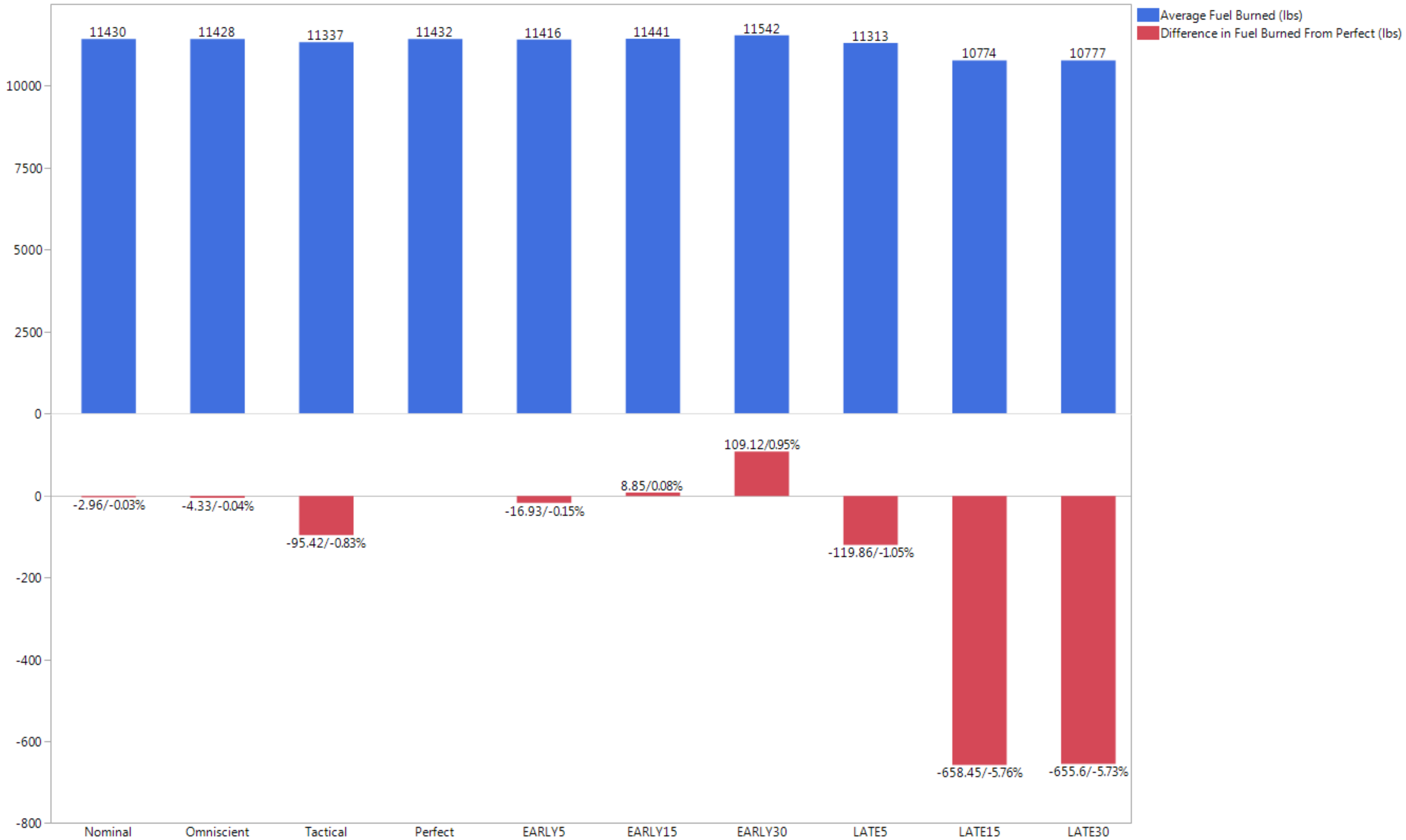

Figure 52: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Arrival Flights Through FLCON

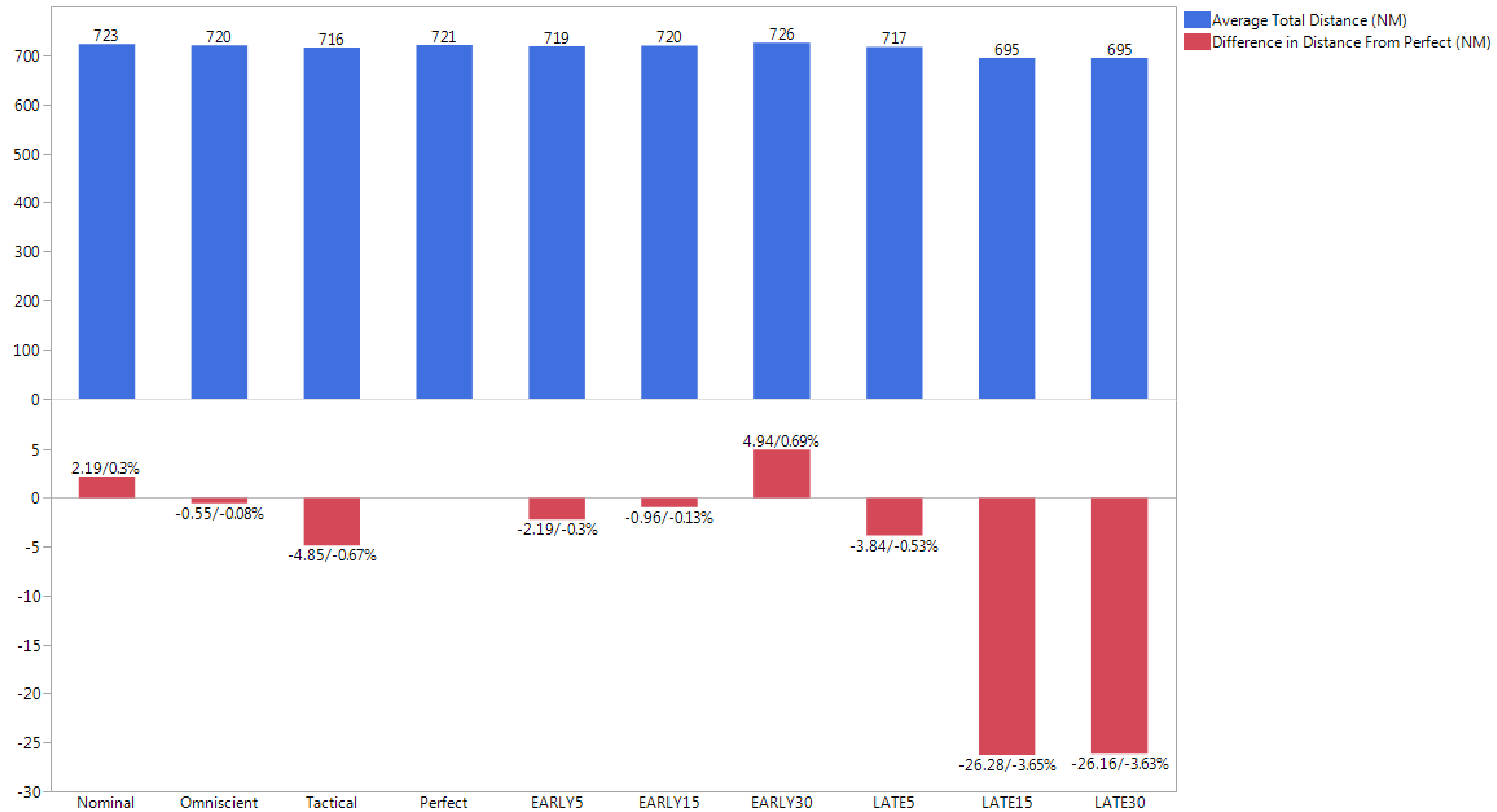

Figure 53: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Arrival Flights Through FLCON

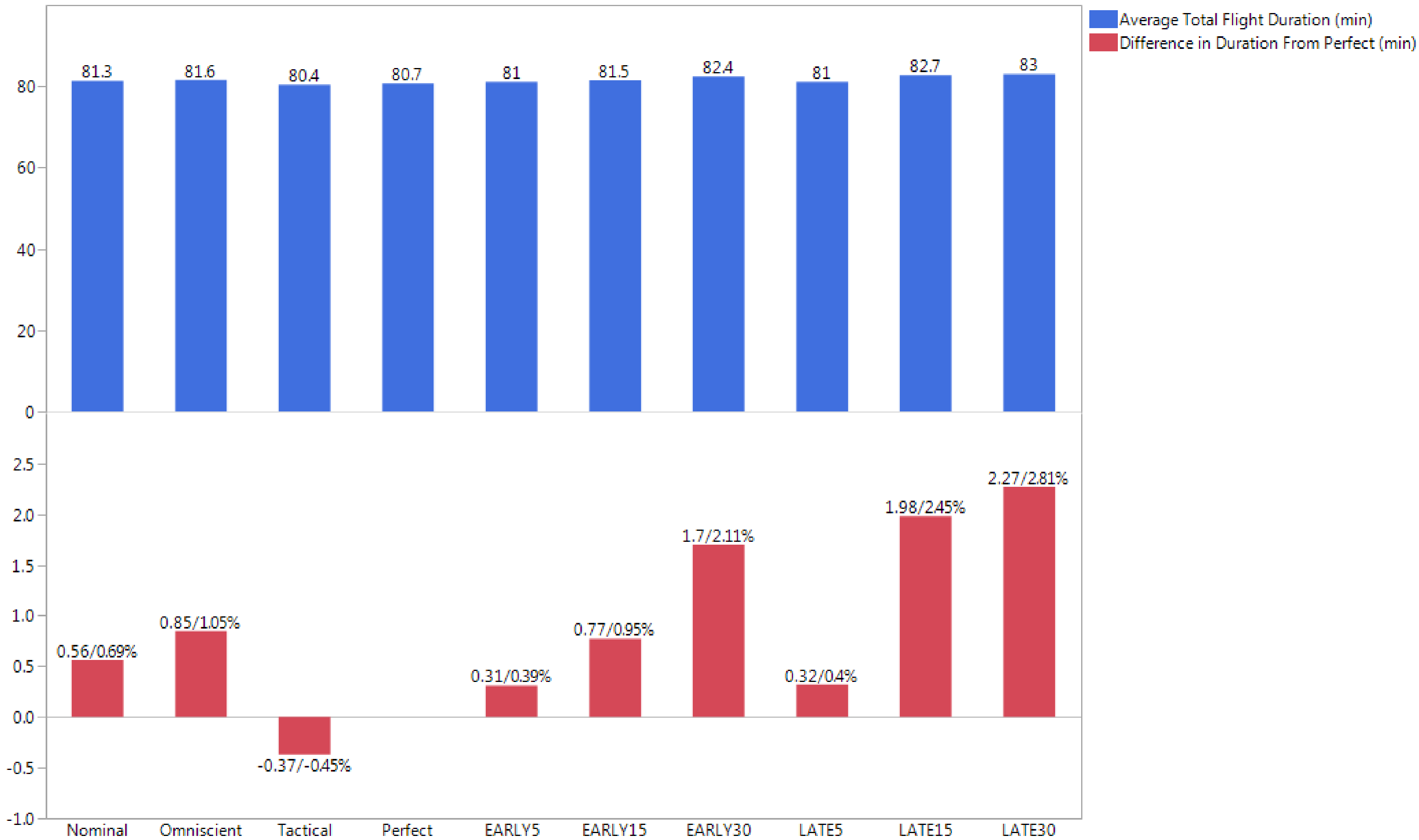

Figure 54: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Arrival Flights Through LGC

