

Uneven inflation load share trends in clusters[‡]

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The use of parachute clusters for payload recovery is still seeing widespread use ever since the early days of WWII. By involving the (near) simultaneous deployment of several smaller and identical canopies connected to the payload, cluster systems offer flexibility in tailoring to needed descent rates and load management, as well as providing robustness against individual canopy deployment or opening failure. Their downside, of course, resides in the possibility of differing inflation rates by each cluster member as caused by deployment variability, canopy-to-canopy interference, etc. Such variability leads to the *lead-lag* phenomenon, which causes uneven loading among the parachutes, often times leaving a single canopy (the “leader”) to take up a significant portion of the system’s inflation loads. Herein we investigate how serious such an effect can be in terms of the number N of cluster members, underinflation drag of the lagging canopies, inflation swiftness of the leader in comparison to the laggards’, disreefing cutter activation staggering and pre-disreefing drag area. Two new metrics are used to highlight load share unevenness, namely, the peak and average leader canopy riser load in comparison to the leader’s drag during no-lead-lag; and leader peak load, as compared to total peak load. Results are calculated from data collected in NASA’s Orion/CPAS test program, as well as from simple algebraic expressions informing leader drag as sustained in different cluster systems (i.e., of different N) and varying leader inflation time relative to the laggards. Generally, using large- N cluster systems confers better load sharing among canopies. However, and in deployments where significant lead-lag occur, large- N systems may feature greater leader overload excursions, oftentimes in excess of 50% the no-lead-lag levels. These excursions are particularly made worse when cutter activation among the members are far from simultaneous and the laggards’ pre-disreefing drag area is small in comparison to the leader’s.

Nomenclature

C_{D0}	=	steady descent drag coefficient based on the nominal diameter
C_{Dref}	=	steady descent drag coefficient based on a “reference” diameter
CDT	=	Cluster Development Test (series)
CPAS	=	Capsule Parachute Assembly System
CQT	=	Cluster Qualification Test (series)
D_0	=	nominal diameter of a fully dis-reefed and inflated canopy
D_{ref}	=	reference diameter
$F_D(t)$	=	generic drag force
$F_D^{(j)}$	=	drag force generated by canopy “j” ($j = 1, 2, \dots, N$)
F_{max}	=	maximum (or “peak”) drag sustained during inflation

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g	= constant of gravitational acceleration
I	= parachute force integral $I = \int_{t_i}^{t_f} T(t) dt / T_{\max} (t_f - t_i)$
m_{leader}	= mass of the leading parachute
m_{laggard}	= laggard's parachute mass (= m_{leader})
$M_{\text{effective}}$	= effective payload mass decelerated by the leading parachute
M_{capsule}	= payload (or “capsule”) mass
N	= Number of parachutes in a cluster
PLF	= Peak load fraction
$R_{<F> \text{ leader}}$	= average force ratio $\langle T_{(ll)}^{\text{leader}} \rangle / \langle T_{(nll)}^{\text{leader}} \rangle$
$S(t)C(t)$	= instant canopy drag area during inflation
$S_{\text{mouth}}(t)$	= instant canopy mouth area during inflation
S/N	= serial number
$S_{\text{ref}} C_{D\text{ref}}$	= drag area of a fully opened canopy during steady descent
S_{ref}	= canopy surface area based on the nominal diameter
t_i	= time at the beginning of inflation
t_f	= time at the end of inflation
t_{infl}	= inflation time (unreefed, reefed, or disreefing)
t_{final}	= duration of a cluster inflation stage, as set by reefing cutter activation by the next stage's leader
T_j	= riser force ($j = 1, 2, \dots, N$)
T_{leader}	= riser force generated by the leader canopy (= T_i)
$V(t)$	= instant fall rate during inflation
V_{desc}	= steady state descent speed post inflation
V_i	= descent speed at the beginning of inflation
V_f	= descent speed at the end of inflation
Greek symbols	
ρ	= air density at suspension line stretch or beginning of next inflation stage
Abbreviated superscripts and subscripts	
desc	= (steady) descent
ll	= lead-lag
nll	= no-lead-lag
Other symbols	
$\langle G \rangle$	= time-averaged value of any time-varying function $G(t)$ $\langle G \rangle = \int_i^f G(t) dt / (t_f - t_i)$

I. Introduction

A. Historical perspective and goal.

The use of parachute clusters for payload recovery is still seeing widespread use ever since the early days of WWII [1]. As many contemporary applications focus on softly landing heavy payloads (1000 lbs. or more), cluster design has involved the use of truly large parachutes ($D_0 > 70\text{ft}$), as with the US Army G-16 Cargo Airdrop system [2] and the Orion capsule recovery system [3]. Although the use of a single and large parachute is theoretically possible, e.g., a $D_0 = 184 \text{ ft}^2$ flat circular canopy used to land a 20,000lb payload at 30ft/s, such a system suffers from the very long inflation time required, a possible liability in low-altitude deployment applications, or for its sheer lack of robustness against deployment problems. On the other hand, using several identical but smaller canopies rigged to simultaneously inflate represents a more practical alternative as it allows quick inflation while still meeting slow landing speed requirements. The downside of the approach is, of course, the possibility of each cluster member inflating at different rates, as caused by deployment variability among each cluster member, canopy-to-canopy interference, etc. Such effects are particularly important in large cluster systems featuring long inflation times and slow descent rates [4]. In turn, inflation rate nonuniformity, or *lead-lag*, entails unevenness in the drag buildup in each canopy and corresponding riser force applied to the payload (a.k.a., “uneven load share”), with possible excursions well exceeding the rated canopy or component ultimate strength (e.g. see [5-10] in the more recent

NASA Orion/CPAS application). In what follows, and during each (cluster) inflation stage under consideration (there are three such stages in Orion/CPAS [3, 12, 13]), a “leader” canopy is seen as inflating more rapidly than the others (“laggards”), to develop excess peak load share *and to remain as leader, more or less, in riser load throughout that stage.*

Over the years, several lead-lag cures have been proposed – and some implemented – such as the use of skirt reefing line(s) [3, 8], secondary/internal parachutes [2], linked canopies [10] and center lines (as mentioned in Heinrich, Noreen and Monahan [9]). And yet, no general analysis has been presented to explore the effect(s) of several other design or deployment parameters that could influence uneven load share, such as the number (N) of parachutes in the cluster, instant drag area particularly prior to disreefing, disreefing cutter time and inflation time disparity among the cluster members, etc. Such an analysis is carried out here via the use of two metrics. Namely, via the ratio of the average load experienced by the leading canopy during lead-lag, in comparison to the average load it sustains when all N canopies are simultaneously and fully inflating (a so-called “no-lead-lag” scenario); and secondly, to the ratio of the peak force sustained by any given canopy (including the leader) as compared to the summed peak loads of all cluster members. In the former analysis, and after use of the momentum-impulse theorem [11, 12], one ends up with algebraic expressions written in terms of N , the time-averaged laggards’ drag, and other parameters. These can be used to answer the type of questions pertaining to load scaling versus N , leader and laggard inflation time, etc. In the latter approach, and per data collected during the NASA CPAS program [3, 12], the peak force-to-total peak force ratio readily describes share unevenness severity in terms of the hastening or delaying disreefing cutter activation among the cluster members, and pre-disreefing drag area generated by each canopy.

This paper will be organized as follows. Section II discusses the application of the momentum-impulse theorem [11] to the leader and laggard canopies of a general cluster system, with the goal of calculating the leader’s peak and average drag that result in both lead-lag and no-lead-lag scenarios. Scaling trends are highlighted using data collected during the NASA CPAS program [3, 12]. Section III discusses the peak-force -to- total peak force ratio using the same data, to show new correlations between load share unevenness and disreefing cutter activation and pre-disreefing drag area. This is followed in section IV with a discussion on the connection between the two metrics and the trend agreement that arises. The paper ends with concluding remarks in Section V.

II. Leader average load during lead-lag vs. no-lead-lag

A. Cluster system parachute inflation per the Momentum-Impulse Theorem

The derivation begins with the identification of all forces and kinematics relevant to a parachute cluster system (Fig. 1). The clusters discussed herein share several features with the 2- and 3- test parachutes tested in the NASA CPAS program [3]. In the interest of simplification, a strictly vertical descent is assumed, along with the omission of payload (or “capsule”) drag. Further, the canopies are imagined as skirt-reefed, and with one or more reefed inflation stages (three such stages in Orion/CPAS). Most importantly, disreefing cutter activation for each cluster member is allowed to occur independently, rather than simultaneously as in past analyses [12]. Although not discussed here, application of the formalism to other disreefing approaches (slider reefing, internal secondary parachutes, etc.) can be carried out as well.

The starting ingredient is the use of the Momentum-Impulse Theorem to estimate the relevant riser forces sustained in a cluster system falling vertically [12]. Considering the payload body force diagram sketched in figure 1 for any inflation stage, the theorem yields the following:

$$(M_{\text{capsule}})(V_f - V_i) = \int_{t_i}^{t_f} (-1)[T_1(t) + T_2(t) + \dots + T_N(t)]dt + (M_{\text{capsule}})gt_{\text{final}} \quad (1)$$

Parameters g corresponds to the acceleration of gravity; and $M_{\text{capsule}}g$ to the weight of the payload, here a crew return capsule, minus the parachutes’ own weights. On the other hand, parameters V_f and V_i correspond to the system’s descent rates at the beginning of the leader’s inflation in the stage under consideration (t_i), and cutter activation of the leader of the *next* disreefing stage (t_f), respectively. One restriction is parameter t_{final} ($t_{\text{final}} \equiv t_f - t_i$) being larger than the leader’s inflation time (t_{infl}), a consequence of a given cluster member staying as the leader throughout a given cluster inflation stage. Finally, variables T_1 , T_2 , etc., refer to the riser tension generated by parachutes #1, #2, etc. (Fig. 1). Note that the vertical axis in the figure is pointing downwards and that the riser angles to the vertical are assumed small (altogether omitted in this analysis).

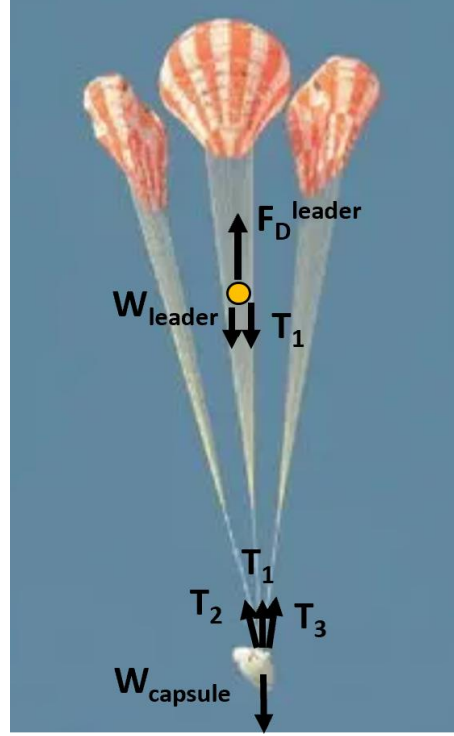


Figure 1. Body force diagram for the capsule “system” and “leader” parachute (here represented by the orange circle) in a $N = 3$ cluster. Symbols T , F_D and W correspond to the riser tension, drag force and weight, respectively. Photo credit: NASA.

For the inflating leader parachute, the theorem implies:

$$(m_{\text{leader}})(V_f - V_i) = \int_0^{t_{\text{final}}} [(-1)F_D^{\text{leader}}(t) + T_{\text{leader}}] dt + (m_{\text{leader}})gt_{\text{final}} \quad , \quad (2)$$

with $T_{\text{leader}} \equiv T_1$. The mass m_{leader} is the parachute’s canopy mass, and F_D^{leader} the drag it generates. (Here all cluster members have the same mass, i.e., $m_{\text{leader}} = m_{\text{laggard}}$.) Note that both leader parachute and system fall at the same descent rates V_i and V_f . At this point, Eq. (1) can be used to eliminate the T_{leader} -term in Eq. (2), to yield:

$$(M_{\text{effective}} + m_{\text{leader}})(V_f - V_i) = \int_0^{t_{\text{final}}} (-1)F_D^{\text{leader}}(t)dt + (M_{\text{effective}} + m_{\text{leader}})gt_{\text{final}} \quad , \quad (3)$$

with $M_{\text{effective}}$ as the leader’s payload mass that it is effectively decelerating. Such a mass is calculated as:

$$M_{\text{effective}} \equiv M_{\text{capsule}} + \frac{\int_{t_i}^{t_f} [T_2(t) + \dots + T_N(t)] dt}{(V_f - V_i) - gt_{\text{final}}} = M_{\text{capsule}} - \frac{t_{\text{final}} \sum_{j=2}^N \langle T_j \rangle}{|(V_f - V_i) - gt_{\text{final}}|} \quad . \quad (4)$$

Here symbol $\langle T_j \rangle$ corresponds to the time-average of the riser force T_j produced by laggard canopy “ j ” over time interval t_{final} – a measurable input in fully instrumented payloads and one that is independent of the laggards’ individual cutter activation times. Note that the 2nd term in equation (4) turns out negative given the inequality $V_f < V_i$ (with $V_{f,i} > 0$ by convention), thereby conferring $M_{\text{effective}}$ a value that is smaller than M_{capsule} but in amounts that depend on the time history of laggards’ riser loading and canopy drag production. As a final step, Eq. (3) is re-written in terms of the time-average of the leader’s load ($\langle T_{\text{leader}} \rangle$), after approximating the leader drag by $F_D^{\text{leader}}(t) \approx T_{\text{leader}}(t)$ (given $m_{\text{leader}} \ll T_{\text{leader}}$) and using the definition $\langle T_{\text{leader}} \rangle = \int_i^f T_{\text{leader}}(t)dt / (t_f - t_i)$:

$$\langle T_{\text{leader}} \rangle t_{\text{final}} = (M_{\text{effective}} + m_{\text{leader}}) g t_{\text{final}} + (M_{\text{effective}} + m_{\text{leader}}) (V_i - V_f) \quad (5a)$$