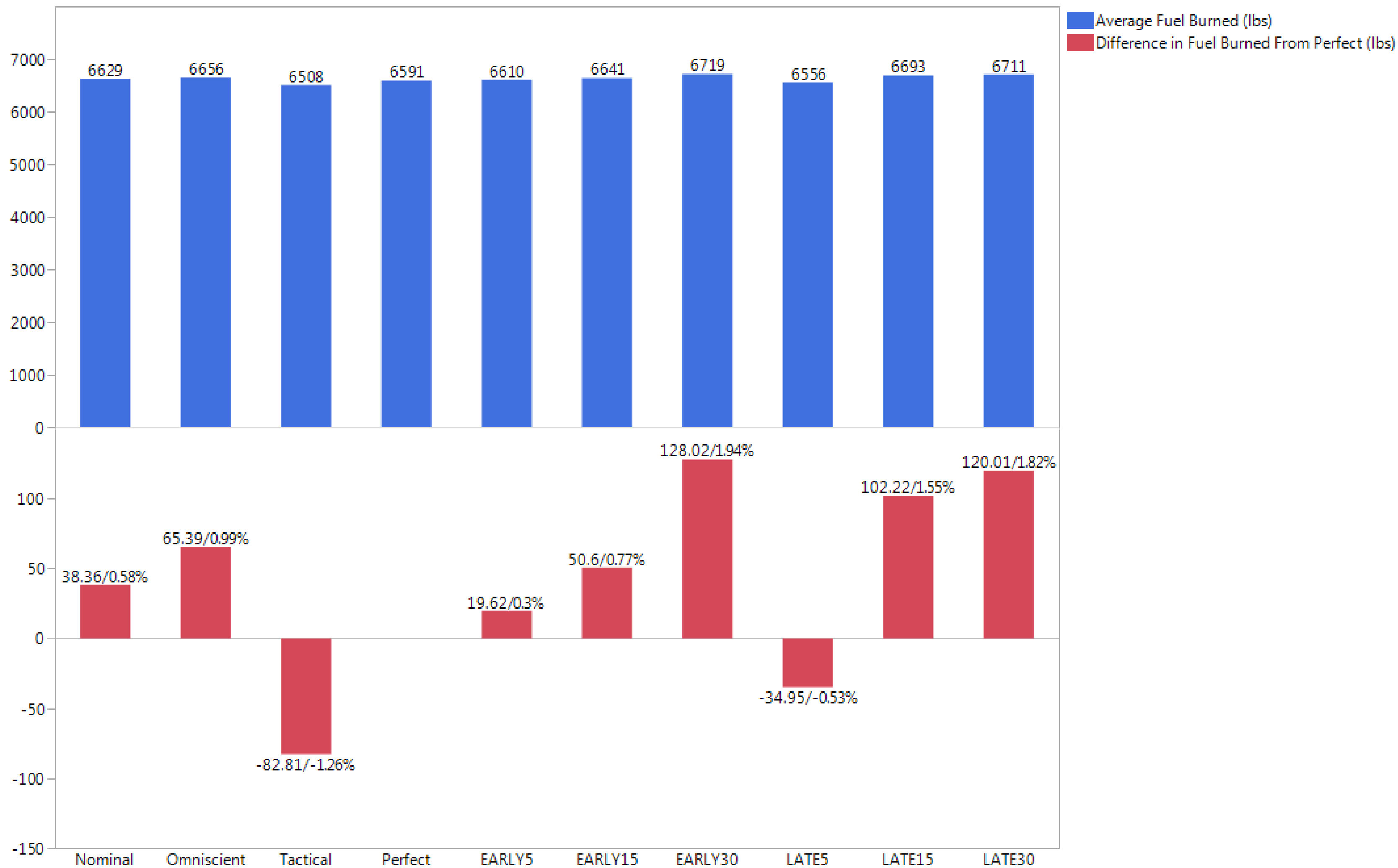

Figure 55: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Arrival Flights Through LGC

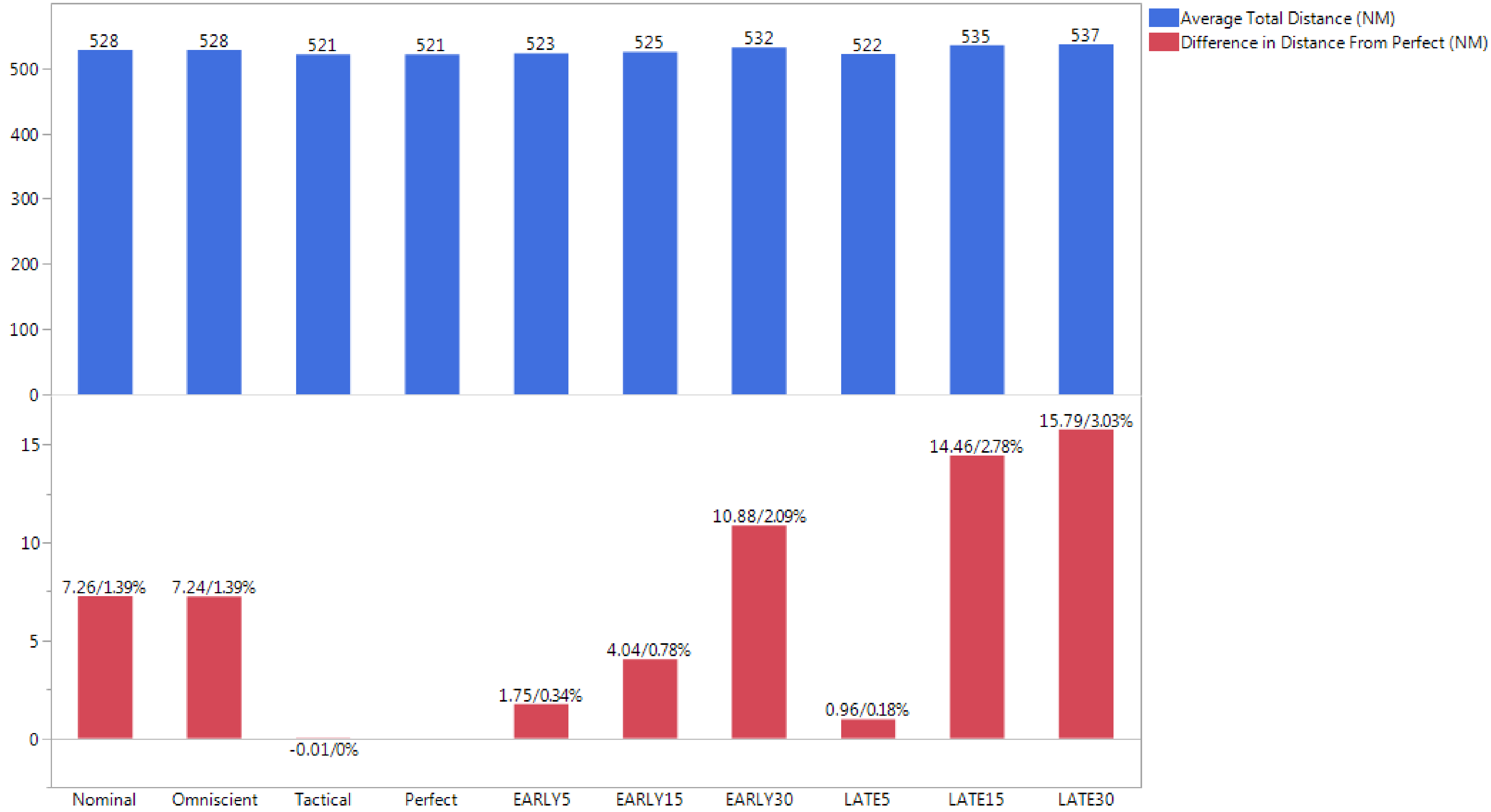

Figure 56: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Arrival Flights Through LGC

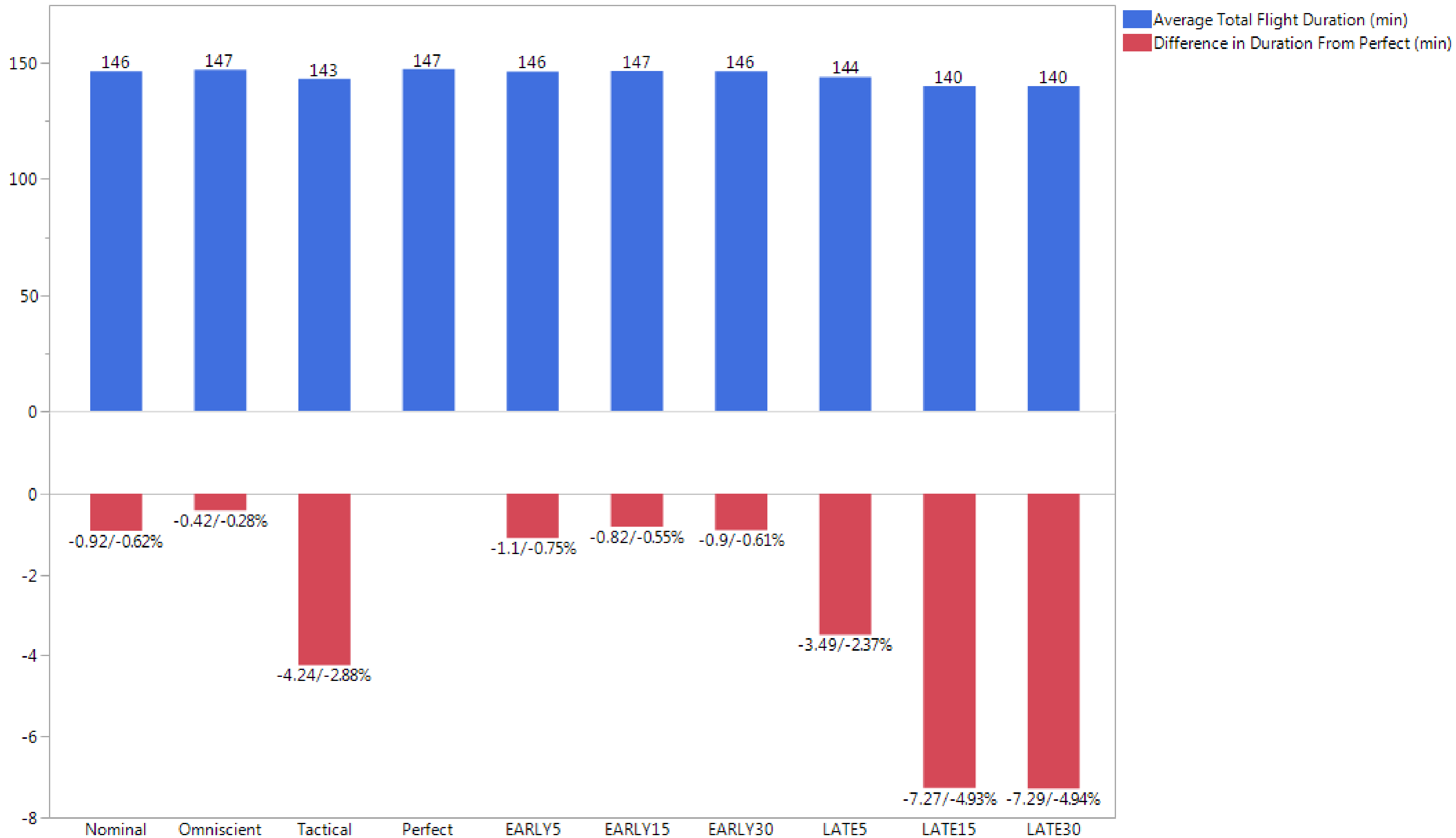

Figure 57: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Arrival Flights Through RMG

Figure 58: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Arrival Flights Through RMG

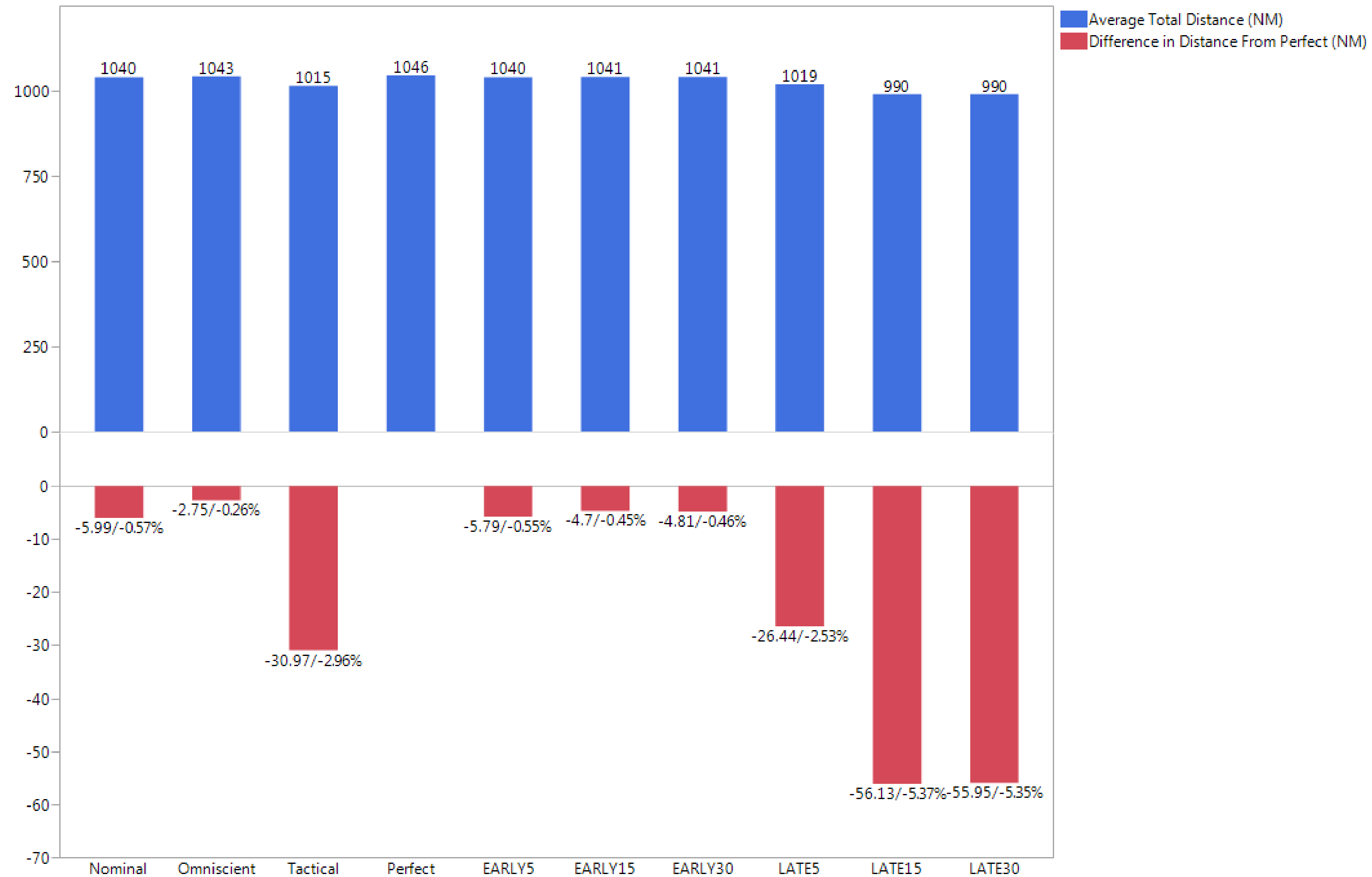

Figure 59: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Arrival Flights Through RMG

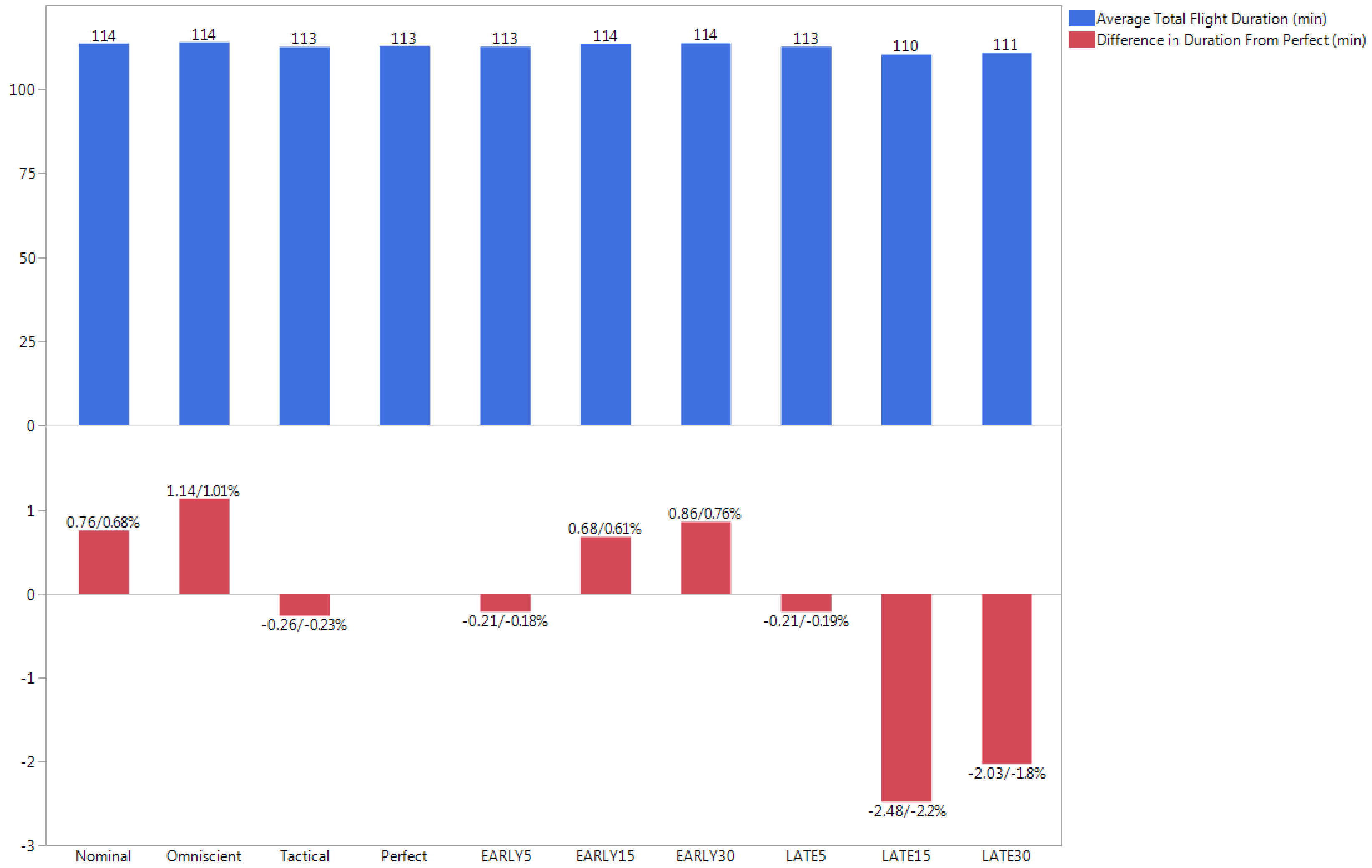

Figure 60: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Arrival Flights Through SINCA