This result can be written in a simpler form after factoring out the masses and parameter t_{final} , to result in one expression that can be used in both lead-lag (“ll”) and no-lead-lag (“nll”) scenarios:

$$\langle T_{\text{leader}} \rangle = (M_{\text{effective}} + m_{\text{leader}}) g \cdot \left[1 + \frac{(V_i - V_f)}{g t_{\text{final}}} \right] \quad (5b)$$

Eq. (5b) can be further simplified in the no-lead-lag case (“nll”) where all $\langle T_j \rangle$ have same value (in principle), which per Eq. (1) yields:

$$N \langle T_{\text{leader}} \rangle_{\text{nll}} = M_{\text{capsule}} g \left[1 + \frac{(V_i - V_f)}{g t_{\text{final}}} \right]_{\text{nll}} \quad (6)$$

Taking the ratio of Eq. 5b (for lead-lag “ll” cases) and Eq. (6) finally yields the following, after cancelling out the factors in square brackets:

$$\begin{aligned} R_{\langle F \rangle}^{\text{leader}} &\equiv \frac{\langle T_{\text{leader(II)}} \rangle}{\langle T_{\text{leader(nll)}} \rangle} \approx \frac{(M_{\text{effective(II)}} + m_{\text{leader}}) g}{(M_{\text{capsule}} / N) g} \\ &= N \cdot \frac{\left(M_{\text{capsule}} g - \frac{g t_{\text{final}} \sum_{j=2}^N \langle T_{j\text{-laggard}} \rangle_{\text{ll}}}{(V_f - V_i) - g t_{\text{final}}|_{\text{ll}}} + m_{\text{leader}} g \right)}{M_{\text{capsule}} g} \end{aligned} \quad (7)$$

The first line of Eq. (7) is an approximation to the extent that the factors $\left[1 + (V_i - V_f / g t_{\text{final}}) \right]_{\text{ll}}$ and $\left[1 + (V_i - V_f / g t_{\text{final}}) \right]_{\text{nll}}$ are nearly equal, a result of $g t_{\text{final}}$ being larger than each velocity decrements and of the same value in both lead-lag and no-lead-lag scenarios. (Accounting for their difference can be done in a more detailed analysis.) Note also that the extra factor $\left[1 + (V_i - V_f / g t_{\text{final}}) \right]_{\text{ll}}$ in the second line cannot be approximated away and must be accounted for in the calculation of the load ratio $R_{\langle F \rangle}^{\text{leader}}$ as will be done in Sect. II.B. In similarity with the effective mass ($M_{\text{effective}}$), the value of $R_{\langle F \rangle}^{\text{leader}}$ also depends on the laggard’s inflation history as well as the net amount of drag they generate.

B. Values of lead-lag -to- no-lead-lag load ratio from Orion/CPAS data

In the following, the data collected during the NASA Orion/CPAS test program [3] are used to calculate representative values of $R_{\langle F \rangle}^{\text{leader}}$. Most inputs have been described in [12, 13]. Calculation of the laggard forces can be carried out from knowing the peak load and force integral “ I ” via the use of the identities $\langle T^{\text{leader}} \rangle = I_{\text{leader}} T_{\text{max}}^{\text{leader}}$ and $\langle T^{\text{laggard}} \rangle = I_{\text{laggard}} T_{\text{max}}^{\text{laggard}}$ which, from Eq. (7), leads to the following in 3-parachute clusters (where $M_{\text{capsule}} \gg m_{\text{leader}}$):

$$\frac{\langle T_{(ll)}^{leader} \rangle}{\langle T_{(nll)}^{leader} \rangle} \approx 3 \left(1 - \frac{I_{laggard\#1} T_{max}^{laggard\#1} + I_{laggard\#2} T_{max}^{laggard\#2}}{M_{capsule} g \cdot \left(1 + \frac{(V_i - V_f)}{gt_{final}} \right)_{ll}} \right) \quad (8)$$

and with 2-clusters:

$$\frac{\langle T_{(ll)}^{leader} \rangle}{\langle T_{(nll)}^{leader} \rangle} \approx 2 \left(1 - \frac{I_{laggard} T_{max}^{laggard}}{M_{capsule} g \cdot \left(1 + \frac{(V_i - V_f)}{gt_{final}} \right)_{ll}} \right) \quad (9)$$

The results for the 3-cluster cases are shown in figure 2, which also shows the expected values of the average force ratio $R_{<F>^{leader}}$ in no-lead-lag cases ($R_{<F>^{leader}} = 1$), as well as in an extreme lead-lag case where only one parachute is deployed and inflating ($R_{<F>^{leader}} = 3$; as obtained from Eq. (8) with $T_{max}^{laggard} = 0$). Note the kinematic factor $|(V_i - V_f) - gt_{final}|$ being approximated by $|(V_i - V_f) - gt_{infl}|$, for which t_{final} has been replaced by the leader's inflation time [12] thereby overcorrecting the negative term in both Eqs. (8) and (9). The horizontal axis in Fig. 2 tracks the leader's inflation time in relation to the that of the slowest-inflating laggard during that same lead-lag opening event,

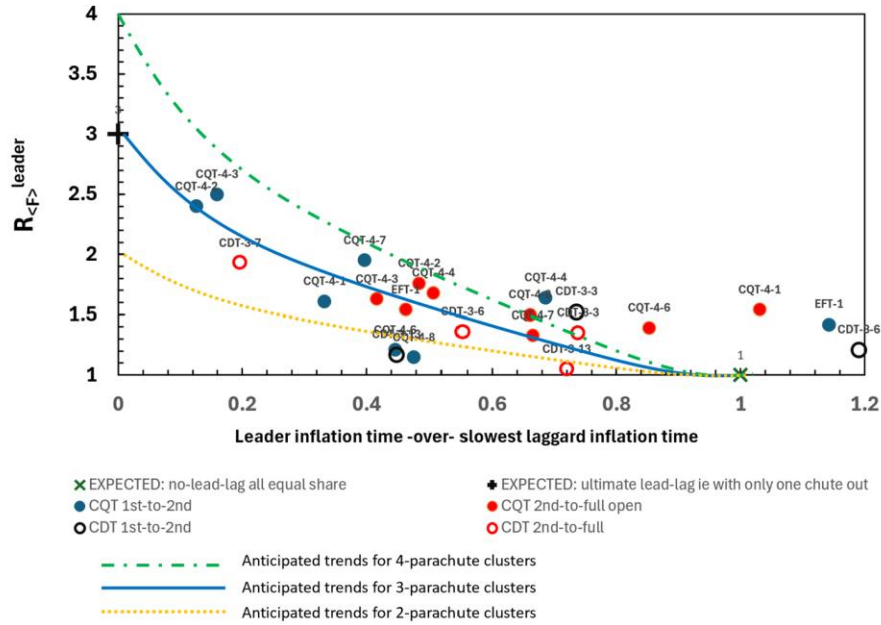


Figure 2. Calculation of the average force ratio $R_{<F>^{leader}}$ ($\equiv \langle T_{(ll)}^{leader} \rangle / \langle T_{(nll)}^{leader} \rangle$) via Eq. (8) using the data of the NASA Orion/CPAS program. The labels correspond to a test drop number. The curves are not data fits but are hand-drawn to track the expected trends for each N -cluster type.

to reflect an obvious correlation in which the leader experiences greater loads (vs. no-lead-lag cases) whenever its inflation time becomes significantly shorter than the inflation time of the slowest laggard. With the leader typically being the first to inflate fully, all data are expected to be characterized by inflation time ratios smaller than unity. The

fact that a handful data points violate this expectation is probably the result of determining “who inflates first” in near no-lead-lag cases where the load force of the leader is similar to those of the laggards (i.e., with differences of 1500lb or less).