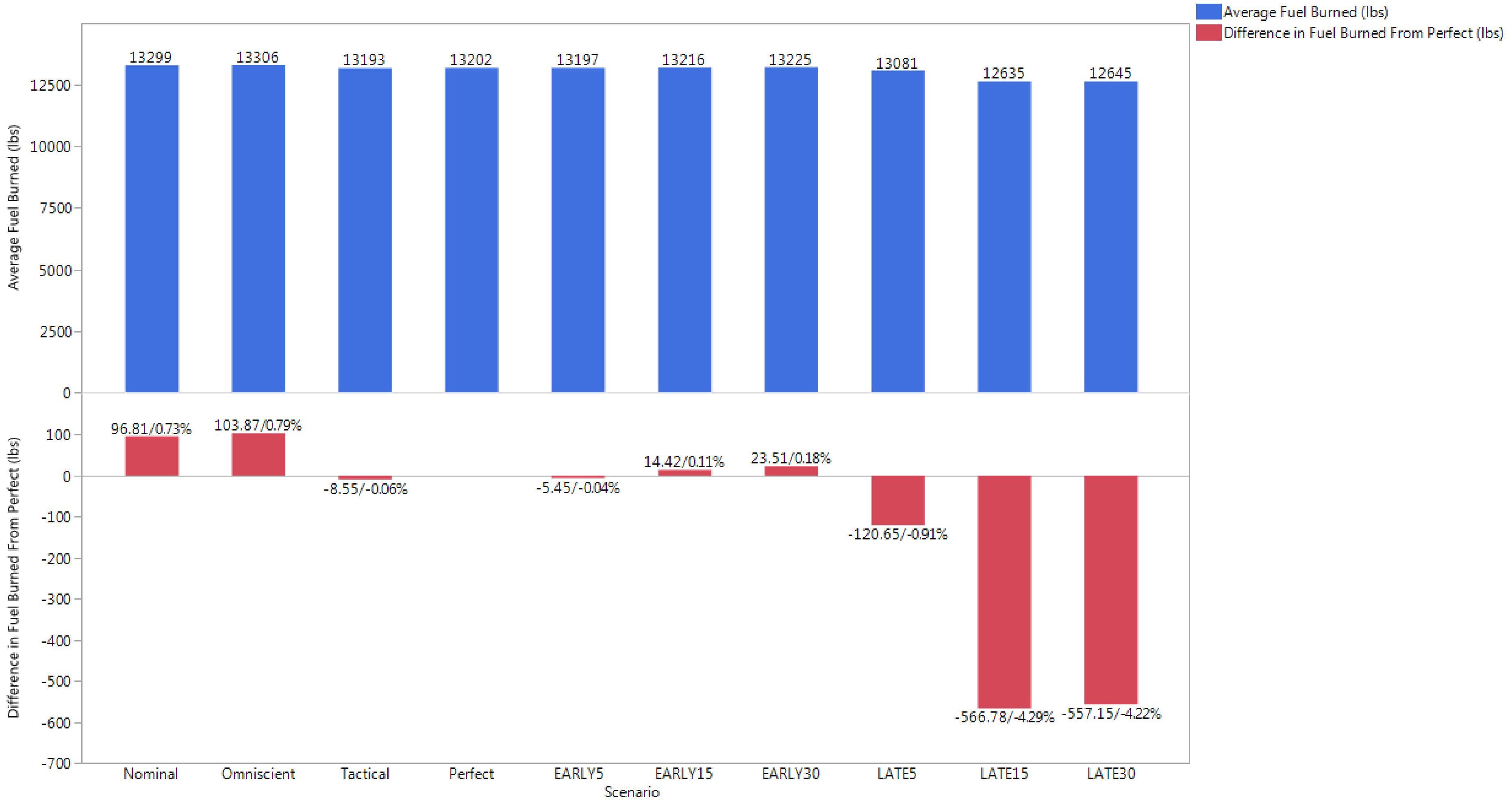

Figure 61: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Arrival Flights Through SINCA

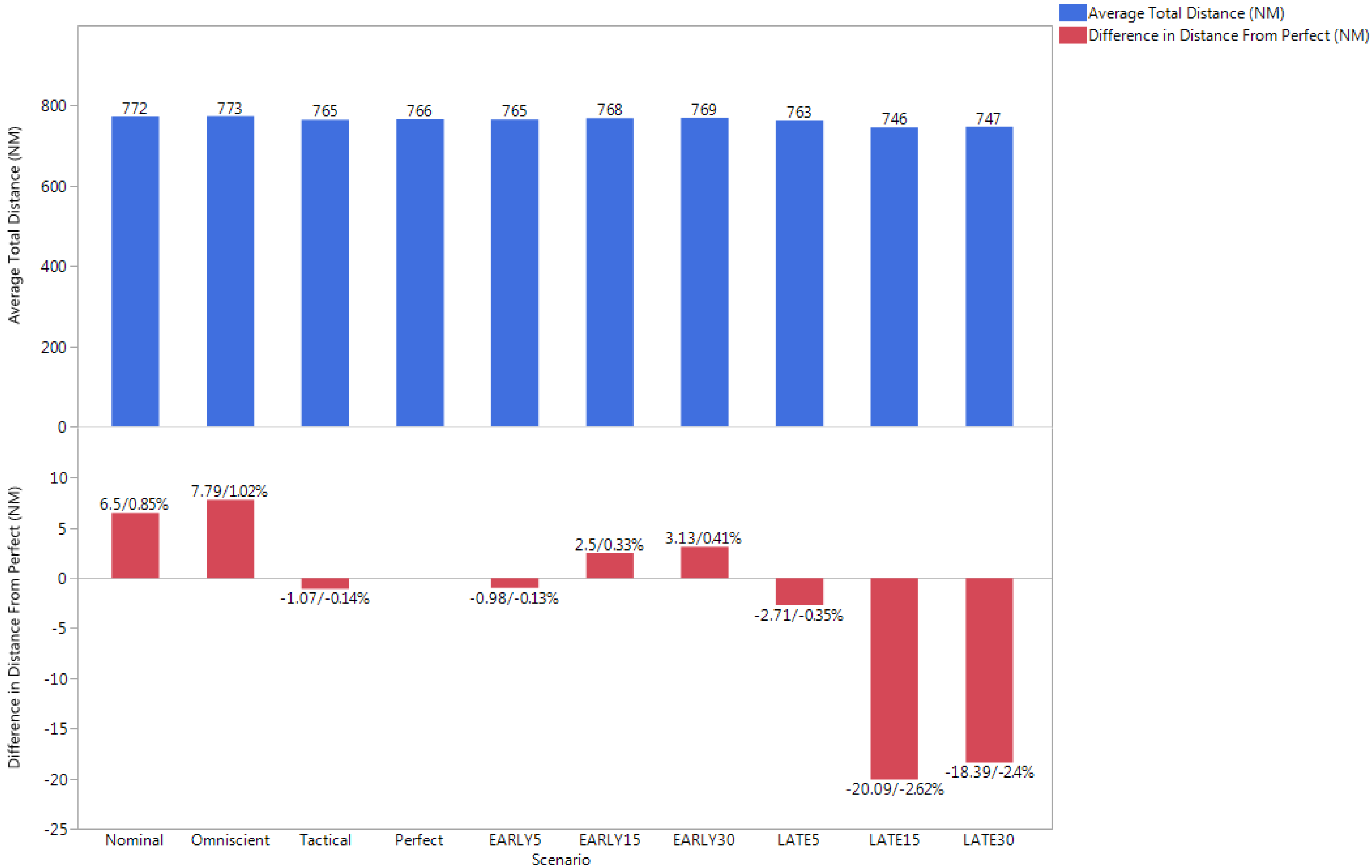

Figure 62: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Arrival Flights Through SINCA