Generally, most $R_{<F>^{leader}}$ -values hover around $1.5 (\pm 0.4)$ at most relative inflation times, reflecting the effect of uneven inflation among the laggards from case to case. Of note also are the data at low relative inflation times (less than 0.2) which tend to converge toward the theoretical limit of $N = 3$ (for 3-clusters). Not shown is a similar trend in the 2-cluster cases in which the handful of data at our disposal are trending towards $R_{<F>^{leader}} = 2$ at small relative inflation times (< 0.2) and towards $R_{<F>^{leader}} = 1.1$ at inflation times approaching unity.

Interestingly, figure 2 also shows the expected trends for $N = 2$ vs. 3 and vs. 4. This is a comparison that points to excursions to higher leader loads at large- N (i.e., higher values of $R_{<F>^{leader}}$ at large- N) where the leader inflates more swiftly. As further discussed in the next section, using larger clusters (i.e., larger N) would be accompanied by greater proportions of uneven load shares on the payload, an effect that somewhat negates the benefits of larger clusters involving smaller individual canopies to decelerate smaller effective payload masses near the no-lead-lag regime.

C. Scaling laws

The trends highlighted in Fig. 2 can be further understood from the N -scaling properties of Eq. 7. Regardless of their simplicity, scaling assessments based on the above remain tricky given the several input parameters that may be dynamically linked. For example, decreasing payload mass (at fixed N) incurs greater deceleration and thus smaller values of the time-averaged laggard drag appearing in Eq. (7) (per Eq. (1)). The effect of such a reduction is masked, however, by the reduction in $M_{capsule}$ also appearing in (7) (in the denominator). In such a set up at least, it isn't clear whether payload mass reduction is accompanied by a diminution of leading canopy overload relative to no-lead-lag cases. Although both $\langle F_{D(l)}^{leader} \rangle$ and $\langle F_{D(nll)}^{leader} \rangle$ are expected to decrease, their ratio might do so only minimally. However, the scaling trends become clearer when adding a design-specified constraint. One example is the use of the system's descent velocity ($V_{descent}$) as a fixed parameter (with all canopies deployed, and fully inflated while fully disreefed):

$$M_{capsule} g = \frac{1}{2} \rho (V_{descent})^2 N (S_0 C_{D0stage}) \quad (10)$$

(With again $m_{leader}/M_{capsule} \ll 1$, and the product $S_0 C_{D0stage}$ corresponding to the steady drag area of each fully inflated canopy.) Reducing payload mass at fixed $V_{descent}$, N and ρ , entails a similar reduction in drag area ($M_{capsule} \propto S_0$). In such a context, the ratio in Eq. (7) is to remain mostly unchanged (again), that is, with no changes in lead-lag overloads relative to no-lead-lag drag loads.

Considering the addition of cluster members (N), on the other hand, is also made clearer in the light of Eq. (10). In this case, and after specifying same-descent speed, canopy drag coefficient and payload mass, one has:

$$NS_0 = \frac{2M_{capsule} g}{\rho (V_{descent})^2 C_{D0stage}} = \text{fixed} \quad (11)$$

Thus, and with $S_0 \sim 1/N$, the greater the number of cluster members used in the system, the smaller surface area of each canopy. Also being proportional to canopy surface area are the leader and laggards' inflation drag forces which will also change like $\sim 1/N$. Thus, one expects $\sum_{j=2}^N \langle T^{j-laggard} \rangle_{(ll)} \propto N (1/N) \sim N^0$ in Eq. (7). (Note that with smaller

canopies come smaller canopy masses, which become even more negligible in the above equations.) At fixed- $M_{capsule}$, one is left with a force ratio proportional to N (i.e., $\langle T_{(ll)}^{leader} \rangle / \langle T_{(nll)}^{leader} \rangle \propto N^1$). Thus, going from a 3- to a 4-cluster would increase the overload (relative to no-lead-lag) by 33%, as can also be seen in Fig. 2.

In terms of absolute forces, such scaling to a larger number of parachutes in the cluster would reduce the average leader drag in no-lead-lag cases by a factor $1/N$ (given $M_{capsule} g \approx \langle T_{(nll)}^{leader} \rangle N$) but leave it to near-same levels in lead-lag openings, following Eq. (7):

$$\langle T_{(II)}^{\text{leader}} \rangle \approx \left(1 - \frac{\sum_{j=2}^N \langle T^{\text{j-laggard}} \rangle_{(II)}}{M_{\text{capsule}} g} \right) M_{\text{capsule}} g \quad (12)$$

Ultimately, reducing the leader's load share dominance boils down to increasing the laggard's drag, presumably via rigging adjustment(s) that yield greater amounts of drag area. This is further highlighted in analysis of the next section.

III. Individual peak load to total peak load - flight test data trends

Focusing on the peak loads generated by both leader and laggards *in any given test*, rather than exclusively on the leader's average load in lead-lag versus no-lead-lag produces another insightful perspective. This also spares the analyst from looking for no-lead-lag data which may not be available where the number of test drops is limited. Formally, and for a 3-cluster, the individual peak load fraction (or “PLF”) for a given parachute (“i”) is defined as follows

$$PLF(i) = \frac{T_{\text{peak}}(i)}{T_{\text{peak}}(1) + T_{\text{peak}}(2) + T_{\text{peak}}(3)} \quad (13)$$

a formula in which the peak load generated by all cluster member contributions are summed. Applications of the approach and lessons learned in 2- and 3-clusters are as follows.