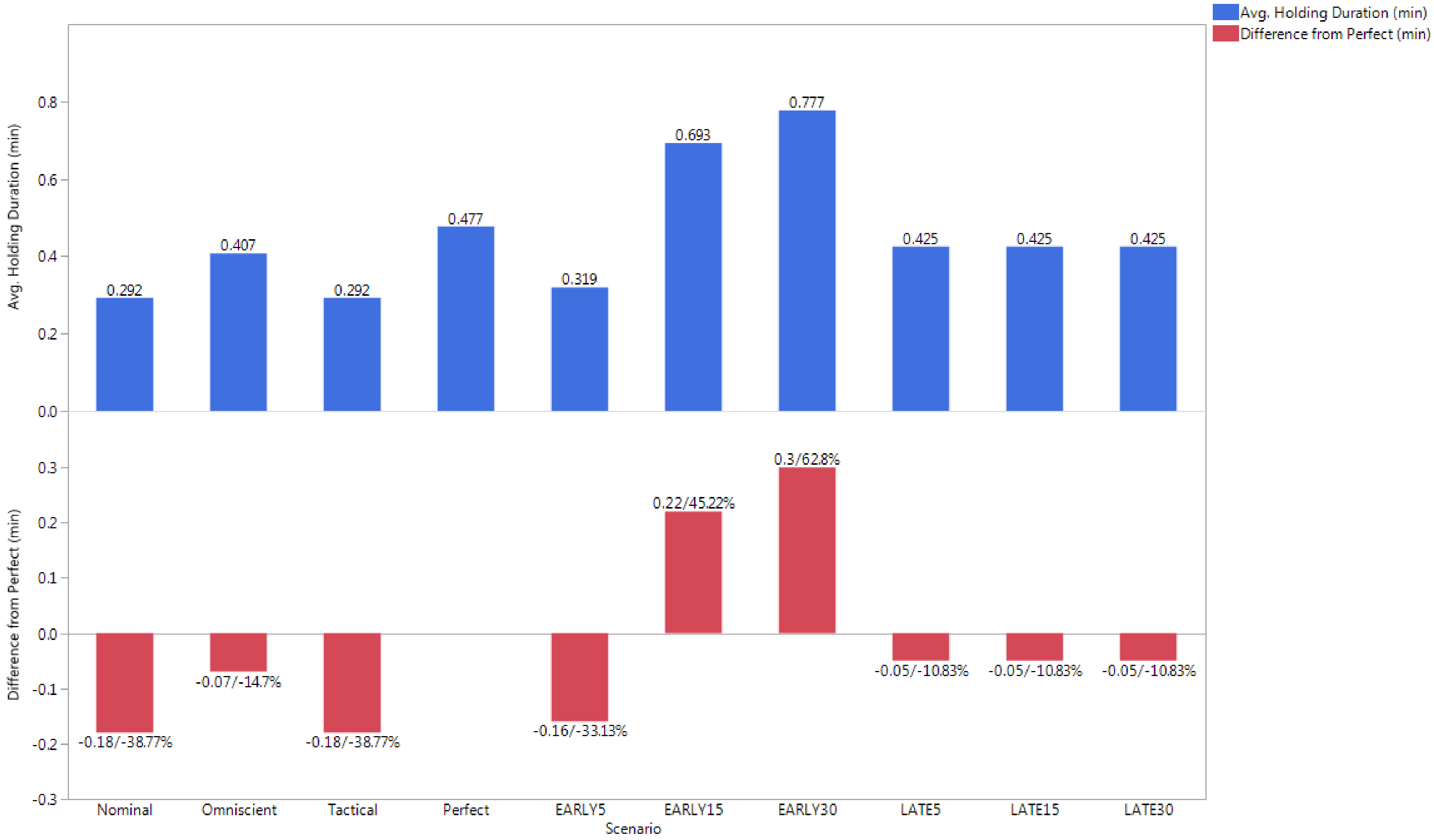

Figure 63: Avg. Airborne Holding Delay (min) for Indirectly Impacted Arrivals Through FLCON

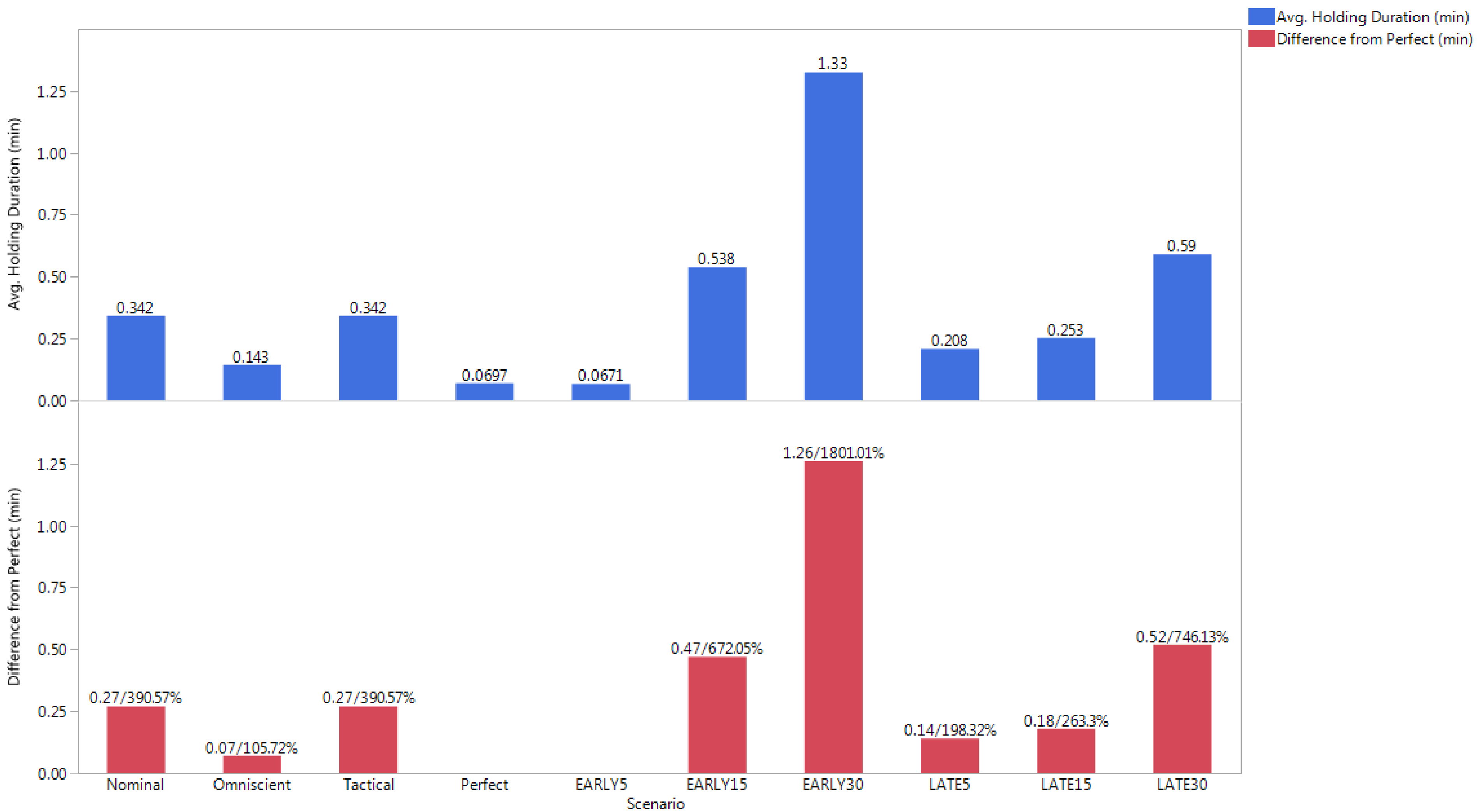

Figure 64: Avg. Airborne Holding Delay (min) for Indirectly Impacted Arrivals Through LGC

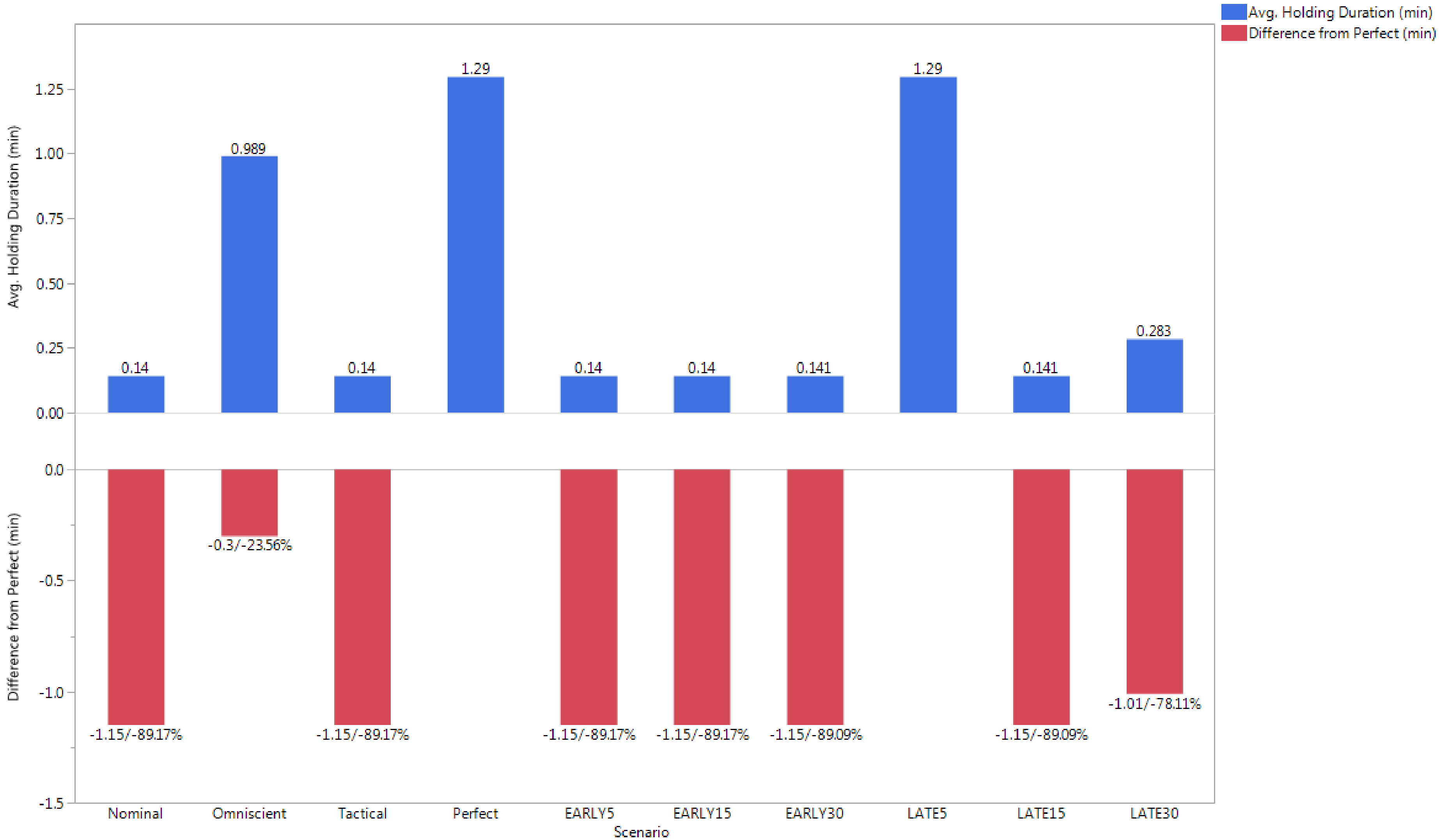

Figure 65: Avg. Airborne Holding Delay (min) for Indirectly Impacted Arrivals Through RMG

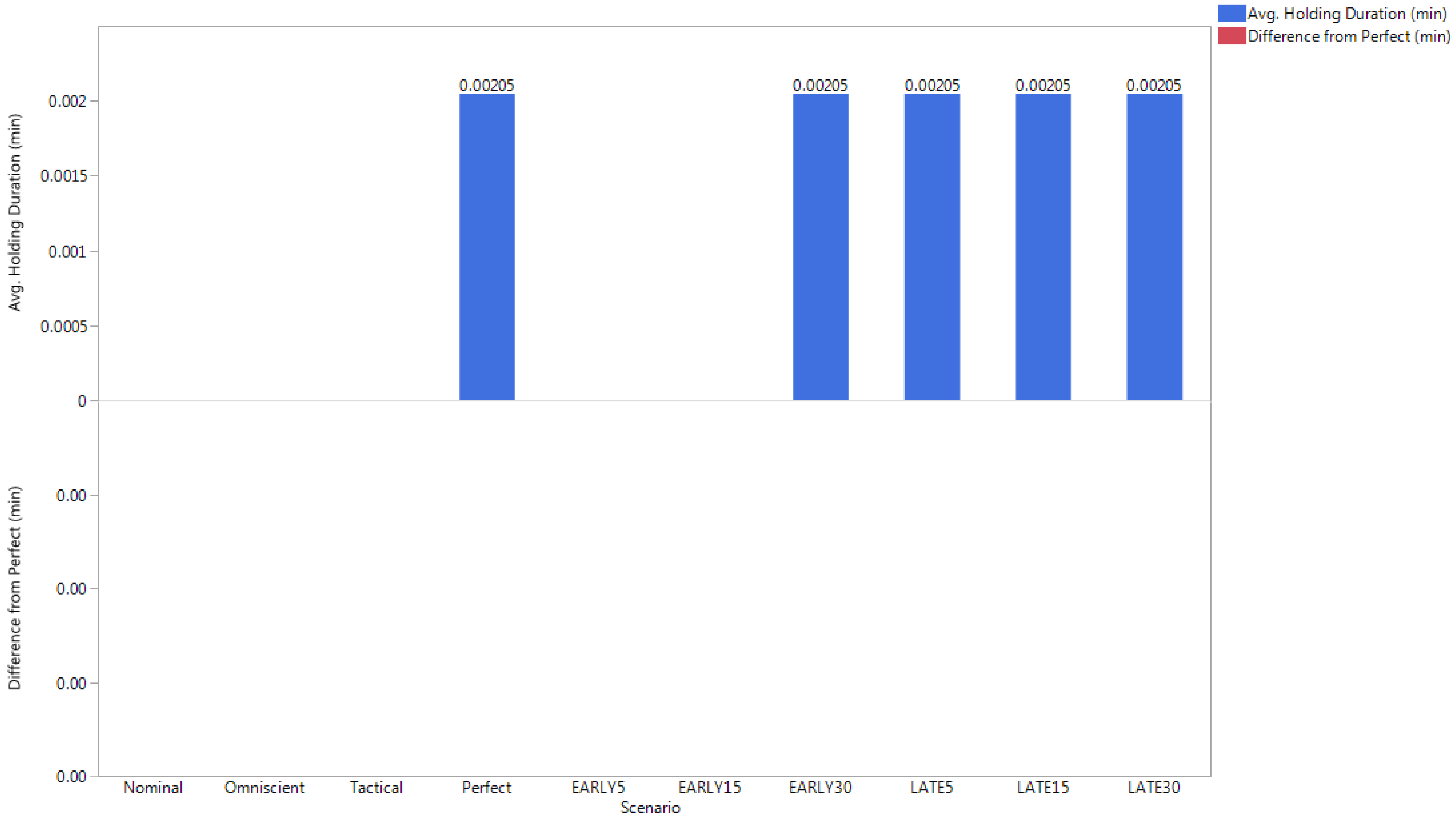

Figure 66: Avg. Airborne Holding Delay (min) for Indirectly Impacted Arrivals Through SINCA

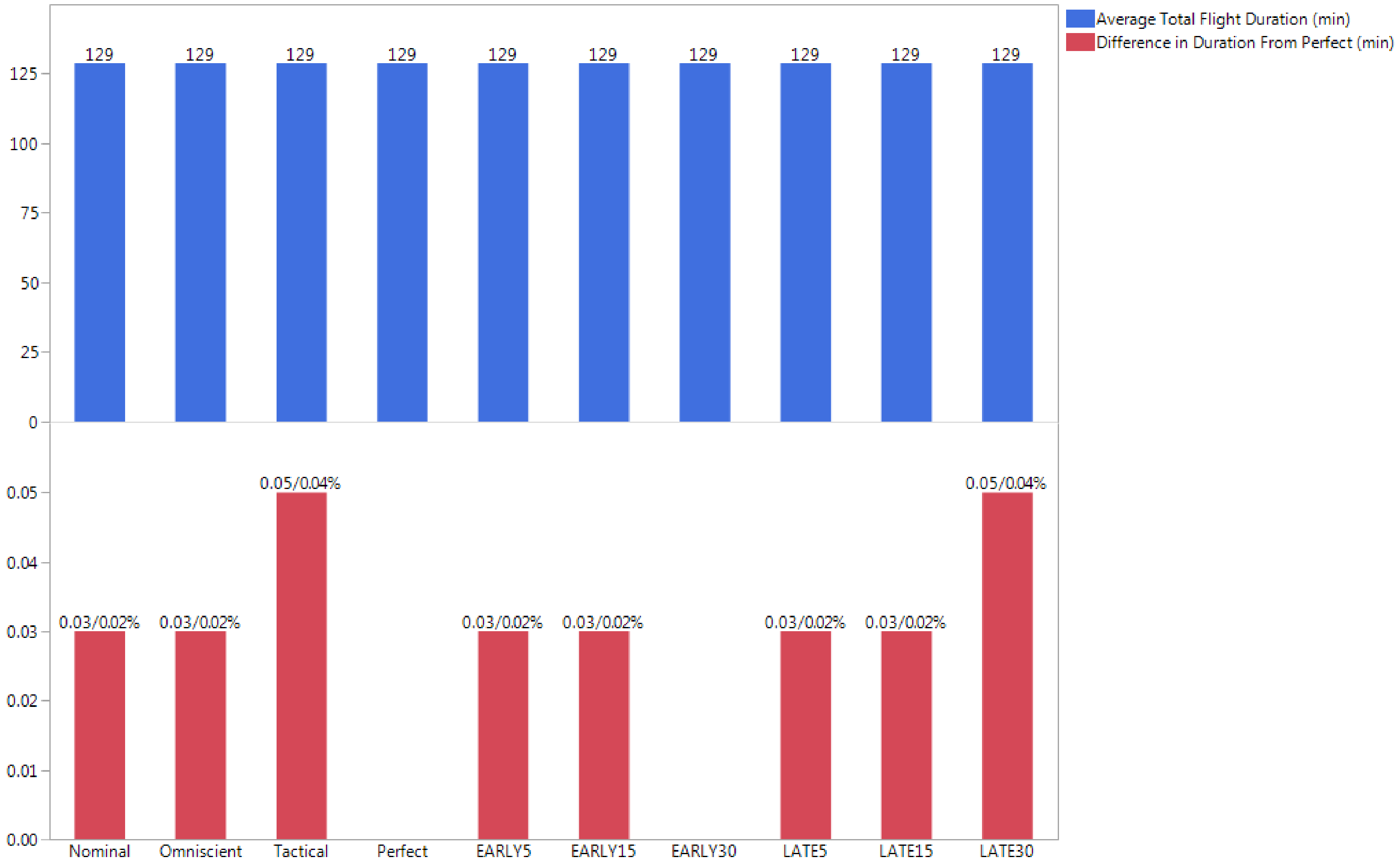

Figure 67: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Departure Flights Through COKEM

Figure 68: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Flights Through COKEM

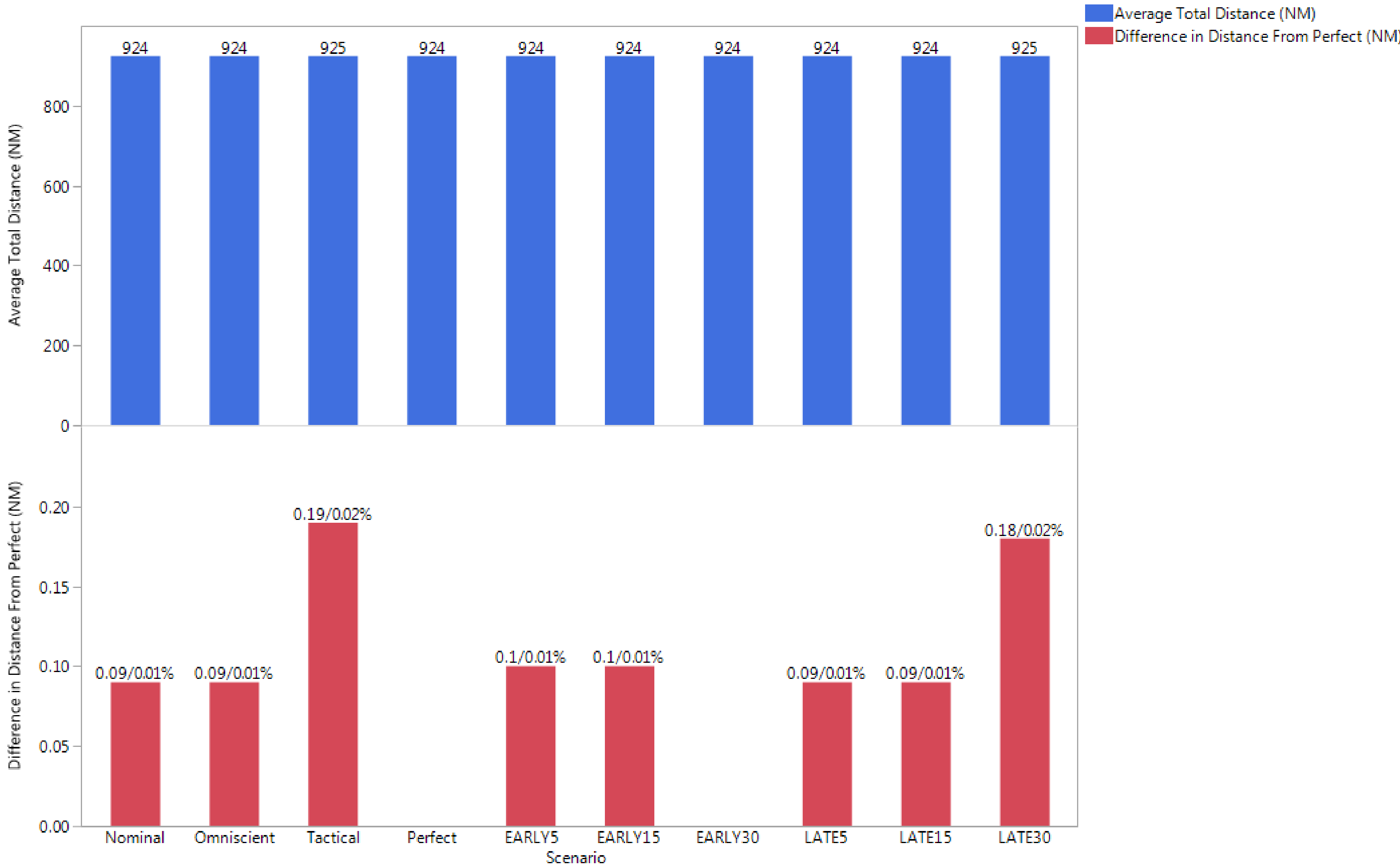

Figure 69: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Departure Flights Through COKEM