A. Data Trends for Two-Parachute Clusters

A recent examination of Orion drop test and spacecraft reentry data was conducted using consistent post-processing methodology. All data were from parachutes with the same geometric porosity from the final design, though some tests used an earlier second stage reefing line length. Some other tests had over-inflation control lines, which were omitted in the final CPAS design. Seven tests used two-parachute clusters and seventeen tests used three-parachute clusters for a total of 65 individual parachute demands. Additional flight tests with skipped stage

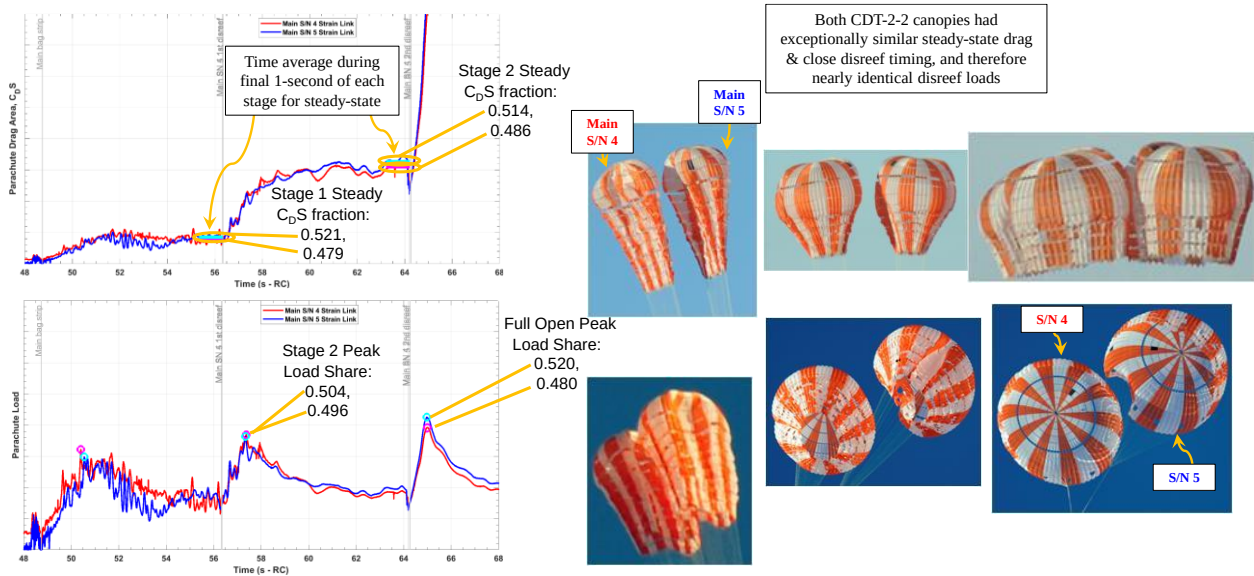


Figure 3. CDT-2-2 displayed very even load share between canopies.

configurations were not included in this study. In general, Orion main parachutes tend to have similar initial inflation performance, but tend to diverge after deployment, possibly due to differences in relative airflow. Two-parachute tests often have a strong lead/lag designations both in visible size (and therefore drag area) and peak

inflation load, though the designation can change from stage to stage. The largest drivers of disreef loads are the steady-state drag areas at the end of each reefed stage and the stagger in disreef timing.

Cluster Development Test (CDT)-2-2 had remarkably similar performance between the two canopies in drag area, load share, disreef timing, and physical presentation, as shown in Fig. 3. The steady-state drag areas at the end of reefed stages were determined from a time average of the final 1-second interval before the earliest disreef event. Steady-state drag area fractions were computed based on each average divided by the total cluster drag area. The peak individual riser load was automatically determined as the maximum over each stage and each load share was computed as the peak load divided by the sum of the peak loads. Note that load share calculations are time independent, which is to say that individual peak loads do not occur at the same time, so the denominator is larger than the actual measured peak cluster load. This test provides an excellent baseline from which to evaluate lead-lag trends, with an almost perfect 50/50 split.

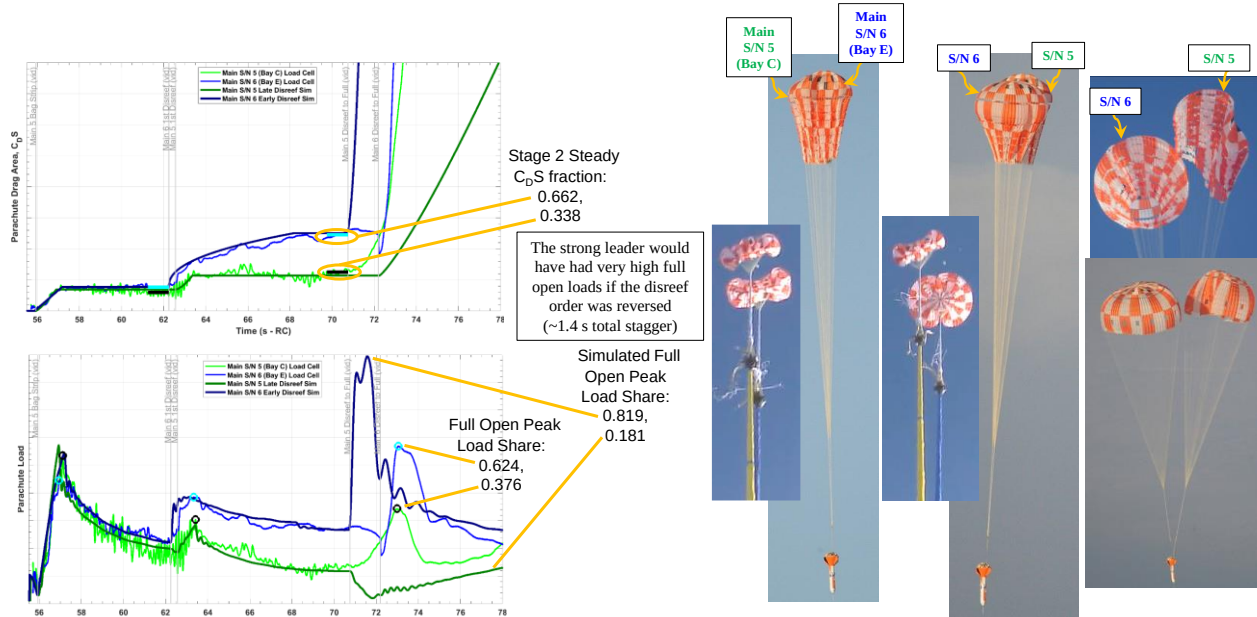


Figure 4. The dominant canopy in CDT-3-2 had a large delay in disreef time going into full open, yet still took a relatively large load share. Simulated loads are much higher if the disreefing timing was reversed.

CDT-3-2 (Fig. 4) showed a more typical lead-lag situation for two-parachute clusters. After a similar first stage inflation, the canopies diverged in size during second stage. The lead canopy disreefed to full open about 1.4 s after the less-dominant canopy, yet still took a higher percentage of the full open load. A simulation of a scenario where the cutter timing was reversed indicates the leader would have taken the largest load of the CPAS campaign. Both the actual data and this theoretical case are included in the overall trends to bound the model.

The most extreme case of uneven load share experienced during the test campaign was CDT-3-15, as shown in Fig. 5. A leader emerged during deployment and maintained its dominance, aided by disreefing slightly early in both stages. The CPAS design was modified for only this test with an extremely short riser, which may have contributed to the discrepancy. The final load share split was nearly 80/20.

B. Data Trends for Three-Parachute Clusters

Orion data confirm that an additional parachute tends to even out the extreme cases, which one would intuit from statistical probabilities alone, though there may be modulating effects due to the physical configuration.

The first spaceflight for Orion was Exploration Flight Test (EFT)-1. The uncrewed spacecraft landed safely under three main parachutes, which performed in a typical manner, shown in Fig. 6. Although one canopy was slightly dominant at the end of second stage, it was the last to disreef, reducing the potential full open load share.

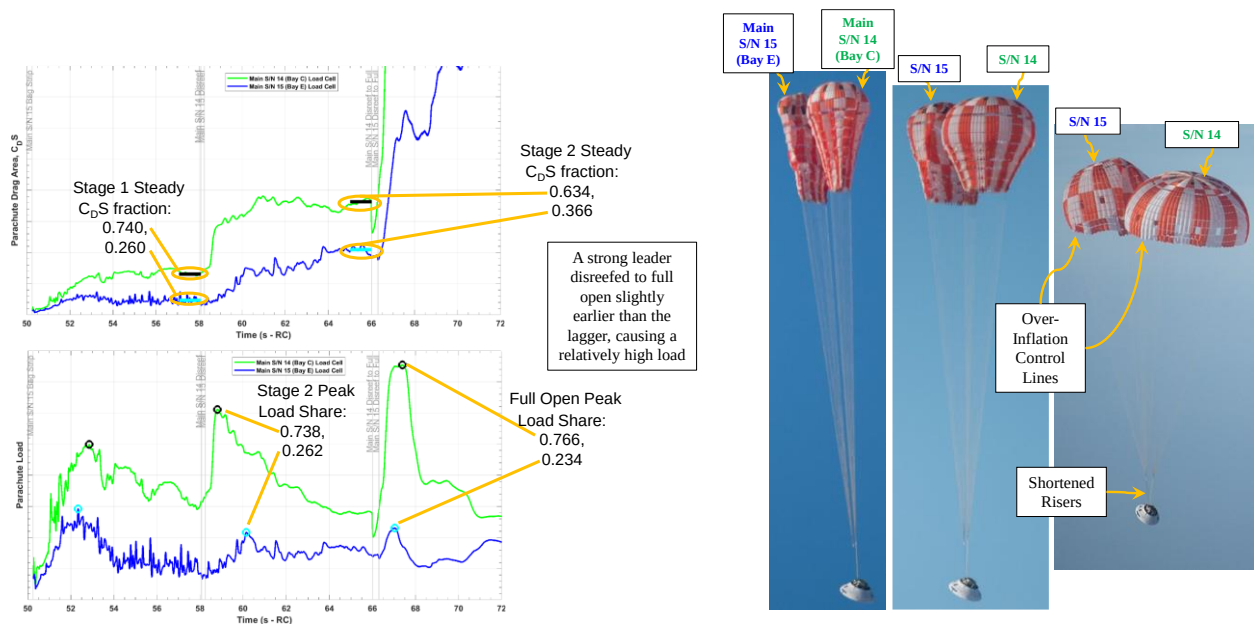


Figure 5. CDT-3-15 had the most uneven load share of all CPAS tests, possibly due to the nonstandard shortened riser lines.

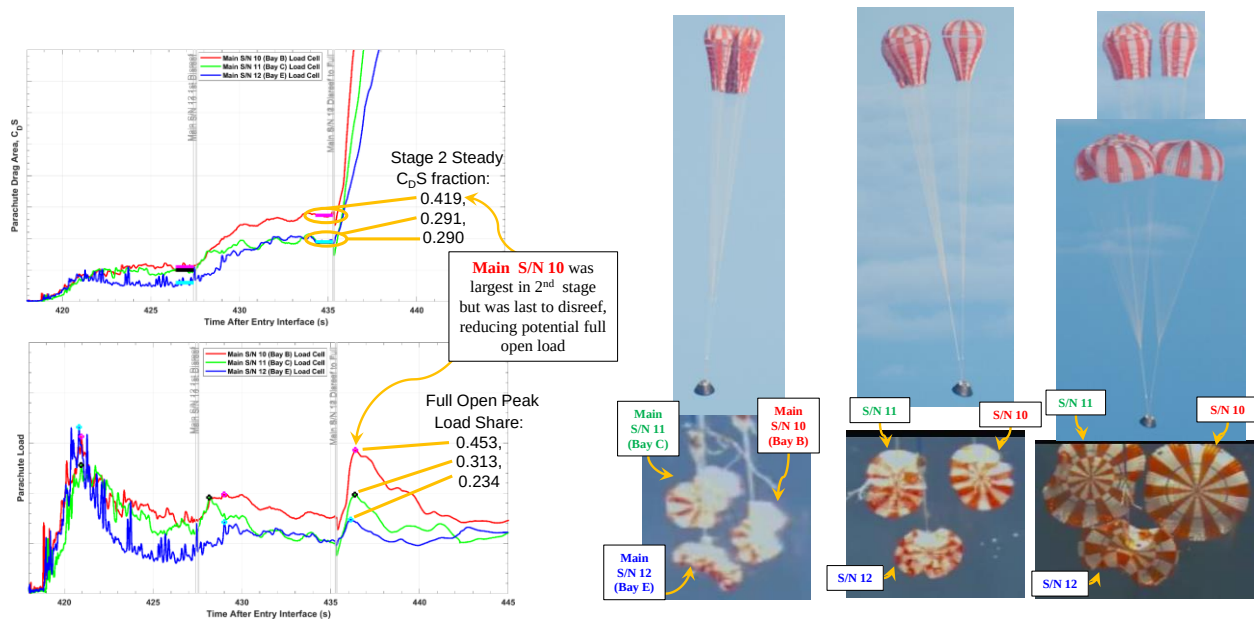


Figure 6. EFT-1 had relatively typical three-parachute performance.

The second spaceflight for Orion was Artemis-1 (Fig. 7), which also had a typical performance for all three main parachutes. In this case, the canopy with slightly higher drag at the end of the second stage disreefed first, resulting in a slightly higher load share than EFT-1. Early CPAS design guidance assumed a 50/25/25 load share based on Apollo experience. Given that both spaceflights to date have already seen up to that amount, more extreme cases are expected for future flights, which are predicted with robust Monte Carlo simulations.