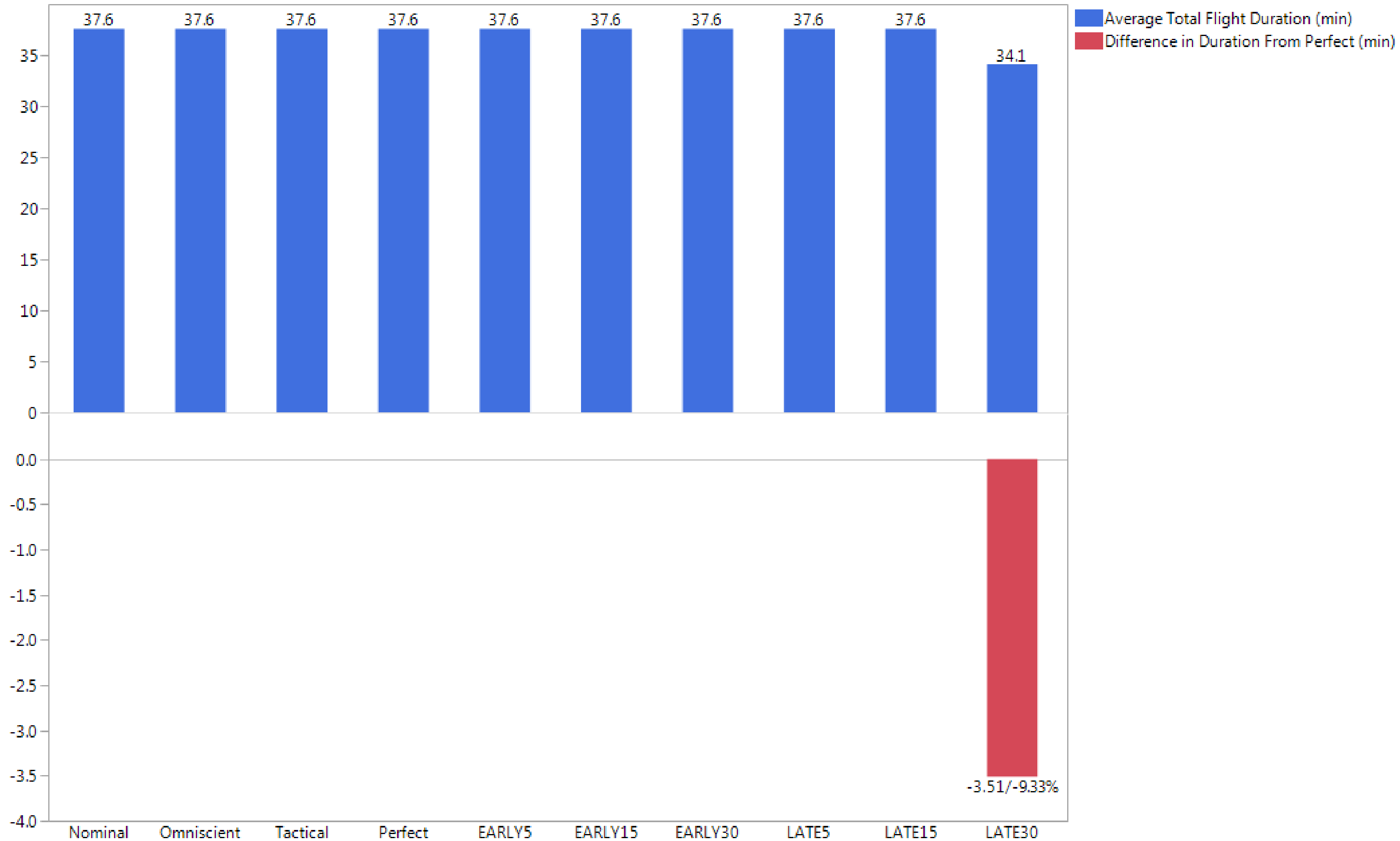

Figure 70: Avg. Change in Flight Duration (min) from Perfect Scenario for Indirectly Impacted Departure Flights Through NOVSS

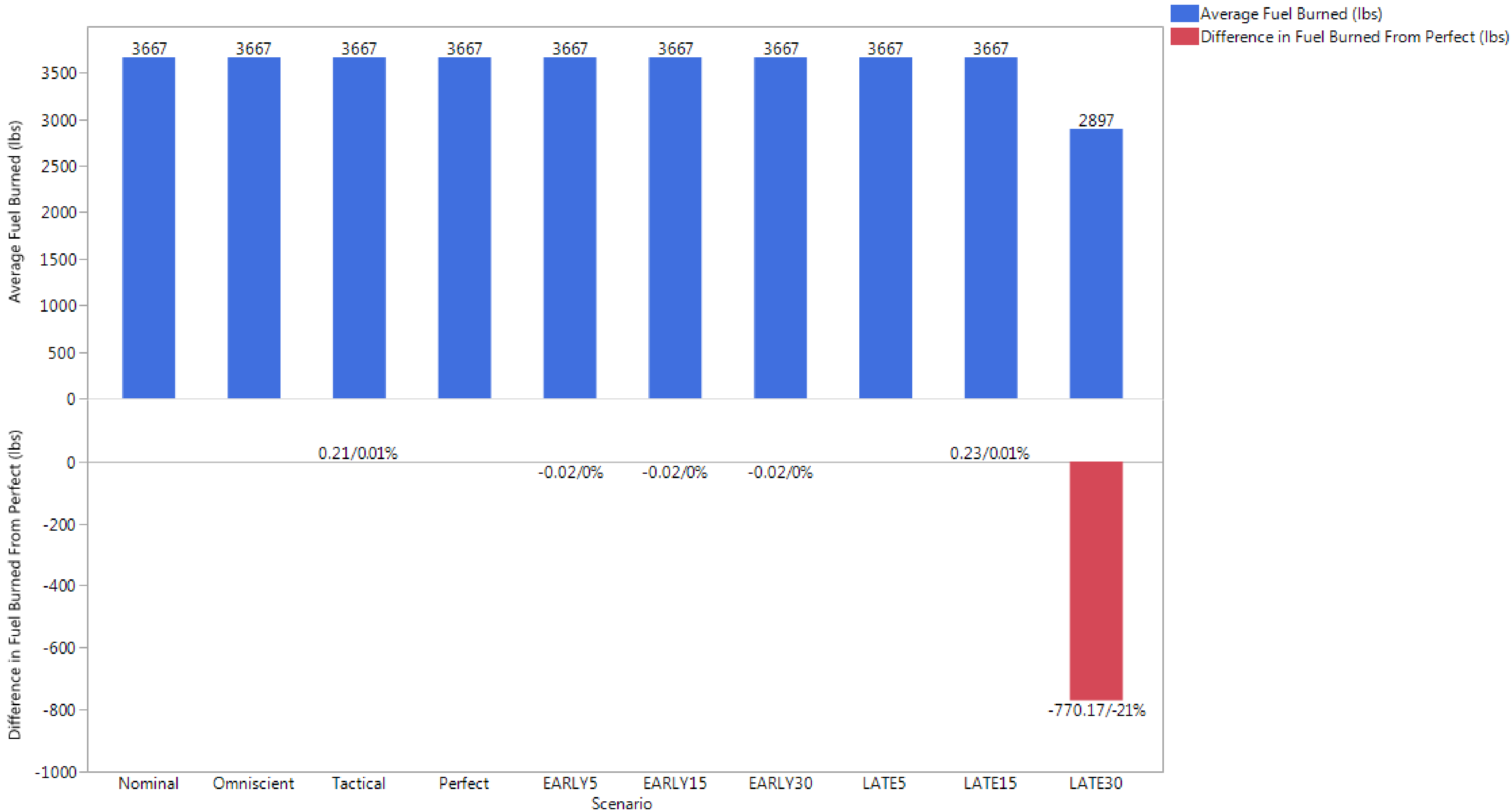

Figure 71: Avg. Change in Fuel Burn (lbs) from Perfect Scenario for Indirectly Impacted Departure Flights Through NOVSS