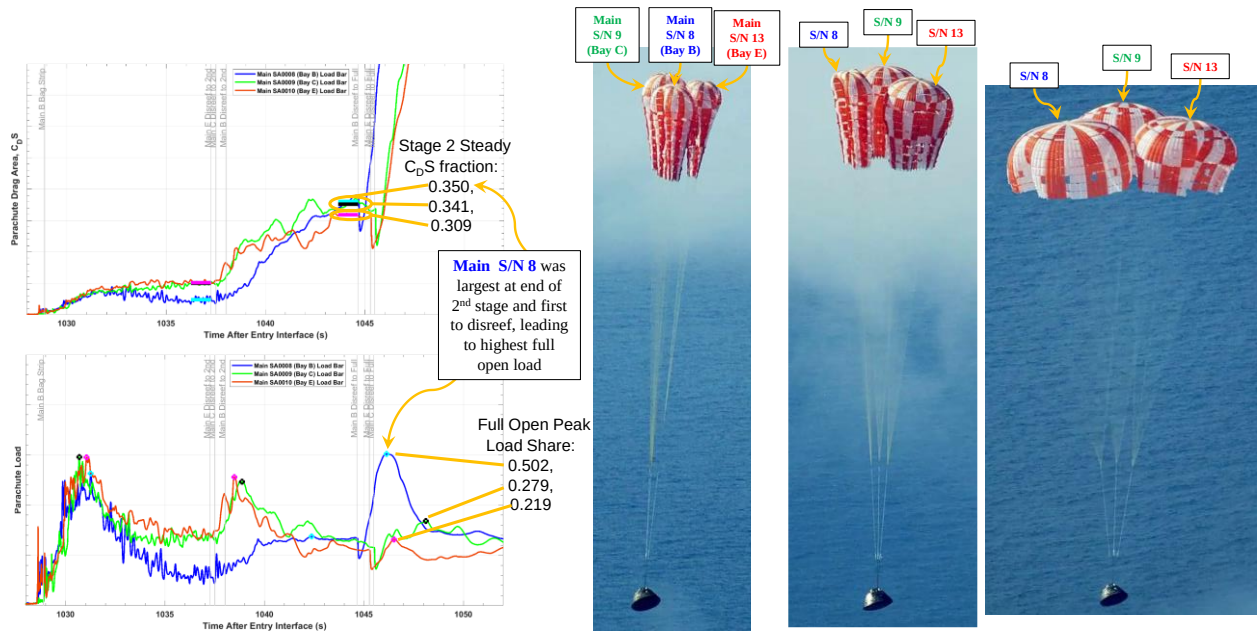


Figure 7. Artemis-1 had relatively typical three-parachute performance.

A survey of the test data shows that CDT-3-7 had the most extreme disreef load case during full open, as shown in Fig. 8. The parachute with the largest drag in second stage was also the first to disreef to full open, leading to a relatively high full open load. The highest absolute riser load for a three-main configuration was actually during the first stage of another test (CQT-4-4), which occurred beyond the deployment envelope through a non-flight-like freefall, and is therefore outside the scope of this paper. The highest three-main disreef loading was still lower than several two-parachute tests, which were fewer in number. Information from both configurations allows for a sensitivity analysis in the next section.

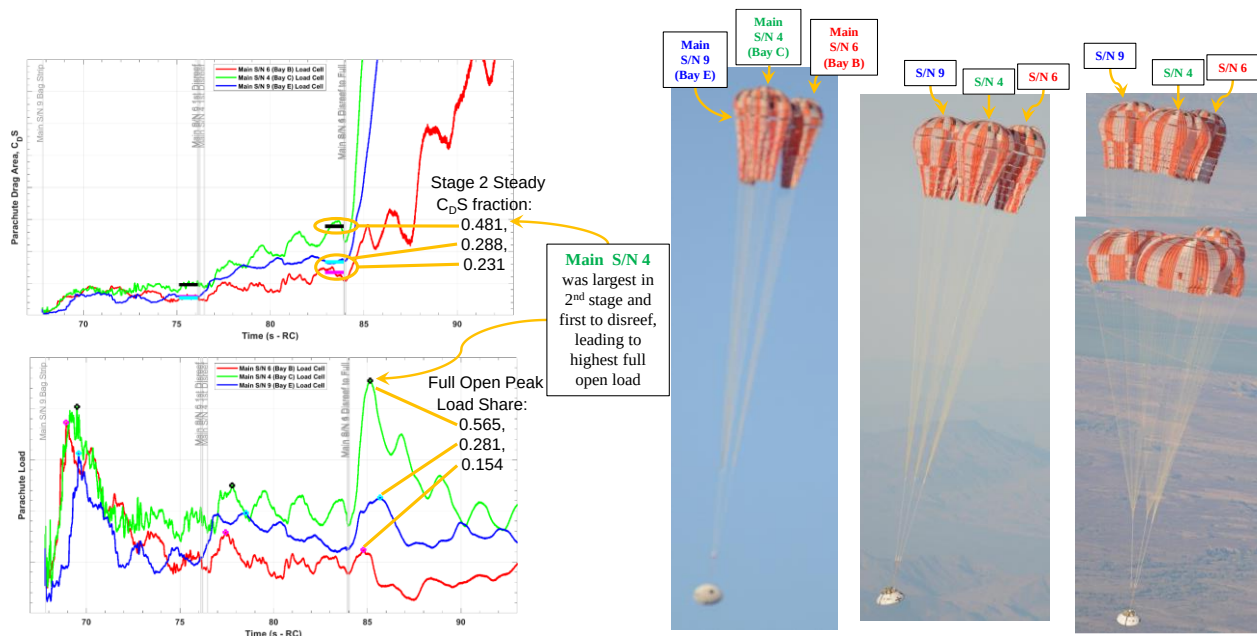


Figure 8. CDT-3-7 had the most extreme full open load share for a cluster of three parachutes.

C. Combined Data Trends for Driving Factors

To visualize loading trends, the influence of drag area fraction and disreef stagger can be plotted in two horizontal dimensions with the resulting peak load share in the vertical dimension. A series of plots were created to build up a comprehensive picture.

Figure 9 shows the second stage loads and drivers. The two-parachute tests in (a) each have two data points and the three-parachute tests in (b) each have three data points. Surfaces are fitted to the data to indicate trends. As with previous discussion, a primary driver is an increase in steady-state drag area just before disreef. The three-parachute configuration generally has a lower variation in the drag area fraction dimension because there are more parachutes to share the system drag. Disreef stagger is plotted relative to the cluster average, such that an early disreef has a negative value associated with higher loads (the axis is reversed for visualization). Dispersion in reefing cutters are generally proportional to delay column time, so the 8-second nominal first stage has a lower dispersion than the 16-second nominal second stage cutter (shown later). The smaller number of samples in (a) have a narrower dispersion in disreef stagger than larger number of samples in (b). Loads are generally lower in (b) because a cluster of three decelerates the system faster than a cluster of two and will have lower dynamic pressure (and therefore lower individual loads) at each disreef event. A case with a large starting drag area and an early disreef will have the largest expected disreef load. The trends generally hold for the combined data set in (c), which indicates that the physics are consistent for both configurations. The extreme corner case in (c) has not yet been experienced in flight and is inferred through extrapolation.

The data for full open disreef loads are plotted in Figure 10. The extreme discrepancy in disreef time on CDT-3-2 was probably due to using cutters from multiple lots, though it has not been thoroughly investigated. Orion flight configuration requires all reefing cutters to originate from the same lot to minimize stagger. As mentioned previously, a simulation of the opposite cutter timing offers additional theoretical data (plotted with dashed lines) bounding all four corners in (a). The surface fit in (b) is not as stable using only three-parachute data, but the combined data set in (c) shows consistent trends.

IV. Connecting the two metrics

Connecting the metrics discussed in Sects. II and III starts with expressing the peak load fraction (PLF) of Eq. (13) in terms of the average force ratio $R_{<F>^{leader}}$ (Eqs. (7) and (8)) as follows, i.e. in the case of a 3-cluster in which canopy #1 is the leader:

$$\begin{aligned}
 \frac{1}{PLF(1)} &= \left[1 + \frac{T_{\max}^{(2)} + T_{\max}^{(3)}}{T_{\max}^{(1)}} \right] \\
 &= \left[1 + \frac{\left(\langle T^{(2)} \rangle / I^{(2)} \right) + \left(\langle T^{(3)} \rangle / I^{(3)} \right)}{\left(\langle T^{(1)} \rangle / I^{(1)} \right)} \right] \\
 &= \left[1 + \frac{I^{(1)} \left(\langle T^{(2)} \rangle + \langle T^{(3)} \rangle \right)}{I^{(2)} \langle T^{(1)} \rangle} \right] \\
 &= \left[1 + \frac{I^{(1)} M_{\text{capsule}} g \left\{ 1 - \frac{R_{<F>^{leader}}}{3} \right\}}{I^{(2)} \langle T^{(1)} \rangle} \right]
 \end{aligned} \tag{14}$$

(Note that in the second line of Eq. (14), the identity $\langle T \rangle = IT_{\max}$ was utilized again.) In an extreme lead-lag scenario where the laggards' load is near zero (and $R_{<F>^{leader}} = N$), Eq. (14) leads to $PLF = 1$. On the other hand, and in no-lead-lag scenarios where the force integrals I are similar in value, one has $\langle T^{leader} \rangle = M_{\text{capsule}} g / 3$ so that the force ratio becomes $R_{<F>^{leader}} = 1$ and $PLF = 1/3$. Such bounds on PLF are borne out in Figs. 9-10 in which the leading canopy PLF -value is bounded in between 0.33 and 1.00. (Too little data is available for the 2-cluster cases which should show $0.5 \leq PLF \leq 1$.) The bottom line here is that both approaches to load share investigation ultimately yield consistent predictions and bounds.

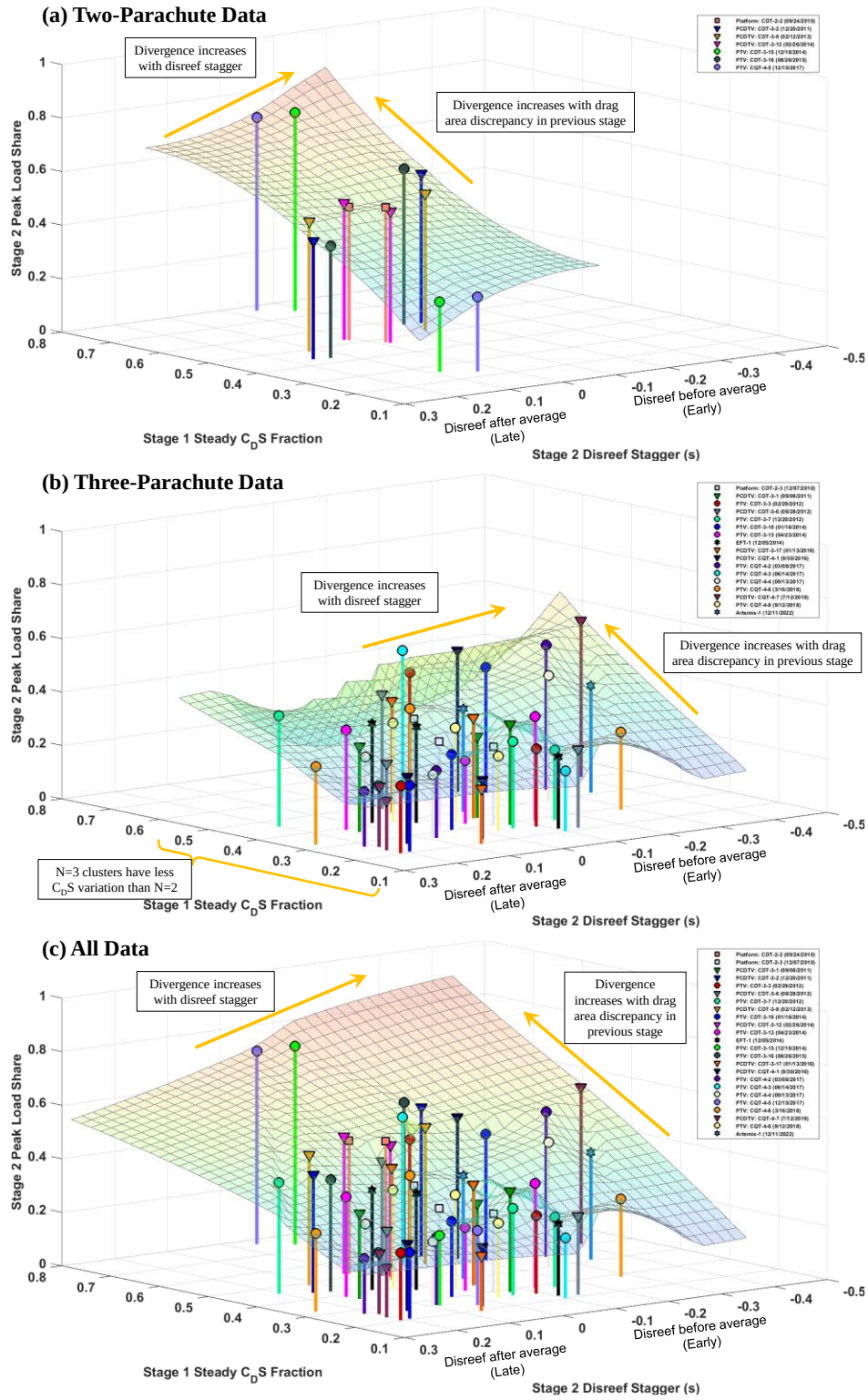


Figure 9. Trends for peak second stage load share are plotted vertically. The inputs of steady-state drag area at the end of first stage and disreef stagger are plotted horizontally. Two-parachute test data are plotted in (a), three-parachute test data are plotted in (b), and the combined set are plotted in (c).

V. Concluding remarks

By design (but with some exceptions [10]), the parachutes of a cluster can inflate at different rates, as caused by deployment variability among each cluster member, canopy-to-canopy interference, etc. Such variability causes lead-lag which translates into uneven loading among the parachutes, often times leading to a single canopy taking up most of the system's inflation loads. Here we investigated how serious such an effect can be, particularly while considering different cluster designs with different numbers of parachutes, different values of the laggards' underinflation drag, inflation swiftness of the leader (vs. the laggards'), cutter activation dispersion, pre-disreefing drag, etc. The key conceptual element embodied in Eqs. (3), (4) (and elsewhere) is the *effective payload mass* that the leader ends up decelerating during its inflation. Thus, the more underinflated the laggards, the higher the leader's effective payload mass (and the lower the mass ratio [12]) and therefore the higher the load share unevenness (Figs. 9-10). Moreover, delayed laggard cutter activation do restrict further canopy drag area and also enhances load share unevenness, particularly where leader inflation times are much shorter than cluster inflation stage duration ($t_{infl} < t_{final}$) (Figs. 2, 9-10). Because of these effects, our analysis has shown that using large- N cluster systems may confer, in lead-lag cases, leader overload excursions that well-exceed 50% the no-lead-lag load (Figs. 2, 9 and 10). Such share unevenness may counteract the advantageous reduction in force per unit drag area conferred by the use of larger number of cluster members (during steady descent at least). Choosing a larger or smaller number of cluster members thus becomes another trade worthy of consideration.

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