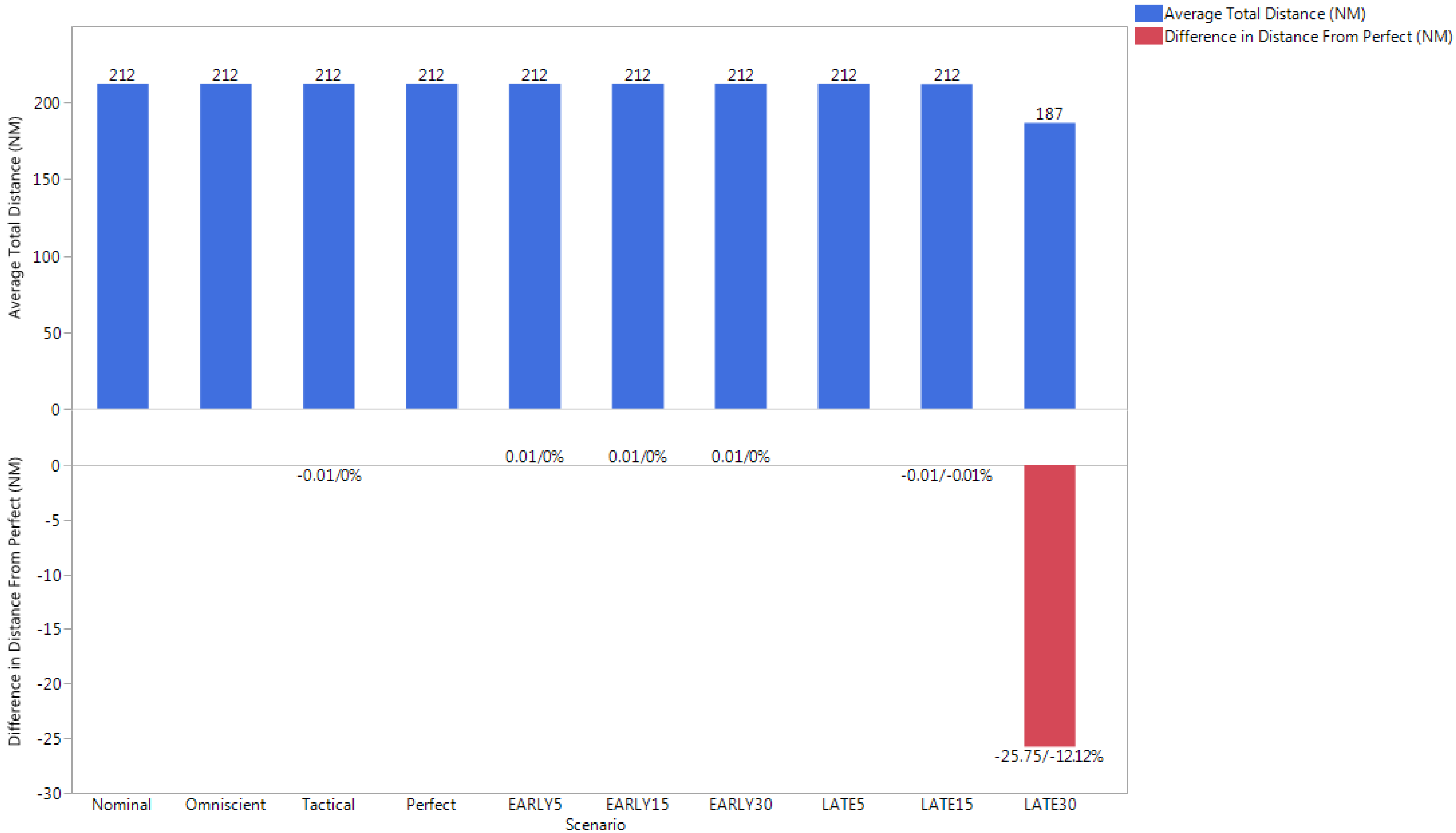

Figure 72: Avg. Change in Flight Distance (NM) from Perfect Scenario for Indirectly Impacted Departure Flights Through NOVSS

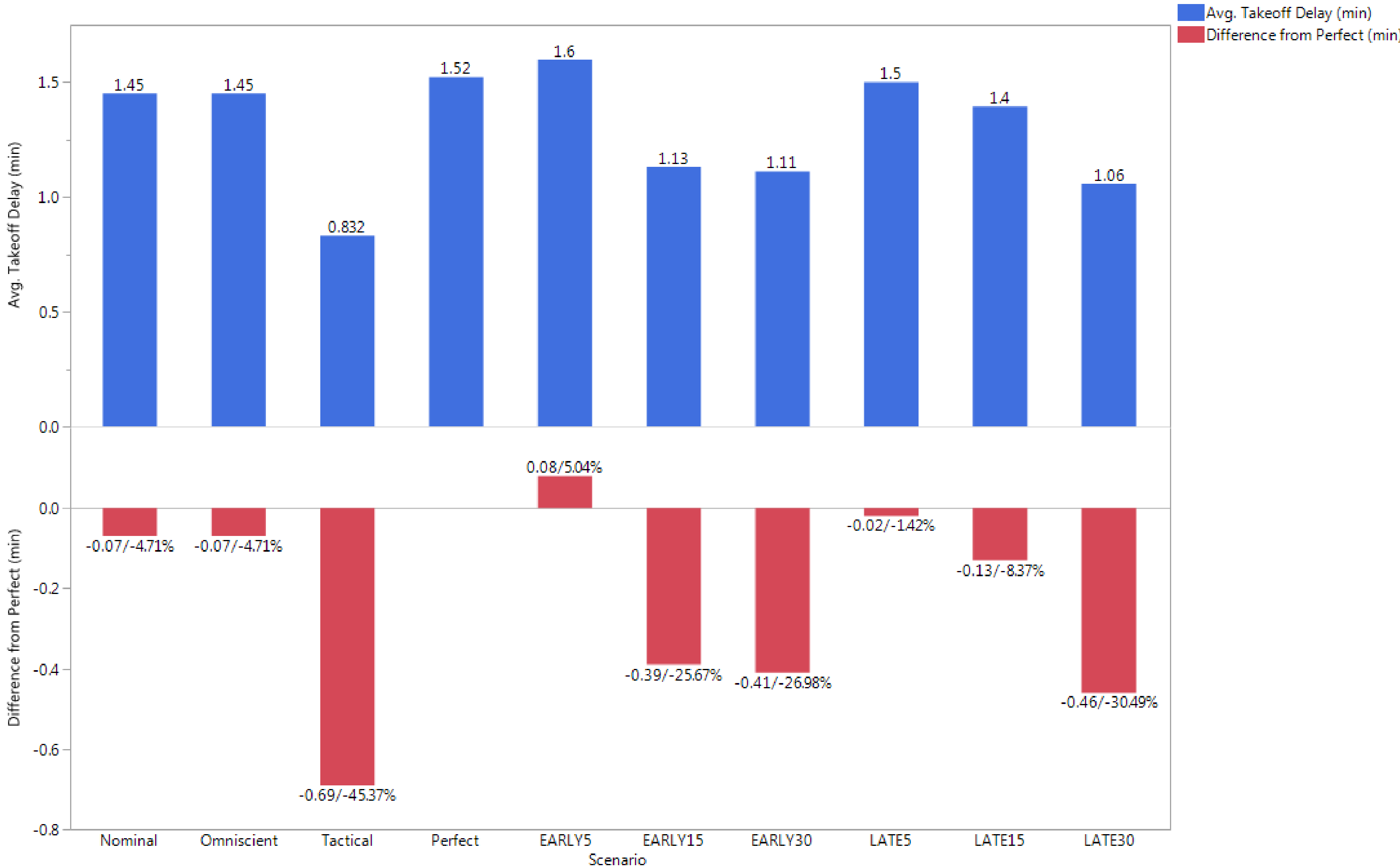

Figure 73: Avg. Departure Delay (min) for Indirectly Impacted Departures Through COKEM

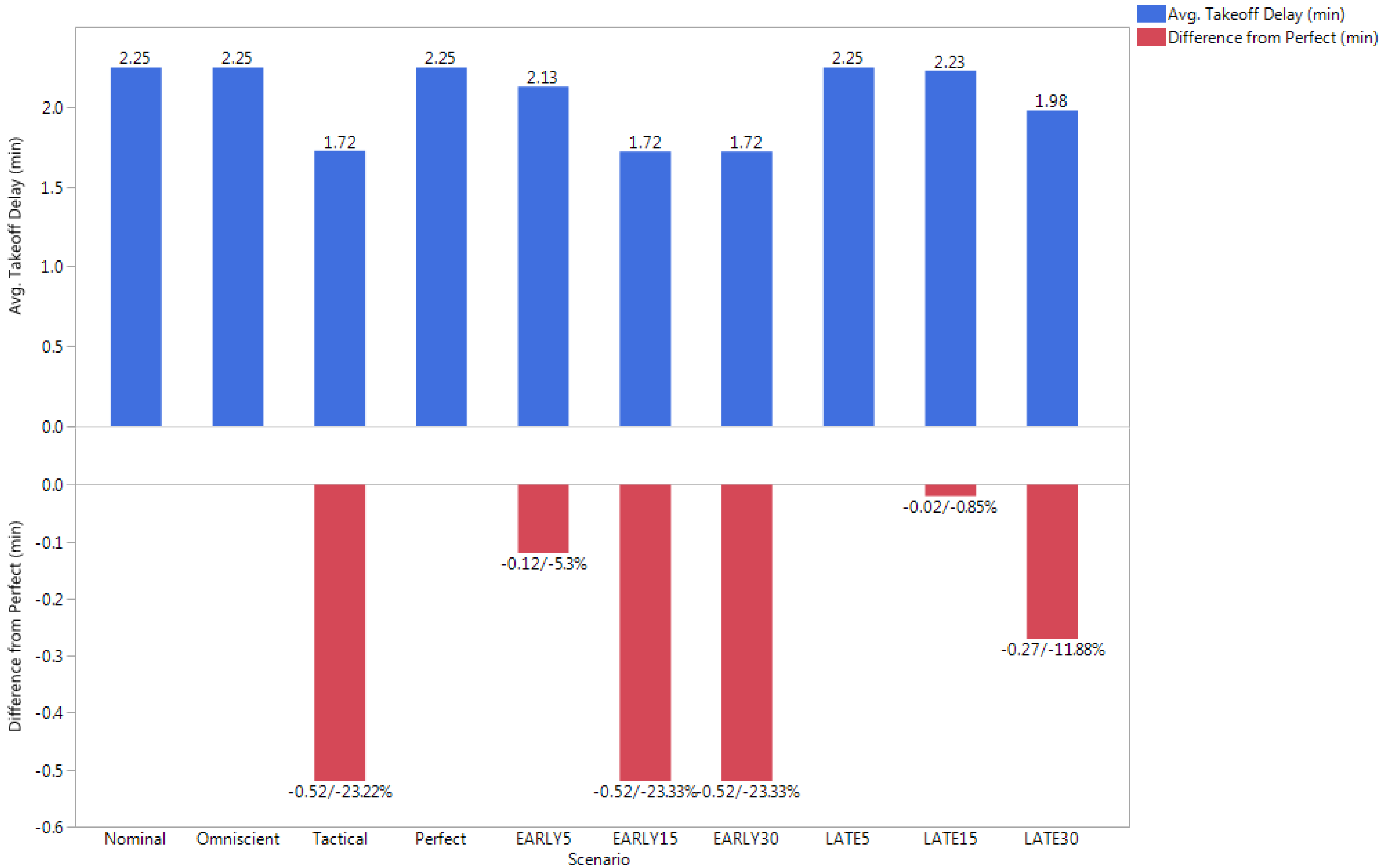

Figure 74: Avg. Departure Delay (min) for Indirectly Impacted Departures Through NOVSS